Observation of the \( \Upsilon(2^3D_1) \) and indication of the \( \Upsilon(1^3D_1) \)

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We present evidence, from published BABAR data, for the existence of further excitations in the \( bb \) spectrum, namely the long-awaited \( \Upsilon(1^3D_1) \) and \( \Upsilon(2^3D_1) \), with central masses of 10098±5 MeV and 10495±5 MeV, respectively. The significance of the \( \Upsilon(1^3D_1) \) and \( \Upsilon(2^3D_1) \) signals is found to be 3.0 and 10.7 standard deviations, respectively.

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In order to clarify the relation between each set of data in Fig. 2 and the corresponding distributions shown in Fig. 1, we have numbered the bins in the inset of Fig. 1 as well as the sets of data in Fig. 2. Of course, each set of data in the latter figure should start out at 0 events for $\Delta = 0$ (window closed). However, plotting the data this way would result in a confusion of points and curves. For clarity, we have thus increased the number of events in Fig. 2 by a constant, for each set of data. Hence, for all data sets the number of events in reality vanishes where the distributions meet the left-hand vertical axis. So the annotations on the axis denote the scale, and not the number of events corresponding to each data point.

![Graph](image)

**FIG. 2.** Number of events for the reaction $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S) \rightarrow \pi^+\pi^-e^+e^-$, scaled up by a constant, for increasing window openings $\Delta$, from 1 MeV to 200 MeV in steps of 1 MeV, in each of the 20 bins of the inset of Fig. 1. The corresponding bin numbers are given on the right-hand vertical axis. Each data set corresponding to a single bin is fitted by a curve quadratic in $\Delta$ (solid lines) that vanishes for $\Delta = 0$. The data are taken from Ref. 1.

Each of the data sets corresponding to a particular interval in invariant $e^+e^-$ mass is fitted with a quadratic curve, where we assume that an infinite data set would lead to a smoothly growing number of events according as the window is further opened. From the standard deviation of the actual data with respect to smoothness, we determine the size of the uncertainty in the number of events in each bin, also for the bins not shown in Fig. 2.

One may easily verify that the sizes of the error bars shown in Fig. 2 are in agreement with the deviations from smoothness in Fig. 2.

One observes in Fig. 2 that the number of events in bin no. 7 increases faster for small values of $\Delta$ than the number of events in the neighboring bins. We believe this can be explained by assuming that events from the narrow-width $\Upsilon(1^3D_1)$ fall well within the 10 MeV bin for not too large windows, but start spilling to neighboring bins when the window is further opened. In the following, this issue will be dealt with more quantitatively.

In Fig. 3 we study, for the chosen signal bin (number 7 in the inset of Fig. 1), the amount of events and also the signal-to-background ratio, as a function of the window size $\Delta$. For that purpose, we determine the background signal by choosing the maximum of the number of events in the neighboring bins (numbers 6 and 8 in the inset of Fig. 1).

![Graph](image)

**FIG. 3.** Signal height (gray dots, pink in the online version) and signal-to-background ratio (black) for increasing window openings $\Delta$ from 1 MeV to 140 MeV in steps of 1 MeV, for bin no. 7 of the inset of Fig. 1. Annotations on the vertical axis correspond to the signal-to-background ratio; the signal heights are 4 times larger.

We have also studied all other bins shown in the inset of Fig. 1. None of these has a behavior for the signal height and the signal-to-background ratio that is even comparable to what we observe in Fig. 3 for bin no. 7. For example, bin no. 12, at 10.15 GeV, has a maximum signal height of 8 events, which vanishes for windows larger than $\Delta = 32$, while bin no. 13, at 10.16 GeV, has no positive signal for windows smaller than 80 MeV and, moreover, a totally negligible signal-to-background ratio for even wider windows. From all this we may conclude that, in the invariant-mass interval from 10.05 to 10.22 GeV, only one bin shows a very stable signal for all possible windows, and a reasonable signal-to-background ratio for windows up to about 70 MeV.
We assume that, for wider windows, possible events associated with the supposed $\Upsilon(1^3D_1)$ signal start to spill over to the neighboring bins. As a consequence, the background increases, whereas signal is lost. Hence, we prefer to study the statistical relevance for a smaller window, but still large enough for the signal height to be already reasonable. One may conclude from Fig. 3 that taking windows ranging from $\Delta = 25$ MeV to $\Delta = 35$ MeV is a good choice, since for lower values the signal is relatively small, whereas for higher ones the signal-to-background ratio decreases rapidly. For the purpose of our data analysis, we have chosen $\Delta = 30$ MeV, as shown in Fig. 1.

The relevant bin for the $\Upsilon(1^3D_1)$ contains $30 \pm 3.07$ events. For this bin, a global fit to the data (see Fig. 1) gives a background of $18.0 \pm 2.53$ events, leaving $12.0 \pm 3.98$ events for the signal. Thus, the signal has a significance of $3.0\sigma$, which implies a strong indication of the $\Upsilon(1^3D_1)$ at $10098 \pm 5$ MeV.

