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Antideuteron production in $\Upsilon(nS)$ decays and in $e^+e^- \to q\bar{q}$ at $\sqrt{s} \approx 10.58\,\mathrm{GeV}$

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We present measurements of the inclusive production of antideuterons in e^+e annihilation into hadrons at ≈ 10.58 GeV center-of-mass energy and in $\Upsilon(1S, 2S, 3S)$ decays. The results are obtained using data collected by the *BABAR* detector at the PEP-II electron-positron collider. Assuming a fireball spectral shape for the emitted antideuteron momentum, we find $\mathcal{B}(\Upsilon(1S) \to \bar{d}X) = (2.81 \pm 0.49(\mathrm{stat})^{+0.20}_{0.24}(\mathrm{syst})) \times 10^{-5}$, $\mathcal{B}(\Upsilon(2S) \to \bar{d}X) = (2.64 \pm 0.11(\mathrm{stat})^{+0.26}_{0.21}(\mathrm{syst})) \times 10^{-5}$, $\mathcal{B}(\Upsilon(3S) \to \bar{d}X) = (2.33 \pm 0.15(\mathrm{stat})^{+0.31}_{0.28}(\mathrm{syst})) \times 10^{-5}$, and $\sigma(e^+e \to \bar{d}X) = (9.63 \pm 0.41(\mathrm{stat})^{+1.17}_{1.01}(\mathrm{syst}))$ fb.

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The production of nuclei and anti-nuclei in hadronic collisions and in hadronization processes has recently attracted considerable theoretical and experimental interest [1–3], since cosmic anti-nuclei may provide a sensitive probe of dark matter annihilation. Dark matter particles might annihilate into two colored partons – quarks (q) and gluons (g) – which could hadronize into mesons and baryons, potentially forming bound states such as light (anti)nuclei. The latter process, requiring at least six q or $\overline{q}$ in close proximity, is poorly understood both theoretically and experimentally, and precise measurements of both total rates and momentum spectra are needed. With no initial-state hadrons, e^+e^- annihilations provide a clean probe of this process not only for q and $\overline{q}$ but also for g via decays of Υ and other vector resonances.

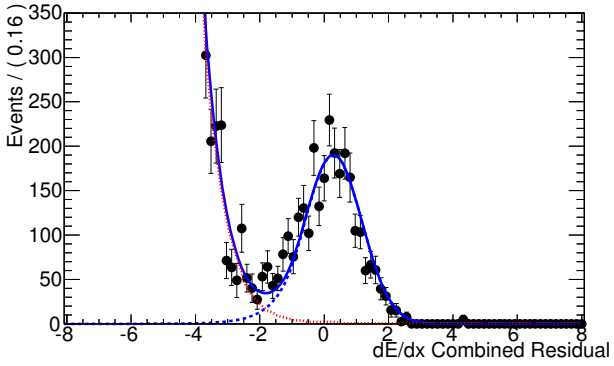
Experimental measurements focus on antideuteron ($\overline{d}$) production as such studies are not limited, as in the deuteron (d) production case, by the high rate of nuclei production via interactions with the detector materials. The ARGUS [4] and CLEO [5] experiments observed $\overline{d}$ production at the level of 3×10^{-5} per $\Upsilon(1S)$ and $\Upsilon(2S)$ decays, and set limits on production in $\Upsilon(4S)$ decays and $e^+e^- \to q\overline{q}$ at 10.6 GeV. The ALEPH [6] experiment observed a 3σ evidence for $\overline{d}$ production in $e^+e^- \to q\overline{q}$ at 91.2 GeV. In these measurements, the accessible kinematic range, $0.4 - 1.7$ GeV/c, was representing less than 20% of the phase space where d and $\overline{d}$ could be identified.

In this Letter, we present studies of $\overline{d}$ production in e^+e^- annihilation data taken on and just below the $\Upsilon(2S)$, $\Upsilon(3S)$ and $\Upsilon(4S)$ resonances. To avoid any ambiguity, we refer to d and $\overline{d}$ separately everywhere in this note, so that charge conjugation is not implied anywhere. We also study the $\overline{d}$ production from $\Upsilon(1S)$ using the $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$ decay chain. The boost of the center of mass (CM) allows a wide momentum range to be accessed, $0.3 - 3$ GeV/c, which corresponds to $0.5 - 1.5$ GeV/c in the laboratory frame. We confirm the $\Upsilon(1S)$ rates, improve the coverage and precision for $\Upsilon(2S)$ decays, measure $\overline{d}$ production in $\Upsilon(3S)$ decays, and also, for the first time, in $e^+e^- \to q\overline{q}$ near 10.6 GeV.

