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The hadronic transitions from $\Upsilon(2S)$ to $\Upsilon(1S)$

ARGUS Collaboration

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Abstract. Using the ARGUS detector at DORIS, we have investigated the hadronic transitions of the $\Upsilon(2S)$ to the $\Upsilon(1S)$. The decays to $\Upsilon(1S)\pi^+\pi^-$, $\Upsilon(1S)\pi^0\pi^0$ and $\Upsilon(1S)\eta$ where the $\Upsilon(1S)$ subsequently decays into e^+e^- and $\mu^+\mu^-$ have been investigated. The transition via two charged pions has also been studied inclusively. We obtain branching ratios of the $\Upsilon(2S)$ into $\Upsilon(1S)\pi^+\pi^-$ of $(18.1\pm0.5\pm1.0)\%$, into $\Upsilon(1S)\pi^0\pi^0$ of $(9.5\pm1.9\pm1.9)\%$ and into $\Upsilon(1S)\eta$ of less than 0.5% with 90% confidence. From the exclusive events we find the leptonic branching ratios of the $\Upsilon(1S)$ to be $B_{ee}=(2.42\pm0.14\pm0.14)\%$ and $B_{\mu\mu}=(2.30\pm0.25\pm0.13)\%$. Kinematical parameters of the two pion transitions have been investigated in detail and found to be consistent with current algebra and colour-field multipole expansion.

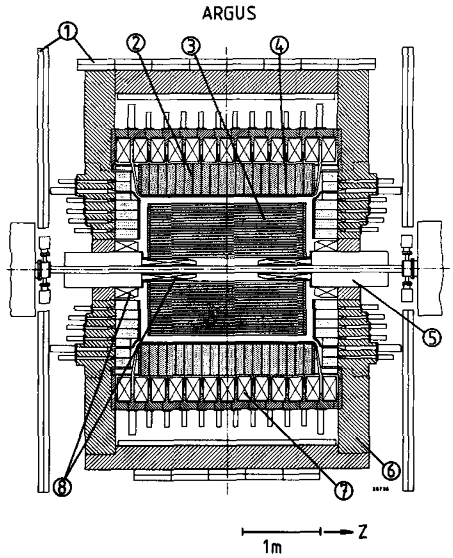

Fig. 1. The ARGUS detector, cut along the beam tube. (1) muon chambers, (2) shower counters, (3) main drift chamber, (4) time-of-flight counters, (5) mini-beta quadrupole, (6) iron yoke, (7, 8) coils

Introduction

With a view to understanding heavy quark bound systems, the hadronic transitions between heavy quarkonia are of considerable interest. They can provide hints on the structure of confining QCD in a nonrelativistic system as well as on the gluon contents of ordinary, light hadrons. The transitions $Q\bar{Q}(2S)\to Q\bar{Q}(1S)+hadrons$ have already been investigated in the J/ψ system [1, 2] and in the Υ system by several groups [3–8]. Here we present an analysis of the complete data sample collected on the $\Upsilon(2S)$ with the ARGUS detector.

The data, comprising an integrated luminosity of 37/pb at the $\Upsilon(2S)$ energy and of 2.7/pb in the continuum at 9.98 GeV, were taken in 1983 and 1984 at the DORIS II electron-positron storage ring at DESY. The ARGUS detector [6, 9] is shown in Fig. 1. It is a solenoidal magnetic spectrometer, with a cylindrical drift chamber in a magnetic field of 0.8 T. We achieve a momentum resolution of

$$\frac{\Delta p}{p}=\sqrt{0.009^2+(0.012\cdot p/(\mathrm{GeV/c}))^2}.$$

The drift chamber is surrounded by time-of-flight and shower counters, arranged as a barrel and two end-caps, a magnetic coil and iron yoke, and finally three layers of proportional chambers for muon identification.

Three different trigger conditions contribute to our event sample. They require in coincidence with a bunch crossing signal:

(1) a total energy $E_{\mathrm{tot}}>0.8$ GeV in each hemisphere of the shower calorimeter, i.e. at $\theta<90°$ and $\theta>90°$ with respect to the positron direction.

(2) three or more charged tracks entering the barrel shower counters, which are defined by a fast coincidence between groups of time-of-flight and shower counters and by a slow coincidence using track masks in the drift chamber. The shower counter information is used to require at least one track in each hemisphere.

(3) a pair trigger defined as in (2), requiring only two tracks, which are back-to-back in azimuth within $\pm60°$.

Using these data, we have investigated the transition $\Upsilon(2S)\to\Upsilon(1S)\pi^+\pi^-$ for both inclusive $\Upsilon(1S)$ decays and the exclusive final states $e^+e^-\pi^+\pi^-$ and $\mu^+\mu^-\pi^+\pi^-$. A search for the decay $\Upsilon(2S)\to\Upsilon(1S)\eta$ with $\eta\to\pi^+\pi^-\pi^0$ and $\Upsilon(1S)\to e^+e^-$ or $\mu^+\mu^-$ has been made and we have reconstructed events of the type $\Upsilon(2S)\to\Upsilon(1S)\pi^0\pi^0$ in $e^+e^-+4\gamma$ and $\mu^+\mu^-+4\gamma$ exclusive final states.

Inclusive final states with $\pi^+\pi^-$

Events of the inclusive $\pi^+\pi^-X$ final state were selected by requiring at least 4 charged tracks from the interaction region, defined as a cylinder of 1.5 cm radius and 16 cm length centred on the interaction point. In order to be insensitive to trigger acceptance, a requirement that at least three tracks enter the barrel shower counters was made.

From these events, all charged tracks with $p_\perp>80$ MeV/c and $|\cos\theta|<0.9$, which fit either to the common primary vertex of the event or to no secondary vertex, are considered as pion candidates, and combined to $\pi^+\pi^-$ pairs. The distribution of the miss-

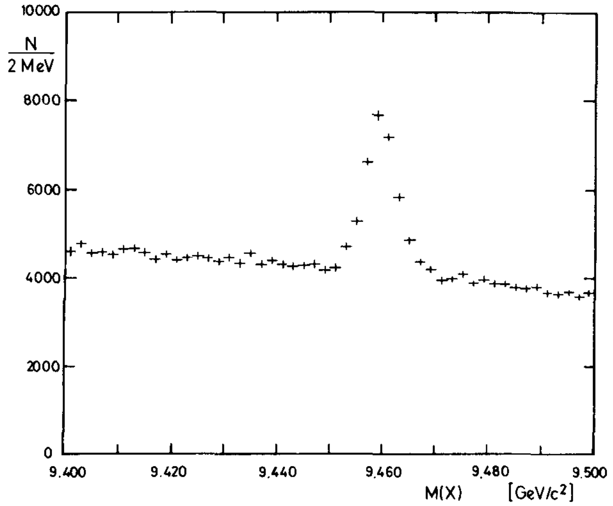

Fig. 2. Missing mass $m(X)$ from $e^+e^- \to \pi^+\pi^- X$ of all events at 10.023 GeV cms energy