For the uncertainty in the mass of the $\Upsilon(1^3D_1)$, we take half the bin width, as we do not expect this state to have a width larger than 1 MeV. Consequently, the scattering of the data within the 10-MeV-wide bin entirely stems from the method to collect data.

The difference between the aforementioned value of 10.113 GeV and the observed mass can be understood from the predicted small mass shifts of $^3D_1$ bottomonium states due to open-bottom meson-loops.

The CLEO Collaboration announced [4] the discovery of a $J^{PC} = 2^{−−}$ $b\bar{b}$ resonance with a central mass of $(10161.1 \pm 0.6 \pm 1.6)$ MeV. Although CLEO reported a significance of 10.2 standard deviations, their observation is still today omitted from the Summary Tables of the Particle Data Group [2]. Our identification of the $1^{−−}$ $\Upsilon(1^3D_1)$ state, which comes out 63 MeV below the $2^{−−}$ $\Upsilon(1^3D_2)$, makes CLEO’s assignment of quantum numbers very plausible, also in view of the quite different couplings of vector and tensor states to open-bottom channels.

The observation of CLEO was recently confirmed by BABAR [2], obtaining a value of $10164.5 \pm 0.8_{stat} \pm 0.5_{syst}$ MeV for the $\Upsilon(1^3D_2)$ mass. However, in the same paper BABAR claimed a mass of 10151 MeV for the $\Upsilon(1^3D_1)$, which is close to the model prediction in Ref. [1], but about 53 MeV above our value. In the present study, as mentioned before, we do not find any other relevant signal in the invariant-mass interval from 10.05 to 10.22 GeV.

For the signal stemming from the $\Upsilon(2^3D_1)$, we follow precisely the same strategy as discussed above for the $\Upsilon(1^3D_1)$. In Fig. 2, we display how the number of events develops when the window ($\Delta$) is increased from 0 to 200 MeV, in steps of 1 MeV, for all 10-MeV-wide bins shown in Fig. 1. The sets of data in Fig. 1 from the bottom to the top curve, correspond to the bins in Fig. 2 from left to right. For example, data set no. 12 counted from below in Fig. 2 which starts out at the annotation for 500 events on the left-hand vertical axis, corresponds to the bin no. 12 counted from the left in Fig. 1. This is the bin that contains more events than any other shown in Fig. 1. We observe for the latter set of data a substantially faster rise in the number of events for increasing values of the window size $\Delta$, up to about $\Delta = 120$, than for the data sets associated with the neighboring bins. The most obvious explanation for this behavior is the presence of an enhancement in bin no. 12, for which the most likely candidate is the $\Upsilon(2^3D_1)$.

![FIG. 4. Number of events for the reaction $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S) \rightarrow \pi^+\pi^- e^+e^-$, scaled up by a constant, for increasing window openings $\Delta$, from 1 MeV to 200 MeV in steps of 1 MeV, in each of the 34 bins of Fig. 1. Each data set corresponding to a single bin is fitted by a curve quadratic in $\Delta$ (solid lines) that vanishes for $\Delta = 0$. The data are taken from Ref. 1.](image)

In Fig. 4 we depict the signal and the signal-to-background ratio for the relevant bin. From this result we conclude that a window of $\Delta = 22$ MeV is appropriate for analysis. However, we admit that an equally good analysis is certainly possible for a window of $\Delta = 82$ MeV. We show the data for the latter window in Fig. 7 using a data binning of 5 MeV, but shall not further analyse this case, for the same reason as we have discussed for the $\Upsilon(1^3D_1)$. Namely, for larger windows we suspect data to spill over to neighboring bins.
The data for the $\Upsilon(2^3D_1)$ are depicted in Fig. 6. The relevant bin contains $130 \pm 4.51$ events, while from a fit to the global data (solid curve in Fig. 6) we find a background signal of $81 \pm 0.81$ events. For the signal we thus obtain $49 \pm 4.58$ events, and so a significance of $10.7\sigma$.

![Signal height (gray dots, pink in the online version) and signal-to-background ratio (black) for increasing window openings $\Delta$, from 1 MeV to 200 MeV in steps of 1 MeV, for the bin containing the $\Upsilon(2^3D_1)$ signal of Fig. 5. Annotations on the vertical axis correspond to the signal-to-background ratio; the signal heights are 100 times larger.](image1)

![Invariant-mass distribution for 2311 events in $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S) \rightarrow \pi^+\pi^-e^+e^-$, for window and bin sizes of $\Delta = 22$ and 10 MeV, respectively. Data are taken from Ref. [3]. Our fit to the background is shown by a solid curve. The $\Upsilon(2^3D_1)$ signal has a significance of $10.7\sigma$. For completeness, we have also indicated the $BB$ and $BB^* + BB^*$ thresholds.](image2)

![Invariant-mass distribution for 8337 events in $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S) \rightarrow \pi^+\pi^-e^+e^-$ for window and bin sizes of $\Delta = 82$ and 5 MeV, respectively. Data are taken from Ref. [3]. For completeness, we have also indicated the $BB$ and $BB^* + BB^*$ thresholds.](image3)

FIG. 5. Signal height (gray dots, pink in the online version) and signal-to-background ratio (black) for increasing window openings $\Delta$, from 1 MeV to 200 MeV in steps of 1 MeV, for the bin containing the $\Upsilon(2^3D_1)$ signal of Fig. 5. Annotations on the vertical axis correspond to the signal-to-background ratio; the signal heights are 100 times larger.

