Antideuteron production in Y(nS) decays and the nearby continuum


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Using CLEO data, we study the production of the antideuteron, $\bar{d}$, in Y(nS) resonance decays and the nearby continuum. The branching ratios obtained are $\mathcal{B}^{\text{dir}}(Y(1S) \rightarrow dX) = (3.36 \pm 0.23 \pm 0.25 \times 10^{-5}$, $\mathcal{B}(Y(1S) \rightarrow dX) = (2.86 \pm 0.19 \pm 0.21) \times 10^{-5}$, and $\mathcal{B}(Y(2S) \rightarrow dX) = (3.37 \pm 0.50 \pm 0.25 \times 10^{-5}$, where the “dir” superscript indicates that decays produced via reannihilation of the $b\bar{b}$ pair to a $\gamma'$ are removed from both the signal and the normalizing number of Y(1S) decays in order to isolate direct decays of the Y(1S) to $ggg$, $ggg$. Upper limits at 90% C.L. are given for $\mathcal{B}(Y(4S) \rightarrow dX) < 1.3 \times 10^{-5}$, and continuum production $\sigma(e^+e^- \rightarrow dX) < 0.031$ pb. The Y(2S) data is also used to extract a limit on $\chi_{b\bar{b}} \rightarrow dX$. The results indicate enhanced deuteron production in $ggg$, $ggg$ hadronization compared to $\gamma' \rightarrow q\bar{q}$. Baryon number compensation is also investigated with the large Y(1S) → $dX$ sample.

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I. INTRODUCTION

Antideuteron production has been observed in $e^+e^-$ collisions at both the $Y(1S)$ [1] and $Z$ [2] resonances as well as in a variety of other interactions [3]. The study of antideuterons rather than deuterons avoids large backgrounds from interactions with beam gas and detector material in colliders and nuclear breakup in fixed-target and heavy ion collisions. Since the various hadronization processes we wish to explore are expected to be charge symmetric, there is no loss of information incurred by studying only the experimentally cleaner antideuterons.

Theoretical descriptions of antideuteron formation are generally based on a coalescence model, according to which an antineutron and antiproton nearby to each other in phase space bind together [4]. Simple calculations may be based on empirical antibaryon production rates, but subtleties arise. Nearby in phase space largely means nearby in vector momentum since the hadronization occurs in a compact region. But the finite size of this region and the presence of short-lived intermediate resonances, such as the $\Delta$ quartet, lead to questions concerning the necessary degree of coherence, which can only be addressed with further assumptions. The combined $Y(1S)$, $Y(2S)$ result from ARGUS [1] as well as an upper limit from OPAL at the $Z$ [5] were accommodated by Gustafson and Hakkinen [6] on the basis of a string model calculation used to supply details of the fragmentation process. ALEPH [2] also compared their recent result to this model but limited precision and momentum range preclude any definitive conclusions. A more accurate experimental result is desirable to further refine models.

Practical limitations of particle identification restrict the momentum range over which antideuterons may be studied. However, the lower mass of the $Y(1S)$ means that a larger fraction of the momentum spectrum is accessible compared to events at the $Z$ pole. Also, baryon production in $Y(1S)$ decays is known to be enhanced relative to continuum hadronization [7]. The $Z$ pole provides a generous rate enhancement but the hadronization proceeds via an initial $q\bar{q}$ pair just as the $e^+e^-$ continuum, whereas the $Y(1S)$ decays primarily via three gluons which may be contrasted with nearby continuum $q\bar{q}$ data. Glue-rich $Y(1S)$ decays might also produce exotic multiquark states, beyond $q\bar{q}$ and $ggq$ [8]. As with antideuterons, these may form in a similar coalescence process of intermediate hadrons or from the primary $ggg, gg\gamma$ hadronization [9]. It is also interesting to search for evidence of antideuteron production inconsistent with coalescence. The frequency with which baryon number is compensated via two baryons compared to a deuteron accompanying the antideuteron may prove useful in this regard.