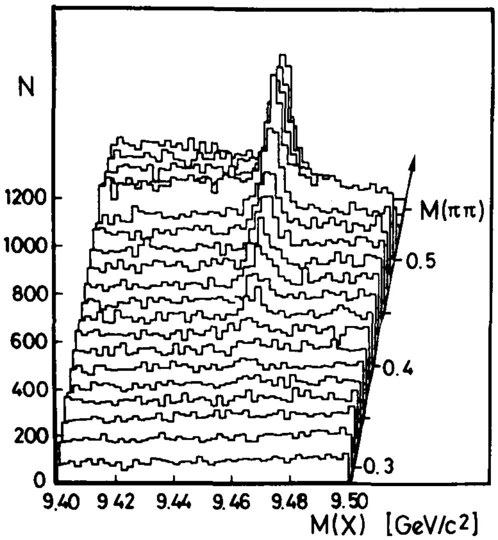

Fig. 3. Missing mass $m(X)$ for different slices in $m(\pi\pi)$

ing mass

$$m(X) = \sqrt{(m_{\Upsilon 2S} - E_{\pi\pi})^2 - \mathbf{p}_{\pi\pi}^2}$$

for all $\pi^+\pi^-$ combinations is shown in Fig. 2. A clear $\Upsilon(1S)$ peak with 13250 entries can be seen, with a width of $\sigma = 3.1$ MeV/c^2.

All distributions shown in this paper on the inclusive process $\Upsilon(2S) \to \pi^+\pi^- \Upsilon(1S)$ have been extracted by the same straightforward procedure, illustrated in Fig. 3 for the $m(\pi\pi)$ invariant mass. The missing mass distribution (Fig. 2) is divided into several bins of the variable under consideration, in this example $m(\pi\pi)$. For each bin the missing mass distribution is fitted with a Gaussian for the Υ peak plus a polynomial background. The fitted number of $\Upsilon(1S)$ is then acceptance corrected on a bin-by-bin basis. The result for $m(\pi\pi)$ is shown in Fig. 4.

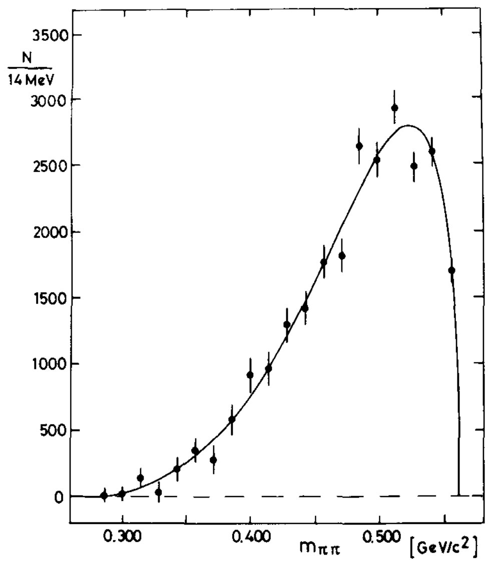

Fig. 4. The invariant $m(\pi^+\pi^-)$ mass distribution achieved by fitting the histograms in Fig. 3, corrected for acceptance

The branching ratio of $\Upsilon(2S)$ into $\Upsilon(1S)\pi^+\pi^-$

From the number of events in the peak in Fig. 2, we can determine

$$\mathrm{BR}(\Upsilon 2S \to \Upsilon 1S\, \pi^+\pi^-) = \frac{N_{\mathrm{incl}}\, \eta_{\Upsilon 2S}}{N_{\Upsilon 2S \to \mathrm{had}}\, \eta_{\mathrm{incl}}}.$$

A subsample of 32.6/pb has been used for which the hadronic cross-section measurement was stable. The number of entries in the $\Upsilon(1S)$ peak in the missing mass distribution for this subsample is $N_{\mathrm{incl}} = 11627 \pm 256$. The number of $\Upsilon(2S)$ mesons has been calculated from the number of observed multihadron events with the cuts noted above, after subtracting the continuum contribution from $q\bar{q}$ jets, using

$$N_{\Upsilon 2S \to \mathrm{had}} = N_{\mathrm{had}}(\Upsilon 2S) - N_{\mathrm{had}}(\mathrm{cont}) \cdot \frac{L_{\mathrm{incl}}\, s_{\mathrm{cont}}}{L_{\mathrm{cont}}\, s_{\Upsilon 2S}}.$$

At $\sqrt{s_{\mathrm{cont}}} = 9.98$ GeV we have $N_{\mathrm{had}} = 9429$ events in a sample of $L_{\mathrm{cont}} = 2.66$/pb. With $N_{\mathrm{had}} = 208713$ at the $\Upsilon(2S)$ energy, we obtain $N_{\Upsilon 2S \to \mathrm{had}} = 94144 \pm 1262$.

The acceptances have been calculated by a Monte Carlo simulation, generating $\Upsilon(2S)$ decays with the known branching ratios [10] to all final states, including e^+e^- and $\mu^+\mu^-$, and with gluons fragmenting like quarks. The events are submitted to a full detector simulation, and subsequently reconstructed and selected in the same way as real data. The acceptance

Table 1. BR($\Upsilon 2S \to \Upsilon 1S\pi^+\pi^-$), inclusive measurements

LENA [3]	$(26 \pm 13)\%$
CLEO [5]	$(21.2 \pm 2.6 \pm 2.1)\%$
CLEO [7]	$(19.1 \pm 1.2 \pm 0.6)\%$
this experiment	$(18.1 \pm 0.5 \pm 1.0)\%$
average	$(18.7 \pm 0.8)\%$

for all $\Upsilon(2S)$ decays, $\eta_{\Upsilon 2S}$, is $(77.4 \pm 0.4)\%$, while the acceptance for the $\Upsilon(1S)\pi^+\pi^-$ channel, including the efficiency for reconstructing the two pions, is $\eta_{\text{incl}} = (52.9 \pm 0.3)\%$. Using these numbers, we find

$$\text{BR}(\Upsilon 2S \to \Upsilon 1S\pi^+\pi^-) = (18.1 \pm 0.5 \pm 1.0)\%,$$

where the first error is statistical and the second systematic, including an uncertainty in the luminosity ratio of 2%, in the event acceptance ratio of 4% and in the track reconstruction efficiency of 2%, contributing to η_{incl}. This result includes the data used in our 1984 publication [6]. Our result is compared to previous measurements in Table 1.

