MEASUREMENT OF THE DECAY $\Upsilon' \to \Upsilon\pi^+\pi^-$

LENA Collaboration

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We report the first observation of the decay $\Upsilon' \to \Upsilon\pi^+\pi^- \to \ell^+\ell^-\pi^+\pi^-$. The 7 events seen yield a branching ratio $B(\Upsilon' \to \Upsilon\pi^+\pi^-) = (19 \pm 8)\%$. A consistent value of $B = (26 \pm 13)\%$ is obtained from the charged multiplicities of the Υ' and Υ decays. Using these values we deduce $\Gamma_{tot}(\Upsilon') = (31^{+10}_{-8})$ keV and $B_{ee}(\Upsilon') = (1.8 \pm 0.5)\%$. Furthermore we estimate $\Gamma(\Upsilon' \to gg\Upsilon) = (10 \pm 5)$ keV in agreement with QCD predictions using vector gluons while one would expect 100 keV with scalar gluons.

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Introduction. The observation of the decay $\Upsilon' \to \Upsilon + \pi^+\pi^-$ constitutes direct evidence for a transition linking two states of the recently discovered bottonium system [1]. The bottonium spectroscopy is expected to be analogous to that of charmonium [2,3]. The main decay mechanisms of the bottonium state $\Upsilon'(10014)$ should then be similar to those of the corresponding charmonium state $\psi'(3685)$.

Here we report the first observation of the decay $\Upsilon' \to \Upsilon\pi^+\pi^- \to \ell^+\ell^-\pi^+\pi^-$ ($\ell = \mu$ or e) using the LENA detector at the DORIS e^+e^- storage ring. We present two independent measurements of the branching ratio $B(\Upsilon' \to \Upsilon\pi^+\pi^-)$. By using the B value we are then able to estimate the total width $\Gamma_{tot}(\Upsilon')$ and finally to determine the mass scaling property of the two gluon partial width $\Gamma_{2g} \equiv \Gamma(\Upsilon' \to gg\Upsilon)$.

The decay $\Upsilon' \to \Upsilon\pi^+\pi^- \to \ell^+\ell^-\pi^+\pi^-$. In 1979/80 we accumulated an integrated luminosity of $\approx$2500 nb^{-1} at CM energies between 9.40 and 10.08 GeV. The luminosity taken was equally distributed among the $\Upsilon(9460)$, $\Upsilon'(10014)$, and the nearby continuum. To identify the $\Upsilon' \to \Upsilon\pi^+\pi^-$ events we have searched for the reaction $e^+e^- \to \ell^+\ell^-\pi^+\pi^-$ by scanning our total data set of 7 million triggers. The yield was seven events under the Υ' resonance curve and none in the Υ region or in the continuum.

The scanning procedure was determined by the properties of the non-magnetic LENA detector. The main components of LENA (see fig. 1) are the inner drift chamber detector for charged particle tracks and the surrounding energy detector consisting of NaI crystals and lead glass blocks. These are in turn surrounded by steel hadron absorbers, outer muon chambers, and time of flight counters [4–6].

The search for events of the type $e^+e^- \to \ell^+\ell^-\pi^+\pi^-$ was done using computer selection followed by a visual scan. The final cuts were:
– 4 tracks in the inner detector,
– 2 to 4 hits in the energy detector (energy clusters),
– 2 opposite tracks within 25° in the polar angle θ and 12° in the azimuthal angle ϕ (for kinematic reasons the largest acollinearity of lepton tracks originating from $\Upsilon' \to \Upsilon \to \ell^+\ell^-$ is 6°),
– the 2 nearly collinear tracks had to be identified as a $\mu^+\mu^-$ or an e^+e^- pair. For the μ-pair both tracks had to penetrate the muon filter and hit the outer muon detectors with the proper time of flight [5,6]. The total deposited energy had to be less than 1.8 GeV which is far above the typical energy deposit for two minimum ionizing muons and two charged pions. For the e^+e^- sample a minimum deposited energy of 3 GeV was required with at least 1.2 GeV behind each of the electron tracks, a safe cut for two 4.7 GeV electron showers.
– the 2 (pion) tracks had to be separated in the angle ϕ from the lepton tracks ($\mu^+\mu^-$ or e^+e^-) by at least 8° or 12°, respectively;
– the 2 (pion) tracks had to deposit less than 0.6 GeV;
– all tracks had to point to the e^+e^- interaction region.