The results presented here are obtained from the complete *BABAR* $\Upsilon(2S, 3S, 4S)$ ($\Upsilon(nS)$) datasets (Onpeak), including data collected at a CM energy 40 MeV below the peak of each resonance (Offpeak). The luminosity [7] collected for each dataset and the corresponding number of $\Upsilon(nS)$ decays are reported in Table I. We also use Monte Carlo (MC) simulated data samples generated using JETSET [8] for $e^+e^- \to q\overline{q}$ ($q = u, d, s$) events and EVTGEN [9] for $\Upsilon(nS)$ decays. The interaction of simulated particles with the *BABAR* detector is modeled using GEANT4 [10]. Neither d nor $\overline{d}$ production is implemented in JETSET, and $\overline{d}$ cannot be simulated in the

TABLE I. Collected luminosity and number of decays for the samples used in the analysis. Integrated luminosity is reported both for the Onpeak and Offpeak samples.

Resonance	Onpeak	# of Υ Decays	Offpeak
$\Upsilon(4S)$	429 fb^{-1}	463×10^6	44.8 fb^{-1}
$\Upsilon(3S)$	28.5 fb^{-1}	116×10^6	2.63 fb^{-1}
$\Upsilon(2S)$	14.4 fb^{-1}	98.3×10^6	1.50 fb^{-1}


Events / (0.16)
350
300
250
200
150
100
50
0
-8
-6
-4
-2
0
2
4
6
8
dE/dx Combined Residual

$m_{\rm recoil} = \sqrt{(E_{\rm beam} - E_{\pi^+\pi^-})^2 - (\vec{p}_{\rm beam} - \vec{p}_{\pi^+\pi^-})^2}$: $[9.453,\ 9.472]\,{\rm GeV}/c^2$ (signal) and $[9.432,\ 9.452]\,{\rm GeV}/c^2$ plus $[9.474,\ 9.488]\,{\rm GeV}/c^2$ (sidebands), and we subtract the yields in the sidebands, rescaled by their relative ranges, from those in the signal range. Due to lower statistics we use only five bins in CM momentum for this measurement.

Corrections due to the requirement on the number of DCH dE/dx samplings can be computed by comparing the distribution for this variable in data and signal simulation for d's in a narrow signal window that provides a high-statistics control sample. This sample has negligible background due to the narrow dE/dx window and the relatively large number of true deuterons produced in material. We correct the fitted yields by -7% to correct for differences between data and simulation, which is not observed to depend on the CM momentum or polar angle. We assume no correlation with the value of the residual itself at this level of precision.

To validate the fit procedure and check for possible biases in the $\overline{d}$ yields, we perform a series of fits to pseudo-datasets generated according to the fit p.d.f.'s and we assign a systematic uncertainty based on any bias found (i.e., the deviation from zero of the mean of the normalized residuals distribution). The uncertainty from our choice of the background model distribution function is estimated by comparing to results obtained using a background model consisting of two Gaussian functions fixed to a common mean. Additional systematic uncertainties result from the weights used to correct for reconstruction efficiency in the detector and kinematic acceptance. To estimate the systematic uncertainty from the event selection and trigger, we compare the nominal efficiency to that computed using a different selection where we consider only a subset of $e^+e^- \to Y \to 2(N\overline{N})X$ events with a p or $\overline{p}$ inside the nominal detector acceptance. We evaluate the effect of finite Monte Carlo statistics by allowing the weights to vary according to a Gaussian distribution centered at the nominal value with the width given by the uncertainties in the weights. We assign uncertainties in each bin from the distribution of fit results. Any data/simulation in tracking efficiency is known to be below the per-mille level [12] and is negligible. The uncertainty in the correction for $\overline{d}$ material interaction is computed similarly, with the width of the Gaussian distribution set to the statistical uncertainty in the calculation plus a 30% uncertainty in the prediction itself.

We estimate the contribution from secondary d's, described above, by fitting the DOCA distributions for data and simulated events in and outside the selected region. The simulation describes the data except for a slowly falling exponential component, which we ascribe to secondary d's. The fits indicate a small contribution to the selected events, which we take as a one-sided systematic uncertainty. We compare DOCA distributions of simulated antiprotons with a control sample of well-identified antiprotons and we assign a $+5.8\%$ one-sided uncertainty. The uncertainty in the event selection efficiency is estimated by comparing the nominal efficiency with the efficiency for events for which at least one of the generated prompt (anti)nucleons is a (anti)proton within the detector angular acceptance. Finally, uncertainties in the cross sections and number of $\Upsilon(nS)$ mesons are propagated along with the other systematics. The contributions to the systematic uncertainties are summed in quadrature separately for the positive and negative sides, and their values for each contribution and the totals are summarized in Table II. Systematic values in each bin are reported in Ref. [17].