Kuang and Yan [11] have calculated the ratio of the widths $\Gamma(\Upsilon 2S \to \Upsilon 1S\pi\pi)$ and $\Gamma(\psi' \to J/\psi\,\pi\pi)$ using non-relativistic colour-field multipole expansion and potential models. With the known parameters for the ψ system [10] they predict

$$\Gamma(\Upsilon 2S \to \Upsilon 1S\pi\pi) = 6 \text{ to } 7\,\text{keV}.$$

As pointed out by Yan [12], this is valid for vector gluons, whereas scalar gluons lead to an expectation of $\Gamma \approx 100$ keV, of the same order of magnitude as for the ψ system. Taking the total width of the $\Upsilon(2S)$ of 30 ± 7 keV [10], we obtain

$$\Gamma(\Upsilon 2S \to \Upsilon 1S\pi^+\pi^-) = 5.4 \pm 1.3\,\text{keV}.$$

If one extrapolates with the isospin zero factor 3/2 to $\Gamma(\Upsilon 2S \to \Upsilon 1S\pi\pi) \approx 8.1$ keV, this value is incompatible with the scalar gluon assumption, and agrees well with the Kuang and Yan prediction.

Exclusive final states with $e^+e^-\pi^+\pi^-$ and $\mu^+\mu^-\pi^+\pi^-$

Exclusive events containing the $\pi^+\pi^-\ell^+\ell^-$ final state were selected by requiring 4 charged tracks from the interaction region, two of them, the lepton candidates, being fast ($p > 1$ GeV/c) and back-to-back ($\cos\theta_{+-} < -0.95$). The pions were required to have a transverse momentum larger than 0.05 GeV/c, and $|\cos\theta| < 0.9$.

Electron and muon pairs were separated on the basis of the associated energy deposited in the shower counters: above 1 GeV the lepton is an electron, below 1 GeV a muon. Pairs are identified uniquely by this procedure. The mixed category, i.e. one track with more and one with less than 1 GeV, is discarded. Such events represent less than 3% of the data at the $\Upsilon(1S)$ missing mass, and originate from shower counter inefficiencies, early muon decays and $\tau^+\tau^-$ pairs decaying into an electron and a muon.

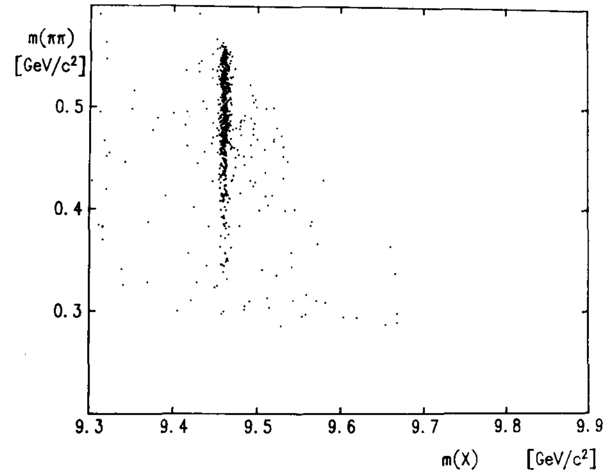

Fig. 5. Invariant mass $m(\pi^+\pi^-)$ versus missing mass $m(X)$ for the selected $e^+e^-\pi^+\pi^-$ and $\mu^+\mu^-\pi^+\pi^-$ events

The main source of background in the $e^+e^-\pi^+\pi^-$ sample are radiative Bhabha events, where the photon has converted in the beam pipe or the inner detector materials into an e^+e^- pair. To reduce this contribution considerably, we demanded in addition that the cosine of the opening angle between the pion pair be less than 0.925.

Figure 5 shows a scatter plot of the missing mass $m(X)$ versus the invariant mass $m(\pi^+\pi^-)$ which exhibits the almost complete background rejection achieved by these cuts. The enhancement to the right of the $\Upsilon(1S)$ band is due to early decays of $\pi^\pm \to \mu^\pm\nu$, where the muon is taken as a pion.

The $\pi^+\pi^-$ missing mass $m(X)$ is determined with much higher precision than the lepton pair invariant mass. Therefore a cut on the latter would not improve the selection, while the missing mass is used to select the $\Upsilon(1S)$ states, with $9.45\,\text{GeV/c}^2 < m(X) < 9.47\,\text{GeV/c}^2$.

The mass difference $m(\Upsilon 2S) - m(\Upsilon 1S)$

Fitting the missing mass $\Upsilon(1S)$ peak shown in Fig. 6, we obtain a precise measurement of the mass difference $\Delta = m(\Upsilon 2S) - m(\Upsilon 1S)$. Using a Gaussian over a very small, linear background, our result is $m(\Upsilon 1S) = 9460.32 \pm 0.16$ MeV/c^2 and $\sigma = 3.34 \pm 0.13$ MeV/c^2 with $m(\Upsilon 2S) = 10023.1$ MeV/c^2 taken as

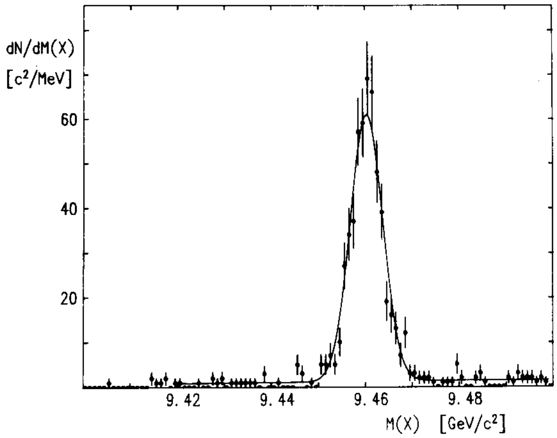

Fig. 6. Projection of Fig. 5 onto the $m(X)$ axis. The fit is a Gaussian plus linear background

$\Upsilon(2S)$ mass. From this we derive a mass difference

$$\Delta = (562.78 \pm 0.16 \pm 0.57)\ \mathrm{MeV/c^2}.$$

The systematic error of 0.57 MeV/c^2 comes from a conservative estimate of our magnetic field precision [13], determining the accuracy of the pion momentum measurement, and the error on energy loss corrections.

The lepton pair branching of the $\Upsilon(1S)$

From the number of inclusive and exclusive events, the branching ratio of the $\Upsilon(1S)$ into e^+e^- and $\mu^+\mu^-$ can be determined by:

$$\mathrm{BR}(\Upsilon 1S \to \ell^+\ell^-) = \frac{N_{\ell\ell} \cdot \eta_{\mathrm{incl}} \cdot L_{\mathrm{incl}}}{N_{\mathrm{incl}} \cdot \eta_{\ell\ell} \cdot L_{\ell\ell}}$$

where N is the number of observed events, η the acceptance and L the luminosity for the sample of inclusive and exclusive events respectively. For the electrons we find $N_{ee} = 307$, with an acceptance of 51.2% in a simple of $L_{ee} = 36.8$/pb. Together with the numbers for the inclusive data given above, we obtain

$$\mathrm{BR}(\Upsilon 1S \to e^+e^-) = (2.42 \pm 0.14 \pm 0.14)\%,$$

where the first error is statistical and the second systematic, including an uncertainty in the event acceptance ratio of 4% and in the charged track reconstruction efficiency of 2%.