The visual scan served to check the computer selection. The cuts listed above had to suppress beam–gas events, cosmic ray muons and annihilation μ-pairs with additional tracks, Bhabha events with additional tracks resulting from showering in the beam pipe, τ-pairs, and hadronic events. By changing the cut limits or omitting cuts – e.g. the time of flight of the muon tracks – we always arrived at the identical final sample:
– 3 events of the type $\mu^+\mu^-\pi^+\pi^-$
– 5 events of the type $e^+e^-\pi^+\pi^-$.
They are listed in table 1. Fig. 1 shows one event of each type. We checked that our event sample did not show the properties expected for the backgrounds: e.g. the e^+e^- pairs do not show the angular distribution expected for Bhabha events.

Seven events out of the 8 found by the scan could be kinematically reconstructed. Knowing the CM energy and the directions of the four identified particles one can calculate their momenta. The invariant masses

Table 1
Invariant masses of the lepton pairs and angle $\theta_{\pi\pi}$ between the two pion tracks.

Event	Type	$m_{\ell\ell}$ (MeV)	$\cos\theta_{\pi\pi}$
1	$ee\pi\pi$	9010^{+720}_{-750}	−0.86
2	$ee\pi\pi$	9030^{+700}_{-2680}	−0.72
3	$ee\pi\pi$	9230^{+500}_{-520}	−0.21
4	$ee\pi\pi$	8800^{+930}_{-2960}	−0.41
5	$ee\pi\pi$	9260^{+470}_{-810}	−0.91
6	$\mu\mu\pi\pi$	8990^{+740}_{-890}	−0.79
7	$\mu\mu\pi\pi$	9310^{+200}_{-200}	+0.07
8	$\mu\mu\pi\pi$	no fit possible	–