Our key result will be a much-improved determination of the rate of antideuteron production from $Y(1S) \rightarrow ggg$, $gg\gamma$ hadronization. The momentum dependence of production may help discriminate production models and is also used to estimate production outside our experimentally accessible momentum range. Given the larger data samples, we do not need to combine $Y(1S)$ and $Y(2S)$ production as done [1] previously, but instead use the $Y(2S)$ data to limit $\chi_{bJ}(1P)$ production of antideuterons. In addition, we obtain a first limit on antideuterons from the $Y(4S)$ and an improved limit on continuum production.

II. DATA AND SELECTION CRITERIA

We use data collected with the CLEO detector at the Cornell Electron Storage Ring, at or near the energies of the $Y(nS)$ resonances, where $n = 1, 2, 4$. The analyzed event samples correspond to integrated luminosities of $1.2\, fb^{-1}$ on the $Y(1S)$, $0.53\, fb^{-1}$ on the $Y(2S)$, $0.48\, fb^{-1}$ on the $Y(4S)$, and $0.67\, fb^{-1}$ of continuum data from just below the $Y(4S)$. The resonance samples contain a total of $21.95 \times 10^6\, Y(1S)$, $3.66 \times 10^6\, Y(2S)$, and $0.45 \times 10^6\, Y(4S)$ decays.

Smaller effective cross sections on the $Y(2S)$ and $Y(3S)$ and complications from feed-down decrease yields and complicate interpretation of these data. Thus, we will emphasize the $Y(1S)$ sample. The $Y(2S)$ sample is used to limit antideuteron production from $\chi_{bJ}(1P)$ decays by assuming that the $ggg, gg\gamma$ production from the $Y(1S)$ and $Y(2S)$ are identical. We choose not to analyze an available $Y(3S)$ sample since the statistical error on a branching ratio would be quite large. It would also not be possible to separate the contributions from $Y(1S)$, $Y(2S)$, $\chi_{bJ}(1P)$, and $\chi_{bJ}(2P)$ feed-down from the direct $Y(3S)$ decays in a meaningful way.

The four innermost portions of the CLEO detector are immersed in a 1.5 T solenoidal field. Charged-particle tracking is provided by a four-layer double-sided silicon microstrip detector [10] and a 47-layer small-cell drift chamber with one outer cathode layer [11]. The drift chamber also provides particle identification via specific ionization ($dE/dx$) measurements. Surrounding the drift chamber is a LiF-TEA ring-imaging Cherenkov (RICH) detector [12], followed by a CsI(Tl) calorimeter [13]. Most critical in the current analysis are the drift chamber, which covers $|\cos\theta| < 0.93$, and the RICH detector, which covers $|\cos\theta| < 0.80$, where $\theta$ is the polar angle with respect to the $e^+e^-$ beams.

Our antideuteron track selection proceeds as follows. First, a candidate charged track must be consistent with originating from the interaction point. The impact parameter with respect to the nominal collision point along the beam direction, $\Delta z$, must satisfy $|\Delta z| < 0.05\, m$; this distribution is dominated by the physical beam bunch length. The impact parameter in the $r - \phi$ plane perpendicular to the beam, $\Delta r$, is required to satisfy $|\Delta r| < 0.005\, m$. Since the transverse beam size is much smaller, the difference here is taken with respect to a time-averaged collision point to account for accelerator lattice changes and other effects. The collision point can be stable over many days for a fixed
lattice. The track must be well measured, based on the reduced $\chi^2$ of the track fit and the fraction of traversed drift-chamber layers with good hits. Because of difficulties in reconstructing low-momentum tracks (especially considering the large energy loss of the softest antideuterons in material before the drift chamber) and the shrinking $dE/dx$ separation between antideuterons and other species at high momentum, we only consider tracks with momenta between 0.45 GeV/c and 1.45 GeV/c. We will later estimate the amount of signal outside this momentum interval.