The analysis for muon pairs is not so straightforward, since for the cuts described above the trigger efficiency cannot be reliably calculated due to uncertainty in the energy thresholds for minimum ionizing particles. We therefore make the more restrictive requirement that all four tracks enter the barrel region, i.e. $|\cos\theta| < 0.65$ and $p_\perp > 0.14$ GeV/c. The number of muon pairs remaining is $N_{\mu\mu} = 86$, with an acceptance of 15.0%, in the same sample of runs ($L_{\mu\mu} = L_{ee}$). We find:

$$\mathrm{BR}(\Upsilon 1S \to \mu^+\mu^-) = (2.30 \pm 0.25 \pm 0.13)\%,$$

consistent with our result for B_{ee}. Both values are considerably lower than the present world average [10], but consistent with any single earlier experimental result.

The product of branching ratios $\mathrm{BR}(\Upsilon 2S \to \Upsilon 1S\pi^+\pi^-) \cdot \mathrm{BR}(\Upsilon 1S \to \ell^+\ell^-)$ from electron and muon pairs is compared with results from other experiments in Table 2.

Table 2. $\mathrm{BR}(\Upsilon 2S \to \Upsilon 2S\pi^+\pi^-) \cdot \mathrm{BR}(\Upsilon 1S \to \ell^+\ell^-)$

LENA [3]	$(0.61 \pm 0.23)\%$
CUSB [4]	$(0.54 \pm 0.03 \pm 0.04)\%$
CLEO [7]	$(0.54 \pm 0.04)\%$
Crystal Ball [8]	$(0.49 \pm 0.04 \pm 0.10)\%$
this experiment	$(0.44 \pm 0.02 \pm 0.04)\%$

In a previous paper [14] we have related $\Upsilon(1S) \to \tau^+\tau^-$ to the other lepton pair final states, finding $B_{\tau\tau}/B_{ee,\mu\mu} = 1.06 \pm 0.16 \pm 0.07$. With our new result on B_{ee}, this implies

$$\mathrm{BR}(\Upsilon 1S \to \tau^+\tau^-) = (2.57 \pm 0.42 \pm 0.18)\%.$$

Combined results from all $\pi^+\pi^-$ final states

The $\pi\pi$ mass distribution

There have been many theoretical predictions of the distribution of the $\pi\pi$ invariant mass since the discovery that for $\psi' \to J/\psi\pi\pi$ transitions this distribution differs significantly from phase space. The approaches to the problem usually start with the emission of two gluons, which subsequently hadronize into two pions (or an eta). The second step, the conversion to hadrons, determines the $m(\pi\pi)$ distribution and can be calculated from low energy theorems in the chiral limit [12, 15–19] or by assuming dominance of a scalar resonance ε [20–25].

For simple three-body phase space the distribution of $M = m_{\pi\pi}$ would have the form:

$$\boxed{\mathrm{PS} = \sqrt{\frac{(M^2 - 4m_\pi^2)\,[m_1^4 + m_2^4 + M^4 - 2(m_1^2 M^2 + m_2^2 M^2 + m_1^2 m_2^2)]}{4m_2^2}}}$$

where we use $m_1 = m(\Upsilon 1S)$ and $m_2 = m(\Upsilon 2S)$.

Brown and Cahn [15] and Voloshin [16] were the first to use chiral symmetry arguments and PCAC to derive a matrix element. Brown and Cahn's ansatz includes three terms with free normalization parameters A, B and C. Neglecting terms involving non-isotropic angular distributions, that is with $B=C=0$, they predict

$$\frac{d\sigma}{dM} \propto \mathrm{PS} \cdot [M^2 - 2m_\pi^2]^2.$$

This is not compatible with the observed shape.

Including the leading contribution from a colour-field multipole expansion, that is a chromo-electric $E1E1$ transition (the two gluon emission in a non-relativistic limit), Yan [12] finds that $C=0$, but that B could be non-zero, although much smaller than A. Therefore he suggests the following more general form deduced from the Brown and Cahn calculations:

$$\frac{d\sigma}{dM} \propto \mathrm{PS} \cdot \left[(M^2 - 2m_\pi^2)^2 + \frac{B}{3A} (M^2 - 2m_\pi^2) \cdot \left(M^2 - 4m_\pi^2 + 2K^2 \left(1 + \frac{2m_\pi^2}{M^2} \right) \right) + O\left(\frac{B^2}{A^2} \right) \right]$$

with

$$K = \frac{m_2^2 - m_1^2 + M^2}{2m_2}$$

where only the ratio B/A remains as a free parameter. This should be independent from the energy scale, i.e. the same for the ψ and Υ systems.

The description of Voloshin and Zakharov [18] is based on the same ideas. They calculated the matrix element in the chiral limit, $m_\pi = 0$, and added a phenomenological term λm_π^2:

$$\frac{d\sigma}{dM} \propto \mathrm{PS} \cdot [M^2 - \lambda m_\pi^2]^2$$

with a free parameter λ, which is supported by an earlier work of Voloshin [16]. The result is equivalent to the suggestion by Morgan and Pennington [17],

$$\frac{d\sigma}{dM} \propto \mathrm{PS} \cdot [\alpha (M^2 - 2m_\pi^2) + \beta m_\pi^2]^2.$$

As will be shown below, this simple perturbation term already suffices to describe the available data satisfactorily.

With several refinements to the ansatz, a very similar approach by Novikov and Shifman [19] yields

$$\frac{d\sigma}{dM} \propto \mathrm{PS} \cdot \left[M^2 - \kappa (m_2 - m_1)^2 \left(1 - \frac{2m_\pi^2}{M^2} \right) + O(\kappa^2) \right]^2$$

where κ is calculable and equal to $\frac{9}{6\pi} \alpha_S(Q^2) \rho^G(Q^2) \approx 0.1$ at a Q^2 fixed by the inverse quarkonium radius, or equivalently by the Υ mass scale. This is particularly interesting, since it might show the effects of a running coupling constant. As a result the Υ and ψ systems would have different shapes in contrast to the model of Yan. The other constant, ρ^G, denotes the fraction of the pion momentum carried by gluons, which is assumed to be of the order of 0.5 by Novikov and Shifman.