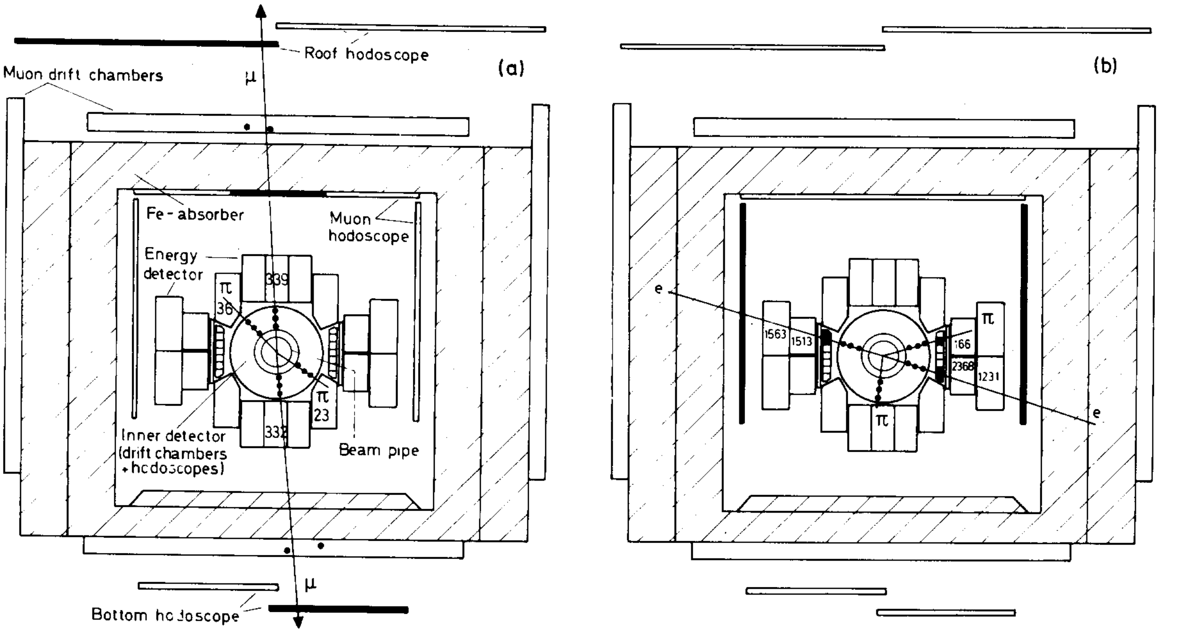

Fig. 1. Two events of the type $e^+e^- \to \ell^+\ell^-\pi^+\pi^-$ in the LENA detector [4–6] seen along the beam direction. The detector components are indicated. Only those drift chamber wires which fired are shown, similarly the hodoscope counters which responded are displayed in heavy lines. The numbers in the blocks of the energy detector give the deposited energy in MeV. Further on, our particle assignment is shown. The almost collinear lepton tracks either penetrate the Fe-absorber and hit the outer muon chambers (a) or shower in the energy detector (b). The pion tracks do not reach the muon chambers and do not shower.

$m_{\ell\ell}$ of the lepton pairs are given in table 1. All the $m_{\ell\ell}$ values are consistent with the mass of the $\Upsilon(9460)$. We note, however, that the errors in some cases are rather large. For one event no fit was possible within the measurement errors, the momentum did not balance. The event was therefore rejected.

Table 1 gives also the angle between the two pion tracks. The $\cos\theta_{\pi\pi}$ distribution clusters at negative values (fig. 2). The asymmetry (A) in positive (N_+) versus negative (N_-) values of $\cos\theta_{\pi\pi}$ [$A = (N_- - N_+)/(N_- + N_+)$] is experimentally found to be (0.7 ± 0.4). This value should be compared with the current algebra prediction [7] of 0.7, while the phase space expectation is 0. These values include the detector acceptance.

It should be mentioned that non-resonant higher order QED processes – for example large angle Bhabha scattering accompanied by electromagnetic pair production – may look in the LENA detector like a $\ell^+\ell^-\pi^+\pi^-$ event. That none of our seven events were found off the Υ' resonance strongly indicates that the cross sections of those higher order processes are very small and their contributions to our $\Upsilon' \to \Upsilon\pi^+\pi^- \to \ell^+\ell^-\pi^+\pi^-$ sample can be neglected.

The branching ratio $B(\Upsilon' \to \Upsilon\pi^+\pi^-)$ was calculated by the relation

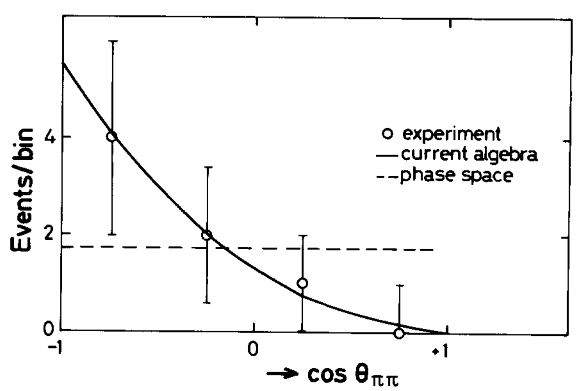

Fig. 2. Angular correlation between the two pions. Our seven events follow the expectation from current algebra [7].