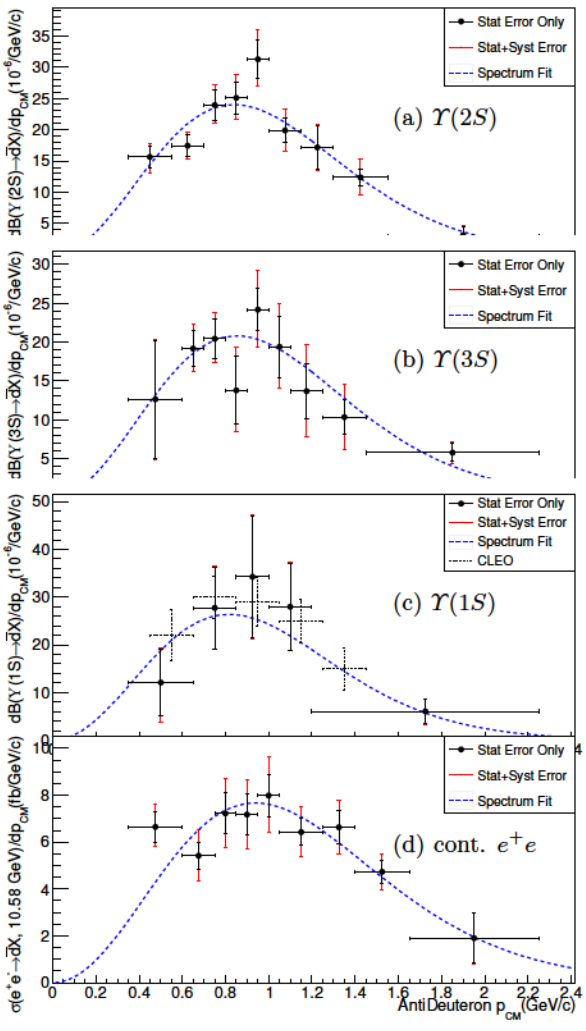


FIG. 2. Measured antideuteron differential spectra in (a) $\Upsilon(2S)$, (b) $\Upsilon(3S)$, (c) $\Upsilon(1S)$ decays, and (d) $e^+e \to q\overline{q}$ at a CM energy of $\approx 10.58\,{\rm GeV}$. The points with inner (black) error bars give the measurements and their associated statistical uncertainties, the outer (red) error bars give the quadratic sum of the statistical and systematic uncertainties, and the dashed (blue) curves show the fit to Eq. 2. Subfig. (c) also includes the CLEO results with dashed error bars for comparison.

TABLE II. Contributions to the systematic uncertainties for the different measurements. Ranges are indicated where the contribution is different for each CM momentum bin.

Source	$\Upsilon(2S)$	$\Upsilon(3S)$	$\Upsilon(1S)$	Continuum
Fit Biases	0.5% — 2.0%	0.1% — 6.6%	0.1% — 2.0%	0.0% — 0.2%
Background Model	0.2% — 7.8%	3.1% — 12.0%	0.9% — 7.6%	0.0% — 8.9%
Reconstruction Efficiency	2.5% — 10.5%	5.2% — 17.0%	1.3% — 7.1%	3.0% — 7.3%
Kinematic Acceptance	0.5% — 10.3%	3.6% — 16.0%	0.6% — 2.9%	1.4% — 8.4%
Material Interaction	2.8% — 10.5%	4.3% — 17.0%	2.0% — 7.3%	2.9% — 7.4%
Fake antideuterons	$^{+0.0\%}_{0.5\%}$ — $^{+0.0\%}_{9.8\%}$	$^{+0.0\%}_{1.1\%}$ — $^{+0.0\%}_{3.0\%}$	$^{+0.0\%}_{1.9\%}$ — $^{+0.0\%}_{32.0\%}$	$^{+0.0\%}_{0.6\%}$ — $^{+0.0\%}_{5.4\%}$
DOCA Selection	$^{+5.8\%}_{0.0\%}$	$^{+5.8\%}_{0.0\%}$	$^{+5.8\%}_{0.0\%}$	$^{+5.8\%}_{0.0\%}$
Event Selection	2.3%	2.3%	1.1%	4.6%
Normalization	1.2%	1.2%	0.2%	0.6%

The numbers of $\overline{d}$'s extracted from the fit are corrected for the differences between data and MC samples mentioned above, and then are converted into branching fractions for $\Upsilon(2S)$ and $\Upsilon(3S)$ using the total number of Υ decays. Using the total luminosity from Onpeak and Offpeak $\Upsilon(4S)$ datasets, we compute the observed cross section for $\overline{d}$ production from $e^+e^- \to q\overline{q}$ at a CM energy of $\approx 10.58\,\mathrm{GeV}$.