The idea [20] of scalar meson form factors dominating the amplitude is discussed in detail by several authors, using a single scalar 0^{++} meson ε. Schwinger and collaborators [21] find

$$\frac{d\sigma}{dM} \propto \mathrm{PS} \cdot \frac{(M^2 - 2m_\pi^2)^2}{(M^2 - m_\varepsilon^2)^2 (1+\delta)^2 + m_\varepsilon^2 \Gamma_\varepsilon^2 R^2}$$

with

$$R = \frac{\sqrt{1 - 4m_\pi^2/M^2}\,(M^2 - 2m_\pi^2)^2}{\sqrt{1 - 4m_\pi^2/m_\varepsilon^2}\,(m_\varepsilon^2 - 2m_\pi^2)^2}.$$

The fractional increase δ in the real part of the ε propagator, is assumed to be small, bounded by about 5%. Almost the same form is found in [23] with $\delta \equiv 0$, but with the important difference that the terms $M^2 - 2m_\pi^2$ and $m_\varepsilon^2 - 2m_\pi^2$ are replaced by the corresponding terms with "+" signs.

Pham et al. [22] suggest

$$\frac{d\sigma}{dM} \propto \mathrm{PS} \cdot \frac{F}{(M^2 - m_\varepsilon^2)^2 + m_\varepsilon^2 \Gamma_\varepsilon^2 (1 - 4m_\pi^2/M^2)}$$

with

$$F = 1 + 2 \cdot \left(\frac{m_1^2 + m_2^2 - M^2}{2m_1 m_2} \right)^2,$$

and another parametrization is obtained in [24]:

$$\frac{d\sigma}{dM} \propto \mathrm{PS} \cdot \frac{\tilde{F} \cdot (M^2 - 2m_\pi^2)^2}{(M^2 - m_\varepsilon^2 + \Gamma_\varepsilon^2/4)^2 + m_\varepsilon^2 \Gamma_\varepsilon^2}$$

with the spin summation term

$$\tilde{F} = 2 + \left(\frac{m_1^2 + m_2^2 - M^2}{2m_1 m_2} \right)^2.$$

In [25] the same ansatz is used, but two scalar mesons ε and ε' and their interference is taken into account, and the spin summation term is replaced by F given above. Since both are varying over the whole $m_{\pi\pi}$ range by only a few permille (and seem not appropriate for a polarized $\Upsilon(2S)$ anyhow), this would not affect our results at all.

Experimental $m(\pi^+\pi^-)$ distributions have been obtained from the exclusive sample, with the additional requirement that at least three of the four tracks fit to a common primary vertex. The subsamples of $\mu^+\mu^-\pi^+\pi^-$ and $e^+e^-\pi^+\pi^-$ events show no significant difference and therefore have been combined.

The inclusive distribution has already been shown in Fig. 4. Although the inclusive study is based on 13250 events compared to only 495 in the exclusive sample, the precision of the theoretical parameters derived from a fit to either result is of the same order. Since there are only very few entries at low mass values, the error on these points is almost completely dominated by the background in the inclusive missing mass plots, whereas the few events in the exclusive data have no background.

Since the error bars of any point of the inclusive distribution shown in Fig. 4 is determined mainly by the statistical fluctuations of the background, the inclusive and exclusive distributions are to a good approximation statistically independent, although the exclusive data contribute as a small fraction to the inclusive sample. Therefore we have calculated the weighted average of both to obtain the combined distribution shown in Fig. 7. Fits of the chiral symmetry parametrizations [12, 18, 19], which cannot be resolved with the eye, are shown by the solid line in Fig. 7. All fit parameters are summarized in the following table:

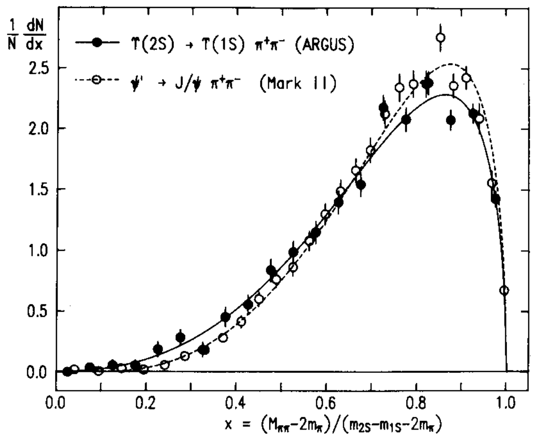

Fig. 7. Combined distribution of the invariant mass $m(\pi^+\pi^-)$ from our inclusive and exclusive data samples, and from the Mark II data on $\psi' \to J/\psi\pi^+\pi^-$ [1]. The fits show the Novikov/Shifman function, but other parametrizations look exactly the same (see text)

whereas Yan predicts identical distributions for Υ and ψ [12].

Since the description by Novikov and Shifman explicitly includes the running coupling constant α_S, a difference is expected between the distributions obtained at different Q^2. We find $\kappa = 0.194 \pm 0.010$ ($\chi^2 = 38/24$ d.f.) for $\psi' \to J/\psi\,\pi^+\pi^-$, which is significantly larger than the Υ values. This can be interpreted as a combined effect of a running α_S and the variation of ρ^G, which describes the gluon content of ordinary mesons. It should be noted that inclusion of the $O(\kappa^2)$ terms given in [19] changes the fit results by much less than the statistical error.

Table 3. Fit results for theoretical parametrizations in $m(\pi\pi)$

Yan [12]	$B/A = -0.154 \pm 0.019$	$\chi^2 = 27.8/19$ d.f.
Voloshin/Zakharov [18]	$\lambda = 3.30 \pm 0.19$	$\chi^2 = 27.4/19$ d.f.
Novikov/Shifman [19]	$\kappa = 0.151 \pm 0.009$	$\chi^2 = 27.7/19$ d.f.
Schwinger et al. [21]	$m(\varepsilon) = 0.86 \pm 0.11$ GeV/c^2 $\Gamma(\varepsilon) = 2.4 \pm 1.3$ GeV/c^2	$\chi^2 = 29.8/18$ d.f.
Genz et al. [23]	$m(\varepsilon) = 0.633 \pm 0.018$ GeV/c^2 $\Gamma(\varepsilon) = 0.37 \pm 0.04$ GeV/c^2	$\chi^2 = 42.7/18$ d.f.
Harrington et al. [24]	$m(\varepsilon) = 0.57 \pm 0.04$ GeV/c^2 $\Gamma(\varepsilon) = 0.39 \pm 0.08$ GeV/c^2	$\chi^2 = 28.4/18$ d.f.

From the χ^2 values one can see that all descriptions work equally well, with the exception of model [23]. The formula given by Pham et al. [22] does not fit our data ($\chi^2 = 125/18$ d.f.), nor does it fit the Mark II data on $\psi' \to J/\psi\pi^+\pi^-$ ($\chi^2 = 809/23$ d.f.).

Comparing the shape with the corresponding distribution from the ψ system [1] in Fig. 7, one can clearly see that they do not coincide. The Yan-parameter of a fit to the Mark II data is $B/A = -0.21 \pm 0.01$, significantly different from our Υ result given above,

Some scalar meson dominance models give acceptable fits to the data, raising the possibility of a low mass 0^{++} state in the $\pi\pi$ channel with large glueball admixture, in the range 0.5 to 0.9 GeV/c^2. However, if we fit the ψ data with the same functions, we find smaller masses and widths for the ε resonance, and the best χ^2 values are 89 (Schwinger et al.) and 73 (Harrington et al.) for 23 degrees of freedom.