$$B(\Upsilon' \to \Upsilon \pi^+\pi^-) = \frac{N(\ell\ell\pi\pi)}{N(\Upsilon' \to X)} \frac{\epsilon(\Upsilon' \to X)}{\epsilon(\ell\ell\pi\pi)} \frac{1}{B_{\ell\ell}(\Upsilon)}, \quad (1)$$

where $N(\ell\ell\pi\pi)$ are the numbers of observed $e^+e^- \to \ell^+\ell^-\pi^+\pi^-$ events. The total number $N(\Upsilon' \to X)$ of Υ decays into anything, contained in our data sample, is obtained by subtracting the non-resonant contribution from the number of all observed events under the Υ' resonance curve. Here the ϵ's are the indicated detector efficiencies and $B_{\ell\ell}(\Upsilon) = B_{\mu\mu}(\Upsilon)$ is the branching ratio of the decay $\Upsilon \to \ell^+\ell^-$. The efficiencies were calculated by Monte Carlo programs and are given in table 2. The angular correlation of the pions and their energy distribution can be taken either from a current algebra approach [7] or from the experimental data of the corresponding ψ' decay [8]. The efficiencies, however, turn out to be rather insensitive to these assumptions. In fact even uncorrelated phase space distributions produced similar numerical results (not shown).

Table 2 contains all relevant numbers used to calculate the branching ratio $B(\Upsilon' \to \pi^+\pi^-)$ by means of eq. (1). The two branching ratio values derived from the $\mu\mu\pi\pi$ and the $ee\pi\pi$ events, respectively, agree and give the combined result $B(\Upsilon' \to \Upsilon\pi^+\pi^-) = (19 \pm 8)\%$.

Multiplicity analysis of the Υ' decay. Next we evaluate the branching ratio by comparing the charged hadron multiplicity of the Υ' and Υ decays. Because of the relatively small Υ'–Υ mass difference their charged multiplicity distributions in 3-gluon decay should be very similar. Any observed multiplicity deviation would point to additional Υ' decay modes, in particular to the $\Upsilon' \to \Upsilon\pi^+\pi^-$ process.

The charged multiplicity n_{ch} of events observed in the LENA experiment was determined by counting the tracks seen in the azimuthal angle projection of the inner detector. No corrections have been applied for beam pipe conversions and overlap of tracks, since only relative changes of n_{ch} are of interest. The multiplicity distributions $D(n_{ch})$ of the Υ' and Υ direct decay events (shown in fig. 3) were obtained from the data taken at the peak of the resonances with an appropriate subtraction of the continuum and the vacuum polarisation contributions [10]. These distributions contain 3127 Υ and 1104 Υ' events.

Table 2
Efficiencies ϵ and numbers N of observed events for calculating $B(\Upsilon' \to \Upsilon\pi^+\pi^-)$.

Decay mode	$\mu^+\mu^-\pi^+\pi^-$	$e^+e^-\pi^+\pi^-$
$\epsilon(\ell\ell\pi\pi)$	0.15	0.375
$\epsilon(\Upsilon' \to X)$	0.77	
$N(\Upsilon' \to X)$	1680 ± 110	
$B_{\ell\ell}(\Upsilon) = B_{\mu\mu}(\Upsilon)$	(3.2 ± 0.8)% [a]	
$N(\ell\ell\pi\pi)$	2	5
$B(\Upsilon' \to \Upsilon\pi^+\pi^-)$	(19 ± 14)%	(19 ± 10)%

[a] World average value [5,9].

We compare the measured n_{ch} distributions of Υ' and Υ. A fit

$$D_{\Upsilon'}(n_{ch}) = \sum_{n\geq 0} p_n D_\Upsilon(n_{ch} - n), \quad \sum p_n = 1, \quad (2)$$

with the weights p_n as non-negative fit parameters give $p_0 > p_2 > p_1 > 0$ and $p_n \approx 0$ for $n \geq 3$. The coefficient p_1 was then fixed to the value of 0.06 to account for the higher energy of the three gluons from the Υ' decay. This value was estimated from the energy dependence of the continuum multiplicity assuming that about 50% of the Υ' decays are 3g processes. We would like to stress that changing p_1 to 0 changes the branching ratio given below by only 2%. The data