FIG. 6. Invariant-mass distribution for 2311 events in $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S) \rightarrow \pi^+\pi^-e^+e^-$, for window and bin sizes of $\Delta = 22$ and 10 MeV, respectively. Data are taken from Ref. [3]. Our fit to the background is shown by a solid curve. The $\Upsilon(2^3D_1)$ signal has a significance of $10.7\sigma$. For completeness, we have also indicated the $BB$ and $BB^* + BB^*$ thresholds.

FIG. 7. Invariant-mass distribution for 8337 events in $e^+e^- \rightarrow \pi^+\pi^-\Upsilon(1S) \rightarrow \pi^+\pi^-e^+e^-$ for window and bin sizes of $\Delta = 82$ and 5 MeV, respectively. Data are taken from Ref. [3]. For completeness, we have also indicated the $BB$ and $BB^* + BB^*$ thresholds.

The here reported $\Upsilon(1^3D_1)$ and $\Upsilon(2^3D_1)$ masses lend further support to the level scheme of the harmonic-oscillator (HO) approximation to the resonance-spectrum expansion (HORSE) (see Ref. [3] and references therein). In particular, the observed spacing of about 380 MeV between the $D$ states [9] makes a $3^3D_1$ assignment for the $\Upsilon(10860)$ more plausible than $5^3S_1$. 

...much stronger signal for the $2^3D_1$ state as compared to the $1^3D_1$ seems puzzling at first sight, also in view of the $2^3S_1$ peak, which is higher than the $3^3S_1$. A possible explanation is offered by coupled channels. Namely, even $b\bar{b}$ systems below the lowest open-bottom threshold $(BB)$ couple to virtual meson pairs, both the $3^3S_1$ and $3^3D_1$ states. This coupling inevitably gives rise to $3^3S_1$-$3^3D_1$ mixing. Now, the farther the $b\bar{b}$ system lies below the $BB$ threshold, the more virtual will the meson pairs be, and so the smaller the $3^3S_1$-$3^3D_1$ mixing. Therefore, the $\Upsilon(2^3D_1)$, which lies only 64 MeV below the $BB$ threshold, will have a significantly larger $3^3S_1$ admixture than the almost 400 MeV lighter $\Upsilon(1^3D_1)$, and so its effective coupling to $e^+e^-$ will be considerably larger.

Nevertheless, the smaller $3^3D_1$ signals may explain why they have not been discovered over the past three decades of $e^+e^-$ accelerator physics. Moreover, these states are probably also quite narrow. This complicates event selection, since on the one hand we prefer a narrow bin size for high resolution, but on the other hand we would also like to have sufficient statistics, which can be achieved by choosing large windows for the invariant masses of the final-state $e^+e^-$ pair around the $\Upsilon(1S)$ mass. However, too large windows inevitably produce several non-candidates and a very noisy background, as may be observed by comparing the distributions shown in Figs. 6 and 7. The choices we have made in the present analysis reflect a compromise between the two criteria.

...the transitions under study here, as can be seen from the large $2^3S_1$ and $3^3S_1$ peaks in Fig. 4 to be contrasted with the more modest $2^3D_1$ (Figs. 6, 7) and especially $1^3D_1$ (Fig. 4) structures. This observation is in line with expectations from theory, since $D$-wave quarkonium states are suppressed in $e^+e^-$ annihilation, due to the small wave function at short distances. However, the
To be more precise, the pure HO, without accounting for meson loops, gives a mass of $2 \times 4.724 + 0.19 \times (4 + 2 + 1.5) = 10.873 \text{ GeV}$ [2]. BABAR obtained 10.876±0.002 GeV [10], while in Ref. [8] we found 10.867 GeV for the $\Upsilon(10860)$ mass. Moreover, this result supports the conclusion of our analysis in Ref. [8] that the $\Upsilon(10580)$ is not the $\Upsilon(4S)$ resonance, but rather a $B\bar{B}$ threshold enhancement [11]. For the $\Upsilon(4S)$ resonance, which in the HORSE is expected some 100–200 MeV below the $\Upsilon(3D)$, due to the effect of the meson loops, we found in Ref. [8] a central mass of 10.735 GeV, by analyzing BABAR data published in Ref. [10]. Finally, the conspicuousness of the $2^3D_1$ signal, when compared to the much feebler $1^3D_1$, is a compelling indication of virtual coupled-channel effects, as explained above. This represents an additional endorsement of the HORSE and its nonperturbative description of decay, including open as well as closed meson-meson channels.

In conclusion, we have observed excellent candidates for the $\Upsilon(1^3D_1)$ and $\Upsilon(2^3D_1)$ states, with central masses of 10098±5 MeV and 10495±5 MeV, respectively. Their observation, if confirmed independently, strongly supports the resonance level scheme of the harmonic-oscillator approximation to the resonance-spectrum expansion for quarkonia.

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