Therefore we conclude that only models giving mass-scale dependent transition matrix elements are able to describe the $\pi^+\pi^-$ transitions of heavy quarkonia. The idea of Novikov and Shifman, to connect PCAC theorems and the QCD running coupling constant, seems most promising.

The angular distributions

In all theoretical models the pions are expected to be dominantly in an S state. However, on general grounds, *even*$^{++}$ states are allowed as well, and their contribution has to be found by experiment [26]. An order of magnitude prediction of the d-wave has been made by Novikov and Shifman [19].

Since the multipole expansion is expected to be dominated by $E1\,E1$ radiation, the angular momentum of the $Q\bar{Q}$ system is not changed in this process. One would therefore expect to observe the same polarization as the $\Upsilon(2S)$ in the subsequent decay of the $\Upsilon(1S)$. This can be verified in the exclusive $\Upsilon(1S)$ decays into e^+e^- and $\mu^+\mu^-$. The $\cos\theta$ and ϕ (azimuthal) distributions with respect to the DORIS e^+e^- frame are shown in Figs. 8 and 9.

The $(1+\cos^2\theta)$ distribution is clearly verified. Moreover, DORIS beam polarisation, visible in the azimuthal distribution, is the same for muon and electron pairs from the $\Upsilon(1S)$ as for muon pairs produced directly in e^+e^--annihilation or from the $\Upsilon(2S)$. A fit to the result shown in Fig. 9 gives a product of polarisations $P_1 P_2 = 0.75 \pm 0.10$, compared to 0.68 ± 0.02 from direct $\mu^+\mu^-$-pairs [27].

Using this information, the primary angular momentum from the gluon emission plus the internal angular momentum of the two pion system must add up to zero, i.e. the primary decay angular momentum is also found as orbital angular momentum of the $\pi\pi$ system. Therefore one can fit the distribution of the helicity angle θ^* of the π^+ in the $\pi\pi$ cms (Fig. 10) to a coherent sum of $J=0$ and $J=2$, $J_z=0$ waves:

$$\frac{dN}{d\cos\theta^*} = N \cdot \left| \sqrt{1-|\varepsilon|^2}\, Y_0^0 + \varepsilon\, Y_2^0 \right|^2 .$$

The fit result is shown with one and two standard deviation contours in Fig. 11. The real part is $\mathrm{Re}\,\varepsilon = 0.018 \pm 0.009$, the best fit for $\mathrm{Im}\,\varepsilon$ is 0 with a large error. If we allow a free phase, the fit gives

$$|\varepsilon| = 0.018 \begin{array}{l} +0.108 \\ -0.009 \end{array}$$

which is just two standard deviations from zero. If $\pi\pi$ rescattering is negligible, ε is expected to be real

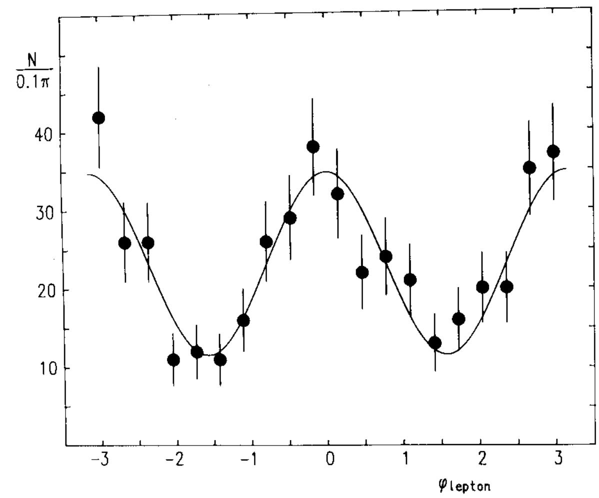

Fig. 9. Distribution in the azimuth ϕ for electrons and muons with $|\cos\theta| < 0.75$ from $\Upsilon(1S)$ decays. The fit gives a beam polarization product of 0.75 ± 0.10 compared to 0.68 ± 0.02 from μ-pairs at the $\Upsilon(2S)$ energy

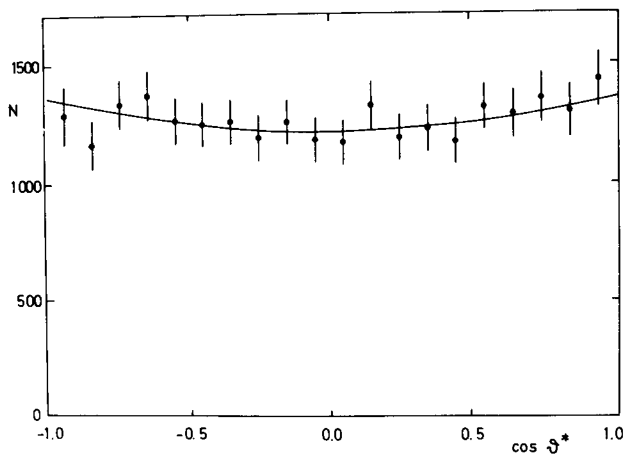

Fig. 10. Acceptance corrected distribution of $\cos\theta^*_{\pi^+}$ in the helicity frame of $\pi^+\pi^-$

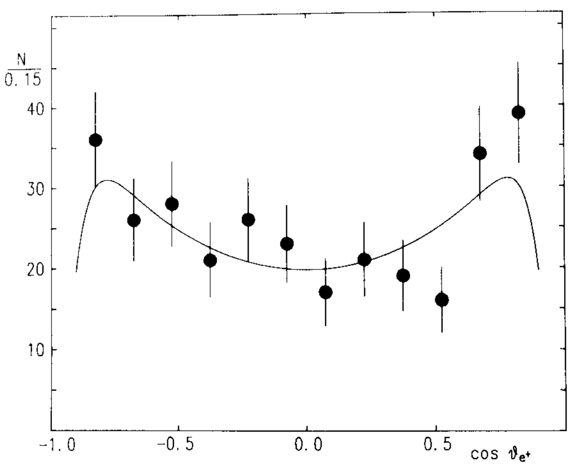

Fig. 8. Observed distribution of $\cos\theta_{e^+}$. The solid line is $N \cdot (1+\cos^2\theta) \cdot \eta(\cos\theta)$