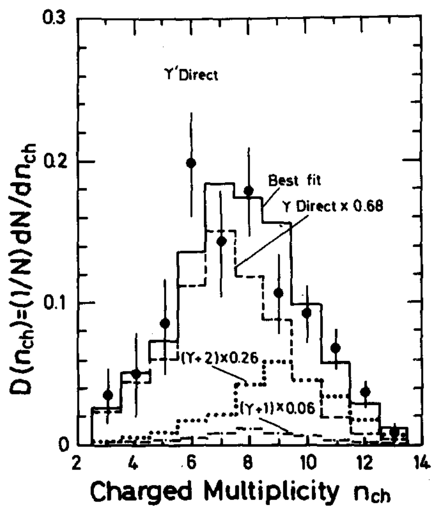

Fig. 3. Measured charged multiplicity distribution for the Υ' direct decay together with the best fit (full line). The components of the fit are: (a) the observed distribution of the direct Υ decay, 68% (broken line), (b) a small contribution of the Υ distribution shifted by 1 unit, 6%, (dashed–dotted line), (c) the Υ distribution shifted by 2 units, 26%, resulting from the $\Upsilon' \to \pi^+\pi^-\Upsilon$ decay (dotted line).

were then refit with p_1 fixed and $p_n = 0$ for $n \geqslant 3$. The result of this fit is $p_2 = 0.26 \pm 0.13$. The error includes the statistical errors of both the Υ' and the Υ distributions and the uncertainty in the vacuum polarisation subtraction.

To interpret the relatively large p_2 term we note that decays of the type $\Upsilon' \to \Upsilon + n\pi$ are for phase space and G-parity reasons essentially restricted to $n = 2$. We therefore consider the process $\Upsilon' \to \Upsilon\pi^+\pi^-$ as the dominant charged multiplicity changing decay mode. The Υ' decays to the P states influence the multiplicity only when they go into two gluons. Thus, we estimate from theoretical expectations [11], that their contribution to our fitted p_2 value is considerably smaller than the statistical error. Ignoring the slightly different detection efficiencies between the resonance and continuum events we can equate p_2 with the $\Upsilon' \to \Upsilon\pi^+\pi^-$ branching ratio and obtain $B(\Upsilon' \to \Upsilon\pi^+\pi^-) = (26 \pm 13)\%$.

Discussion. The weighted average of our experimental $B(\Upsilon' \to \Upsilon\pi^+\pi^-)$ values is $(21 \pm 7)\%$. Isospin conservation requires the decay $\Upsilon' \to \Upsilon\pi^0\pi^0$ to have half the probability of the $\pi^+\pi^-$ mode. Hence the total branching ratio is $B(\Upsilon' \to \Upsilon\pi\pi) = (31 \pm 10)\%$.

Using the above results, some estimates concerning total and partial widths of the Υ' can be made. In analogy to the ψ' case, the total width of the Υ' is given by:

$$\Gamma_{tot}(\Upsilon') \approx \Gamma_{3g}(\Upsilon') + \Gamma_{2g}(\Upsilon') + \Gamma_{P\gamma}(\Upsilon') + \Gamma_{''\gamma''}(\Upsilon'). \tag{3}$$

The subscripts indicate: 3g: $q\bar{q}$ annihilation into 3 hard gluons; 2g: hadronic transition to the Υ by emission of two soft gluons, which fuse into a pion pair (the decay $\Upsilon' \to \eta^0\Upsilon$ has a very small phase space); Pγ: electric dipole transition to the P states; "γ": $q\bar{q}$ annihilation via a virtual photon into leptons or hadrons (vacuum polarisation).