The identification of a quality track as an antideuteron relies on the ionization energy loss measurement in the drift chamber ($dE/dx$). To ensure a high-quality $dE/dx$ measurement, we only use tracks with at least 10 charge samplings remaining after truncation of the highest 20% and lowest 5% of the charge samples for each track. This particular truncation was chosen to optimize the resolution for a sample of electrons and positrons distributed uniformly in solid angle. Further, the track angle with respect to the beam line, $\theta$, must satisfy $|\cos \theta| > 0.2$ in order to avoid large gas-gain saturation effects present at normal incidence with respect to the chamber wires. This limit was chosen by examining the behavior of the large inclusive deuteron sample and observing where the success of the corrections applied to compensate for this saturation begin to degrade.

The $dE/dx$ measurement is converted to a normalized deviation

$$\chi_d = \frac{(dE/dx)_{\text{measured}} - (dE/dx)_{\text{expected,d}}}{\sigma_{dE/dx}}$$

(1)

with respect to the ionization expected for a real (anti-)deuteron. The $dE/dx$ expected mean and resolution ($\sigma$) include dependencies on velocity ($\beta \gamma = p/m$, $\cos \theta$), and the number of hits used to obtain the measured $dE/dx$. We accept a track as a deuteron candidate if $-2 < \chi_d < +3$; the asymmetric cut is chosen to reduce background from the large number of protons, which appear at lower values of $dE/dx$. The lowest momentum antideuterons considered here produce a raw charge deposition on the drift-chamber wires about 10 times larger than a minimum-ionizing particle. The electronic readout has sufficient dynamic range to fully accommodate this.

To suppress $\pi$ and $p$ background, we impose requirements on the number of detected Cherenkov photons in the RICH detector. Proton suppression is important since they are nearest to deuterons in ionization, while suppression of pions is added since they are so numerous; kaon suppression is not employed. For a given particle hypothesis, only photons within 3 standard deviations of the expected ring location are counted; we require fewer than five photons for the $\pi$ hypothesis and fewer than three photons for the $p$ hypothesis. For the entire momentum range, pions are well above Cherenkov threshold and give more than 10 detected photons on average, while protons cross threshold near $p = 0.9$ GeV/c with the mean number of photons increasing with increasing momentum.

### III. YIELD EXTRACTION AND BACKGROUNDS

Our signal is typified by a well-reconstructed track coming from the interaction point, with $dE/dx$ consistent with an antideuteron. We choose to use the distribution of the normalized deviation, $\chi_d$, to determine our raw signal yield. We do this in five 200 MeV/c momentum bins spanning 0.45–1.45 GeV/c.

The backgrounds to our antideuteron signal are from three main sources. The first is particle misidentification. For most of the momentum range considered, $dE/dx$ separation is good; however, since antideuterons are very rare compared to the other hadrons, even a small resolution or mismeasurement tail may be troublesome. Second, spurious hadrons are produced via interactions of beam particles or genuine decay products with residual gas in the beampipe or the beampipe and inner detector material. In practice, this is a much larger issue for deuterons than antideuterons since the gas and material are matter and not antimatter. This is the primary reason we focus on antideuterons in this study. Finally, for resonance decays, there is a possible nonresonant contribution from the continuum events underlying the $Y$ resonance peaks.

Our raw yield and the particle misidentification background are determined as follows. We count the total number of entries between $-2 < \chi_d < +3$, denoting this as $N$. The efficiency of this cut will be discussed below, in Sec. IV B. To estimate the background from misidentification, we fit the $\chi_d$ distribution to a Gaussian signal peak plus an exponential background shape, as shown in Fig. 1. The mean and width of the Gaussian are fixed from fits to the larger deuteron sample in the data. We then define a triangular background shape as shown in Fig. 1. The apex lies on the background curve at the $\chi_d$ value corresponding to the minimum of the total fit function, between the rapidly falling background and the signal peak. The triangle is drawn to decrease to zero height at $\chi_d = +3$. We denote the area of this triangle between $-2 < \chi_d < +3$ as $A$. We then take the central value of the raw yield as $N - A/2$ with an error of $\pm A/4$. The rapidly falling fit would argue for a lower background, while a small accumulation of events at $\chi_d > +3$ balances this. In fact, we know little about the background shape other than naively expecting a falling shape. Our method spans the range from 0 to $A$ for the background size within $\pm 2\sigma$, where $\sigma = A/4$.