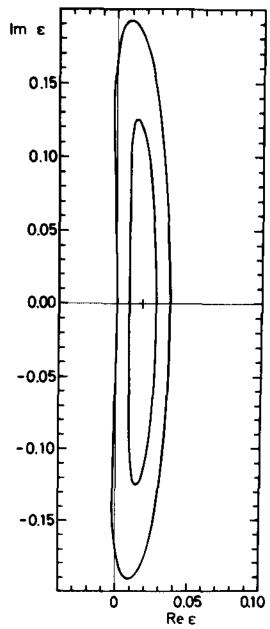

Fig. 11. One and two σ contours for a complex ε describing the d-wave contribution to the $\pi^+\pi^-$-transition

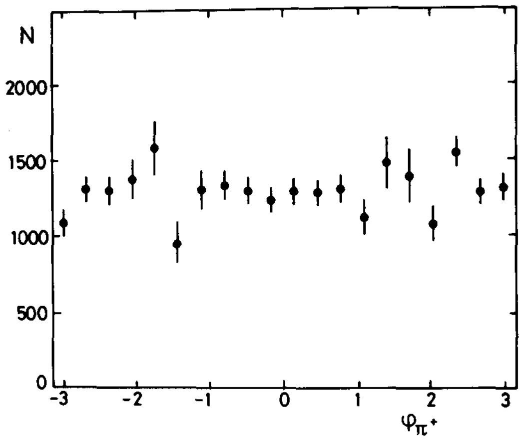

Fig. 12. Azimuthal distribution of the π^+ in the rest frame of $\pi^+\pi^-$, with respect to the production plane (corrected for acceptance)

[26]. In this case, our value of 0.018 is fairly close to the theoretical expectation [19], and proves the strong s-wave dominance in the process.

The azimuthal distribution of the π^+ in the $\pi\pi$-system with respect to the production plane (Fig. 12) is flat, as expected. Also the spatial orientation of the $\pi^+\pi^-$ system in the $\Upsilon(2S)$ frame (Fig. 13a, b) shows no significant deviation from isotropy. If the $\Upsilon(2S)$ were not a pure ^{3}S vector meson, but rather an admixture of the lowest lying **D**-state of the $b\bar{b}$-system, the $\cos\theta_{\pi\pi}$ distribution would no longer be flat. In addition, more entries at low $m_{\pi\pi}$) would be expected [12].

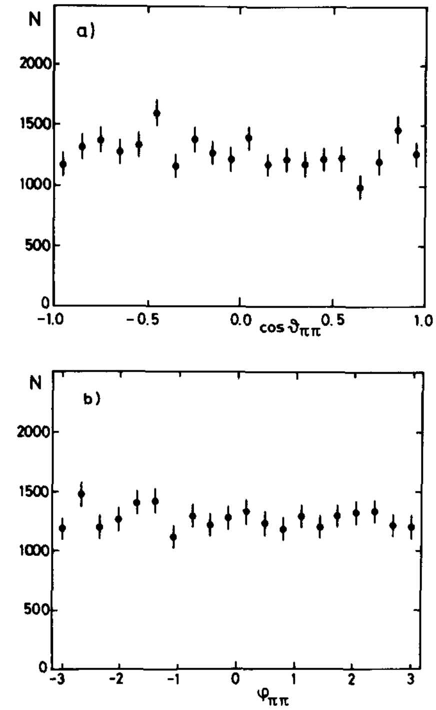

Fig. 13. **a** $\cos\theta$ and **b** ϕ distribution of the $\pi^+\pi^-$ system in the e^+e^- frame (corrected for acceptance)

Exclusive final states with $e^+e^-\pi^0\pi^0$ and $\mu^+\mu^-\pi^0\pi^0$

Final states with two π^0's have been selected from a subsample of 27/pb [28] by requiring two oppositely charged tracks of more than 2 GeV/c momentum and $|\cos\theta|<0.75$, and four photons with energy $E_\gamma>30$ MeV. In order to reduce the contribution from radiative QED events, all photons had to be separated by more than 20° from muons, by more than 30° from electrons or positrons, and by more than 37° from each other. Bhabha contamination was further reduced by the requirement that $\cos\theta_{e^+}<0.2$.

The invariant $\ell^+\ell^-$ mass for these selected events shows a broad $\Upsilon(1S)$ peak. In the range 8 GeV $<m(\ell^+\ell^-)<11$ GeV all $\gamma\gamma$ mass combinations from the $\mu^+\mu^-$ sample have been plotted in Fig. 14. There are 50 entries from 17 events in the $\pi^0\pi^0$ region of 80 MeV$<m(\gamma\gamma)<190$ MeV, corresponding to $\pm 2\sigma$ in energy resolution. Only 4 events have no entry in this region, indicating an almost negligible background.

The acceptance for these events has been evaluated from a Monte Carlo simulation, giving $\eta_{\mu^+\mu^-\pi^0\pi^0}=(8.3\pm 2.0)\%$ and $\eta_{e^+e^-\pi^0\pi^0}=(3.0\pm 0.4)\%$, where the errors reflect systematic uncertainties. The large error for the muon sample derives from a rather uncertain trigger efficiency for muon pairs of $(80\pm 16)\%$. Comparing this number to the exclusive

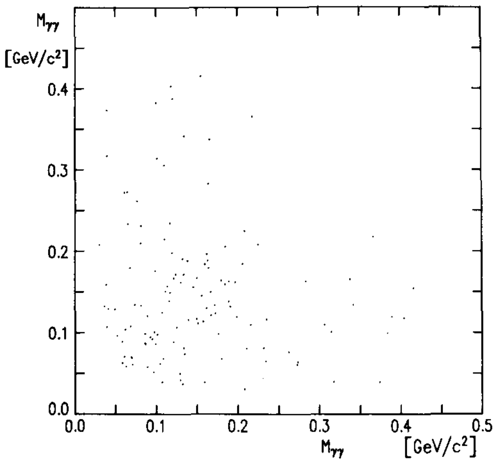

Fig. 14. $\gamma_1\gamma_2$ mass versus $\gamma_3\gamma_4$ mass in $\mu^+\mu^-+4\gamma$ events. Each event gives 6 entries

Table 4. $BR(\Upsilon 2S \to \Upsilon 1S\pi^0\pi^0) \cdot BR(\Upsilon 1S \to \ell^+\ell^-)$

CUSB [4]	$(0.29 \pm 0.05 \pm 0.03)\%$
Crystal Ball [8]	$(0.23 \pm 0.03 \pm 0.03)\%$
this experiment	$(0.23 \pm 0.04 \pm 0.05)\%$

$\pi^+\pi^-$ final states, we find the ratio

$$\frac{BR(\Upsilon 2S \to \Upsilon 1S\pi^0\pi^0)}{BR(\Upsilon 2S \to \Upsilon 1S\pi^+\pi^-)} = \frac{N_{00} \cdot \eta_{+-} \cdot L_{+-}}{N_{+-} \cdot \eta_{00} \cdot L_{00}}$$

to be $0.59 \pm 0.21 \pm 0.08$ from 8 events in the channel $\Upsilon(1S) \to e^+e^-$ and $0.49 \pm 0.12 \pm 0.12$ from 17 events of the type $\Upsilon(1S) \to \mu^+\mu^-$. This is compatible with the isospin zero expectation of 0.5. The combined result is $0.52 \pm 0.10 \pm 0.10$, giving $BR(\Upsilon 2S \to \Upsilon 1S\pi^0\pi^0) = (9.5 \pm 1.9 \pm 1.9)\%$. In Table 4 the existing values of $BR(\Upsilon 2S \to \Upsilon 1S\pi^0\pi^0) \cdot BR(\Upsilon 1S \to \ell^+\ell^-)$ are compared.