Decay modes with very small branching ratios are neglected. For the Υ the decay channels 2g and Pγ are absent. Therefore

$$\Gamma_{tot}(\Upsilon) \approx \Gamma_{3g}(\gamma) + \Gamma_{''\gamma''}(\Upsilon), \tag{4}$$

Γ_{3g} and $\Gamma_{''\gamma''}$ are both directly proportional to Γ_{ee}, the width for annihilation into an e^+e^- pair [3]. Using that proportionality (the same for Υ and Υ') and the definition of $B_{ee} = \Gamma_{ee}/\Gamma_{tot}$ one easily obtains

$$\Gamma_{3g}(\Upsilon') + \Gamma_{''\gamma''}(\Upsilon') \approx \Gamma_{ee}(\Upsilon')\Gamma_{tot}(\Upsilon)/\Gamma_{ee}(\Upsilon) = \Gamma_{ee}(\Upsilon')/B_{ee}(\Upsilon). \tag{5}$$

The width $\Gamma_{2g}(\Upsilon')$ is related to the branching ratio $B(\Upsilon' \to \Upsilon\pi\pi)$ by

$$\Gamma_{2g}(\Upsilon') \approx B(\Upsilon' \to \Upsilon\pi\pi)\Gamma_{tot}(\Upsilon'). \tag{6}$$

A combination of the eqs. (3), (5) and (6) yields

$$\Gamma_{tot}(\Upsilon') \approx [\Gamma_{ee}(\Upsilon')/B_{ee}(\Upsilon) + \Gamma_{P\gamma}(\Upsilon')] \times [1 - B(\Upsilon' \to \Upsilon\pi\pi)]^{-1}. \tag{7}$$

From the LENA value $\Gamma_{ee}(\Upsilon') = (0.56 \pm 0.09)$ keV [6] and the $B_{ee}(\Upsilon)$ given in table 2 it follows:

$$\Gamma_{ee}(\Upsilon')/B_{ee}(\Upsilon) = 18^{+6}_{-5}\ \text{keV}.$$

The only quantity on the right hand side of eq. (7) not yet measured is the electric dipole radiation width $\Gamma_{P\gamma}(\Upsilon')$. Therefore we estimate it by scaling [‡1] the corresponding charmonium value [2,12]:

$$\Gamma_{P\gamma}(\Upsilon') = (e_b/e_c)^2(m_c/m_b)\Gamma_{P\gamma}(\psi') \approx 4.2\ \text{keV}, \tag{8}$$

where e and m are charge and mass of the quarks indicated. The estimated $\Gamma_{P\gamma}(\Upsilon')$ contribution (8) to $\Gamma_{tot}(\Upsilon')$ lies within the error of $\Gamma_{ee}(\Upsilon')/B_{ee}(\Upsilon)$. Using the above $B(\Upsilon' \to \Upsilon\pi\pi)$ value we finally obtain from eq. (7): $\Gamma_{tot}(\Upsilon') = 31^{+10}_{-7}$ keV, $B_{ee}(\Upsilon') = \Gamma_{ee}(\Upsilon')/\Gamma_{tot}(\Upsilon) = (1.8 \pm 0.5)\%$ and $\Gamma_{2g}(\Upsilon') = B(\Upsilon' \to \Upsilon\pi\pi) \times \Gamma_{tot}(\Upsilon') = (10 \pm 5)$ keV.

Let us finally compare the hadronic transition widths Γ_{2g} of Υ' and ψ' [12]. The measured ratio

$$\frac{\Gamma_{2g}(\Upsilon')}{\Gamma_{2g}(\psi')} = \frac{(10 \pm 5)\ \text{keV}}{(110 \pm 22)\ \text{keV}} = 0.09 \pm 0.05,$$

is in agreement with the expected mass scaling behaviour of QCD dipole radiation [2,13],

$$\Gamma_{2g}(\Upsilon')/\Gamma_{2g}(\psi') \approx (m_c/m_b)^2 \approx (M_{J/\psi}/M_{\Upsilon})^2 = 0.11.$$

For scalar gluons the ratio is expected to be near unity [14]. That is incompatible with our experimental results reported here.

‡1 Eq. (8) is valid for the logarithmic quarkonium potential. For potentials proportional to r^n the mass ratio m_c/m_b has to be replaced by $(m_c/m_b)^{1+2n/(2+n)}$. The logarithmic potential is a good approximation to a "Coulomb + linear" potential in the overlap region.

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