For beam particles or decay products interacting with residual gas or beampipe and detector material, the tracks do not peak in both $r$ and $z$ impact parameters as the signal does. We therefore estimate the underlying background from these sources by looking at the impact-parameter sidebands. These backgrounds are small and assumed to be flat for purposes of the modest extrapolation underneath the peaks.
but instead to consider the process section with respect to the resonance sample. We will also
total continuumlike events produced via reannihilation because the physics is the same as the continuum
counting only the decays proceeding via ggg as well. Here, \( B_{\mu\mu} = B(Y(nS) \rightarrow \mu^+ \mu^-) \) and \( R_{\text{had}} = \sigma(e^+ e^- \rightarrow \text{hadrons})/\sigma(e^+ e^- \rightarrow \mu^+ \mu^-) \). The factors of 3 and \( R_{\text{had}} \) scale the value of \( B_{\mu\mu} \) to account for the sum of \( e^+ e^- \), \( \mu^+ \mu^- \), \( \pi^+ \pi^- \), and the sum of allowed g\( \bar{q}q \) pairs, respectively. We use \( R_{\text{had}} = 3.56 \pm 0.01 \pm 0.07 \) [14] and \( B_{\mu\mu} = (2.49 \pm 0.02 \pm 0.07)\% \) [15].

### IV. DETECTION EFFICIENCY

#### A. Tracking and rich efficiency

We use Monte Carlo (MC) event samples to study the antideuteron efficiency of our tracking and RICH criteria. We cannot use antideuterons in our simulations since this particle is not included in GEANT, which is the basis of CLEO Monte Carlo software. However, we do not expect significant differences between deuteron and antideuteron behavior since both the RICH detector and the tracking are largely charge independent, as are our selection criteria. Nuclear interactions do distinguish \( d \) and \( \bar{d} \), but given our large final errors, we may safely neglect this effect as well. In particular, annihilations in the beampipe or silicon vertex detector are estimated to be negligible given our statistics. We also note that our \( Y \) decay hadronization models produce very few deuterons; this leads us to choose the following techniques.

Our first Monte Carlo sample consists of events with one deuteron and no other detector activity. The second consists of overlaying the preceding type of “single-track” events on top of a real \( Y(1S) \) decay from data. The former likely overestimates the efficiency due to the quiet detector environment, while the latter likely underestimates it due to excess activity (since nothing is removed from the full decay when the signal track is added in). We obtain tracking efficiencies of about 70%, with a 10% relative difference between the two methods. Our definition of efficiency
is relative to the number of tracks entering the active tracking volume; two-thirds of the loss is due to the exclusion of tracks with small polar angles mentioned earlier.

We average the efficiencies of our two Monte Carlo samples, taking one-quarter of the difference between them as a systematic uncertainty. The resulting efficiency is fairly flat, except in the lowest momentum bin of 0.45–0.65 GeV/c, where it decreases by about 10% of itself. By reweighting Monte Carlo events according to the momentum distribution of the data across this bin, we find that we are not very sensitive to the detailed spectrum, but we do add an additional systematic error for this effect.

Finally, our signal is consistent with being flat vs $\cos\theta$ in the accepted range $0.20 < |\cos\theta| < 0.93$; we assume it is flat when evaluating the effect of our fiducial cut on the track-finding efficiency.

**B. $dE/dx$ efficiency**

The CLEO Monte Carlo simulation of $dE/dx$ measurements is done at the track level and is based on the calibrated expected means and resolutions. However, (anti)deuterons have not been searched for in any other CLEO analysis to date. Since the calibration is quite challenging for the very high ionization of the lower momentum antideuterons, the $dE/dx$ calibration was redone for the data samples used here. These new calibrations offer less bias versus parameters such as angle and momentum than the standard versions. But, as a result, the CLEO $dE/dx$ simulation designed for the standard calibration is not well suited for our analysis. Instead, we use deuterons from real data, produced by beam-gas interactions, to estimate the $dE/dx$ efficiency. Our impact parameter cuts ensure that these tracks are geometrically similar to signal tracks.