The number of $\Upsilon(1S)$ decays is computed as

$$N_{\Upsilon(1S)} = N^{\mathrm{fit}}_{\Upsilon(1S)} \times \frac{f_{\mathrm{sig}} - f_{\mathrm{sb}}}{\varepsilon_{\mathrm{filter}}}, \qquad (1)$$

where $N^{\mathrm{fit}}_{\Upsilon(1S)}$ is the number of $\Upsilon(2S) \to \pi\pi\Upsilon(1S)$ events reconstructed inclusively, obtained by a fit to the invariant mass recoiling against a reconstructed $\pi^+\pi^-$ system in $\Upsilon(2S)$ data. The quantities f_{sig} and f_{sb} are respectively the fraction of the fitted $\Upsilon(1S)$ recoil mass distribution in the signal and sideband regions used to subtract the contribution from background events, and $\varepsilon_{\mathrm{filter}}$ is the average efficiency of the trigger and the event filter to accept $\Upsilon(2S) \to \pi\pi\Upsilon(1S)$ decays obtained from the $\Upsilon(2S)$ MC sample. After applying these factors, we find $N_{\Upsilon(1S)} = (9.670 \pm 0.023) \times 10^6$. The final values for the differential branching fractions and $e^+e^- \to q\overline{q}$ cross section are shown in Fig. 2.

The total rates, presented in Table III, are obtained from the measured differential spectra by fits to the "fireball" model distribution [18]

$$P(E) = \alpha v^2 e^{-\beta E}, \qquad (2)$$

where E is the $\overline{d}$ CM energy and α and β are free parameters determined by the fit. The fits are shown in Fig. 2. The total rates quoted in Table III are the integral of these distributions from $0\,\mathrm{GeV}/c$ to $4\,\mathrm{GeV}/c$, and the associated uncertainties are those in the integral taking into account the full covariance of α and β. We find that values for the parameter β in Υ decays are mutually compatible within 1σ, and the average value is $\beta = (4.71 \pm 0.19)\,\mathrm{GeV}^{-1}$. Fitting to the $e^+e^- \to q\overline{q}$ spectrum yields a lower value of $(3.92 \pm 0.22)\,\mathrm{GeV}^{-1}$, corresponding to a somewhat harder spectrum. As an additional cross-check on the cross section for $e^+e^- \to q\overline{q}$ production, we fit separately the differential spectra from the $\Upsilon(4S)$ Offpeak dataset only, and obtain a cross section of $12.2 \pm 1.8\,\mathrm{fb}$, where the error is statistical only. Values for both this cross section and other parameters of the fit are in good agreement with the Onpeak plus Offpeak result.

TABLE III. Total rates of antideuteron production. The first uncertainties listed are statistical, the second systematic. For comparison, we also list the ratio of our measurement of the inclusive antideuteron cross section to the cross section for hadronic production at a similar energy evaluated from [19]. Here we only quote our own uncertainties, the hadronic cross section itself has a 7% uncertainty.

Process	Rate
$\mathcal{B}(\Upsilon(3S) \to \bar{d}X)$	$(2.33 \pm 0.15^{+0.31}_{0.28}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(2S) \to \bar{d}X)$	$(2.64 \pm 0.11^{+0.26}_{0.21}) \times 10^{-5}$
$\mathcal{B}(\Upsilon(1S) \to \bar{d}X)$	$(2.81 \pm 0.49^{+0.20}_{0.24}) \times 10^{-5}$
$\sigma(e^+e^- \to \bar{d}X)$ $[\sqrt{s} \approx 10.58\,\mathrm{GeV}]$	$(9.63 \pm 0.41^{+1.17}_{1.01})$ fb
$\dfrac{\sigma(e^+e^- \to \bar{d}X)}{\sigma(e^+e^- \to \mathrm{Hadrons})}$	$(3.01 \pm 0.13^{+0.37}_{0.31}) \times 10^{-6}$

In summary, we have performed measurements of inclusive $\overline{d}$ production in $\Upsilon(1,2,3S)$ decays and in $e^+e^- \to q\overline{q}$. These are the first measurements of $\overline{d}$ production in $e^+e^- \to q\overline{q}$ at a CM energy of $\approx 10.58\,\mathrm{GeV}$ and in $\Upsilon(3S)$ decay, and the most precise measurement in $\Upsilon(2S)$ decay. Our total and differential rates for inclusive $\bar{d}$ production in $\Upsilon(1S)$ and $\Upsilon(2S)$ decay are in good agreement with previous measurements [15], and with the expected spectral shapes from the coalescence model [20, 21]. We additionally note an order of magnitude suppression of $\overline{d}$ production in quark-dominated $e^+e^- \to q\overline{q}$ relative to the gluon-dominated Υ decays.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and

86

236

75

639

$B\ B$

726

82

462

506

$B\ B$

479

$B\ B$

729

41

31

86

24

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37

1011

98