Upper limit for $\Upsilon(2S) \to \Upsilon(1S)\eta$

Finally, we have searched for the transition $\Upsilon(2S) \to \Upsilon(1S)\eta$ in the $\ell^+\ell^-\pi^+\pi^-$ sample, since no constraints were made on additional photons in this selection. Events where $\eta \to \pi^+\pi^-\pi^0$ would appear in this sample with a missing mass in the range $m(\Upsilon 1S) + m(\pi^0) < m(X) < m(\Upsilon 2S) - 2m(\pi^+)$. The precise search region is marked in Fig. 15, which has an acceptance of $(28.7 \pm 1.2)\%$ based on a Monte Carlo simulation. Within this region we find 5 entries in our data (Fig. 5). A visual scan revealed that four of them are radiative Bhabhas, and one has pion candidates clearly not coming from the primary vertex. We conclude, since no event has been found, that an upper limit for this channel is $N < 2.3$ events with

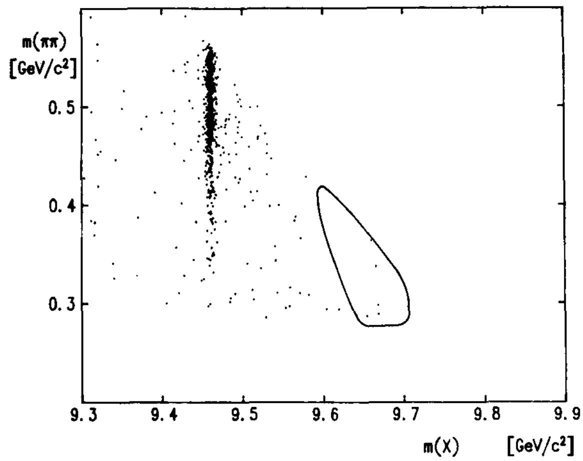

Fig. 15. Same as Fig. 5, with the expected region for events of the type $\Upsilon(2S) \to \Upsilon(1S)\eta$, $\eta \to \pi^+\pi^-\pi^0$

90% confidence. The branching ratio is given by:

$$BR(\Upsilon 2S \to \Upsilon 1S\eta) = \frac{N_\eta \cdot \eta_{+-}}{N_{+-} \cdot \eta_\eta} \cdot \frac{BR(\Upsilon 2S \to \Upsilon 1S\pi^+\pi^-)}{BR(\eta \to \pi^+\pi^-\pi^0)}.$$

Using the acceptance of $\eta_\eta = 28.7\%$ for the cuts described above, our numbers of $e^+e^-\pi^+\pi^-$- and $\mu^+\mu^-\pi^+\pi^-$-events, $BR(\eta \to \pi^+\pi^-\pi^0) = 23.7\%$ [10] and $BR(\Upsilon 2S \to \Upsilon 1S\pi^+\pi^-) = 18.1\%$, we find

$$BR(\Upsilon 2S \to \Upsilon 1S\eta) < 0.5\% \quad \text{with} \quad 90\%\ \text{C.L.}$$

An upper limit of 0.2% has been obtained by CUSB [4], using the channel $\eta \to \gamma\gamma$. Both are still far above the theoretical expectations [11, 18] of $\simeq 0.05\%$.

Our result also implies an upper limit for the G-parity violating channel $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-\pi^0$ of 0.12% with 90% confidence.

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References

1. T.M. Himel: (thesis), SLAC-223 (1979)
2. Crystal Ball Collab., M. Oreglia et al.: Phys. Rev. Lett. 45 (1980) 959
3. LENA Collab., B. Niczyporuk et al.: Phys. Lett. 100B (1981) 95
4. CUSB Collab., G. Mageras et al.: Phys. Rev. Lett. 46 (1981) 1115; CUSB Collab., V. Fonseca et al.: Nucl. Phys. B242 (1984) 31
5. CLEO Collab., J.J. Mueller et al.: Phys. Rev. Lett. 46 (1981) 1181 and update in D.A. Herrup: (thesis), Cornell Univ. 1982, unpublished. The updated branching ratio is also mentioned in CLEO Collab., J. Green et al.: Phys. Rev. Lett. 49 (1982) 617

6. ARGUS Collab., H. Albrecht et al.: Phys. Lett. 134B (1984) 137
7. CLEO Collab., J. Besson et al.: Phys. Rev. D30 (1984) 1433
8. Crystal Ball Collab., D. Gelphman et al.: Phys. Rev. D32 (1985) 2893
9. M. Danilov et al.: Nucl. Instrum. Methods 217 (1983) 153
10. Particle Data Group: Phys. Lett. 170B (1986) 1
11. Y.-P. Kuang, T.-M. Yan: Phys. Rev. D24 (1981) 2874
12. T.-M. Yan: Phys. Rev. D22 (1980) 1652
13. ARGUS Collab., H. Albrecht et al.: Phys. Lett. 153B (1985) 343
14. ARGUS Collab., H. Albrecht et al.: Phys. Lett. 154B (1985) 452
15. L.S. Brown, R.N. Cahn: Phys. Rev. Lett. 35 (1975) 1
16. M.B. Voloshin: JETP Lett. 21 (1975) 347
17. D. Morgan, M.R. Pennington: Phys. Rev. D12 (1975) 1283
18. M. Voloshin, V. Zakharov: Phys. Rev. Lett. 45 (1980) 688
19. V.A. Novikov, M.A. Shifman: Z. Phys. C – Particles and Fields 8 (1981) 43
20. R. Decker, M. Moreno: Lett. Nuovo Cimento 13 (1975) 407
21. J. Schwinger et al.: Phys. Rev. D12 (1975) 2617
22. T.N. Pham, B. Pire, T.N. Truong: Phys. Rev. D13 (1976) 620
23. H. Genz, C.B. Lang: Nuovo Cim. 32A (1976) 513
24. B.J. Harrington, S.Y. Park, A. Yildiz: Phys. Rev. D12 (1975) 2765
25. G.W. Intemann: Phys. Rev. D26 (1982) 611
26. R.N. Cahn: Phys. Rev. D12 (1975) 3559
27. B. Gräwe: (Dissertation), Dortmund 1985, unpublished
28. R. Heller: (Dissertation), Heidelberg 1984, IHEP-HD/84-08