Figure 2 shows the deuteron $\chi_d$ distributions for all five momentum bins; these are mostly deuterons from beam-gas interactions or nuclear interactions in the detector. We define the $dE/dx$ signal efficiency as $\epsilon_{dE/dx} = N_{\text{sig}}/N_d$, where $N_{\text{sig}}$ is the yield in the interval $-2 < \chi_d < +3$ and $N_d$ is our estimate of the total number of deuterons for all $\chi_d$. We estimate $N_d = (N_{\text{tot}} - N_{\text{tail}})/2 + N_{\text{tail}}/4$. Here $N_{\text{tot}}$ is the yield in the interval $-5 < \chi_d < +5$ for the lowest two bins, in $-4 < \chi_d < +4$ for the next two, and in $-3 < \chi_d < +4$ for the highest momentum bin. $N_{\text{tail}}$ is designed to include a possible tail from the large background at low $\chi_d$ and is taken as the yield in the following momentum-dependent intervals: $-5 < \chi_d < -4$ for the first two momentum bins, $-4 < \chi_d < -3$ for the next two momentum bins, and $-3 < \chi_d < -2$ for the last bin. The efficiencies are all about 97%, except for the lowest momentum bin, where it is about 88% due to the lowside resolution tail. Our systematic error on the $dE/dx$ efficiency comes from propagating the error on $N_d$ quoted above.

The width of $\chi_d$ varies with momentum even after our recalibration, especially in the lowest momentum bin. We determine our sensitivity by reweighting the momentum distribution in this bin to better reflect the data, and include an additional systematic error on the efficiency.

**C. Systematic uncertainty summary**

We now summarize our systematic uncertainties; in each case, we give the range across the five momentum bins. The total efficiency uncertainty, including track finding, selection criteria, and yield extraction from the $\chi_d$ plot, ranges from 4.5% to 16%. In addition to systematic issues discussed earlier in this section, we also considered the agreement between data and MC simulations of the number of photons associated with tracks in the RICH detector and the stability of results for variations in track-selection criteria. The number of $Y(1S)$ [$Y(2S)$] in our data sample has an uncertainty of 1.4% [1.5%] and the continuum luminosity is known to 2%. The resulting total systematic uncertainties range from 6.1% to 16.0%. These are on average comparable to the statistical uncertainties in the case of the $Y(1S)$ result, and smaller than statistical errors in all other cases.

**V. RESULTS**

**A. Antideuteron production in $Y(1S)$**

Table I shows the observed number of events from $Y(1S)$ resonance data, off-resonance data, and $\Delta r$ and $\Delta z$ sidebands in the on-resonance data. After subtracting the
TABLE II. Efficiency-corrected antideuteron yields and differential branching ratios for Y(1S) data in momentum bins.

<table>
<thead>
<tr>
<th>Momentum (GeV/c)</th>
<th>Corrected yield</th>
<th>Corrected direct yield</th>
<th>dB_{dir}/dp (10^{-5} GeV/c^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.45–0.65</td>
<td>85.6 ± 14.3</td>
<td>82.1 ± 16.4</td>
<td>2.2 ± 0.5 ± 0.2</td>
</tr>
<tr>
<td>0.65–0.85</td>
<td>111.3 ± 14.2</td>
<td>109.7 ± 15.0</td>
<td>3.0 ± 0.4 ± 0.2</td>
</tr>
<tr>
<td>0.85–1.05</td>
<td>106.2 ± 13.8</td>
<td>106.2 ± 14.5</td>
<td>2.9 ± 0.4 ± 0.3</td>
</tr>
<tr>
<td>1.05–1.25</td>
<td>92.5 ± 12.6</td>
<td>92.5 ± 13.8</td>
<td>2.5 ± 0.4 ± 0.2</td>
</tr>
<tr>
<td>1.25–1.45</td>
<td>60.2 ± 12.7</td>
<td>55.5 ± 14.1</td>
<td>1.5 ± 0.4 ± 0.2</td>
</tr>
</tbody>
</table>

latter sidebands and properly scaled continuum contributions, and correcting for efficiency, we get the number of \( \bar{d} \) events produced by Y(1S) decays shown in Table II. The direct yield column includes a larger continuum scale factor which accounts for the contribution in which \( b\bar{b} \) reannihilate to a virtual photon and form a \( q\bar{q} \) pair whose fragmentation products contain an antideuteron. We use this column to get the yield from so-called direct decays mediated by \( ggg \) and \( g\gamma \) hadronization.

To get the antideuteron yield in the full momentum range, we fit to the Maxwell distribution as used in fireball models [16],

\[
f(p) = a \beta^2 \exp(-E/b),
\]

where \( \beta = pc/E \), and \( a \) and \( b \) are free parameters. We include as a systematic uncertainty the effect of variations of the shape parameter \( b \) within the statistical errors of the fit; we do not include any systematic uncertainty for the accuracy of the model itself. The resulting fit to the CLEO data is shown, along with the earlier ARGUS result, in Fig. 3. Much of the CLEO systematic error is correlated point-to-point, but statistics still dominate the uncertainty. Note that the ARGUS data extends to higher momentum due to their time-of-flight system for particle identification. We also note that ARGUS combined Y(1S) and Y(2S) yields to extract a more precise \( ggg \) rate; it is not clear what was assumed about possible \( \chi_{bf} \) production. However, it seems most likely that the difference in our results is largely statistical; ARGUS has 19 signal events from both resonances combined.

The final branching ratio per direct Y(1S) \( \rightarrow ggg, g\gamma \) decay is

\[
B_{\text{dir}}(Y(1S) \rightarrow dX) = (3.36 \pm 0.23 \pm 0.25) \times 10^{-5}.
\]

For this calculation, we have used only the number of Y(1S) which decay via \( ggg, g\gamma \) as our normalization and subtracted a small amount of yield due to \( b\bar{b} \) reannihilation to \( \gamma^* \) based on the observed off-resonance continuum yield. The more inclusive “conventional” branching ratio result is

\[
B(Y(1S) \rightarrow dX) = (2.86 \pm 0.19 \pm 0.21) \times 10^{-5}.
\]

B. \( d \) production in Y(1S)

Given that the deuteron signal is expected to be identical to the antideuteron signal, but with very much larger backgrounds, analyzing for deuterons would not contribute much statistically to this analysis. However, we can use deuteron production as a consistency check on our antideuteron measurement. We make this comparison for the restricted momentum range 0.6–1.1 GeV/c where the signal-to-noise is best.

Since none of the backgrounds described above peak in both \( \Delta r \) and \( \Delta z \), we use a sideband subtraction to remove them. Empirically, we observe that \( \Delta r \) sidebands are very flat and we therefore subtract \( \Delta r \) sidebands from the good \( \Delta r \) sample and fit the resulting \( \Delta z \) distribution to a Gaussian peak plus a polynomial background. This procedure is displayed in Fig. 4. Here, we only use deuterons which satisfy \( -2 < \chi_d < +3 \) and ignore the small backgrounds from other particle types. The resulting deuteron yield is 352.8 ± 88.6, about 1.7 standard deviations from the antideuteron yield of 201.0 ± 14.2 in the same 0.6–1.1 GeV/c momentum range. The \( \Delta z \) width is somewhat narrower but similar to that for antideuterons.

C. Discussion of \( \bar{d} \) baryon number compensation

Another way to explore consistency of the \( \bar{d} \) and \( d \) yields is to employ baryon number conservation. Assuming many of the \( \bar{d} \) (\( d \)) events are compensated by \( pp \) or \( pn \) (\( \bar{p} \bar{p} \) or \( \bar{p}n \)), requiring at least one \( p (\bar{p}) \) in the event may decrease
background appreciably. As shown in Fig. 5 and summarized in Table III, after the standard selection criteria, we begin with 13140 deuterons and 338 antideuterons candidates (signal plus background). Our proton identification requirements are: $|\chi_p| < 4$ for 0.30–0.85 GeV/$c$, and $|\chi_p| < 3$ for 0.85–1.15 GeV/$c$. Here, $\chi_p$ is a normalized $dE/dx$ deviation with respect to the proton hypothesis and we do not accept candidates outside the two contiguous momentum windows indicated above. With this definition of protons, we can study the effect of cuts on the number, $n_p$, of protons (antiprotons) in antideuteron (deuteron) events. If we require $n_p > 0$, we are left with 149 $\bar{d}$ and 898 $d$; while the nondecay deuterons are very much reduced, the asymmetry indicates residual background from random antiprotons not associated with any baryon number compensation. This is further verified by examining the $\Delta r, \Delta z$ distributions in the fourth row of Fig. 5. The excess is consistent with a spurious deuteron in coincidence with a real physics event containing the antiproton. A fit to the $\Delta r$ distribution yields $122.8 \pm 16.9$ events for the sharp peak, which is now consistent with the antideuteron yield. Adding a requirement of $n_p \geq 2$, we obtain 31 $\bar{d}$ and 35 $d$, which are quite consistent with equality, implying that most spurious $d$ have been removed. (Note that we never observed $n_p > 2$.) The remaining $d$ events peak well both in $\Delta r$ and $\Delta z$, as expected.

Returning to just the clean antideuteron sample, we can take a more quantitative look at baryon number conservation. By considering the effect of proton-finding efficiency, we can determine approximately how baryon compensation is distributed among $pp, \bar{p}n, np, nn$; we will consider compensation by a $d$ later.

In the $-2 < \chi_d < +3$ antideuteron signal region, we observe 338 candidate events from the Y(1S) data sample. Each of these events contains only 1 antideuteron. Among these 338 events: 189 events contain no protons, 118 events contain 1 proton, and 31 events contain 2 protons.

![Fig. 4. Antideuteron and deuteron sample distributions for the momentum range 0.6–1.1 GeV/$c$ in the Y(1S) data. Top row: $\Delta r$ and $\Delta z$ for antideuterons. Middle row: $\Delta r$ and $\Delta z$ for deuterons. Bottom left: $\Delta z$ for deuterons after subtraction of the $\Delta r$ sidebands in the previous panel. The signal Gaussian width is fixed to the antideuteron signal width from the fit to data in the upper right panel.](image)

![Fig. 5. $d$ and $\bar{d}$ yields in the momentum range 0.45–1.45 GeV/$c$ with additional criteria as described. Top row: $\chi_d$ for deuterons (left) and antideuterons (right) with all standard cuts, including $-2 < \chi_d < +3$. Second row: As above, but requiring at least one antiproton (left) or proton (right) candidate in addition. Third row: As above, but requiring two antiproton (left) or two proton (right) candidates instead. Fourth row: $\Delta r$ and $\Delta z$ for deuterons with $n_p > 0$. The curve on the left shows a fit to a signal Gaussian plus a polynomial background. Fifth row: $\Delta r$ and $\Delta z$ for deuterons with $n_p = 2$.](image)

### Table III. Antideuteron and deuteron yields from Y(1S) data with requirements on accompanying protons and antiprotons.

<table>
<thead>
<tr>
<th>Standard cuts, plus:</th>
<th>Number of antideuteron candidates</th>
<th>Number of deuteron candidates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\cdots$</td>
<td>338</td>
<td>13 140</td>
</tr>
<tr>
<td>$&gt; 0p/ &gt; 0\bar{p}$</td>
<td>149</td>
<td>898</td>
</tr>
<tr>
<td>$\geq 2p/ \geq 2\bar{p}$</td>
<td>31</td>
<td>35</td>
</tr>
</tbody>
</table>

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Assuming \( d \) is compensated by \( pp, pn, np, nn \) (neglecting \( d \) for now) with an equal probability of 25\%, we may estimate what is expected, given a proton-finding efficiency. We cannot distinguish \( pn \) and \( np \), but it makes the assumed equality clearer to list them separately. For the proton identification cuts given above, the efficiency is about 60\%, where we assume the spectrum of protons accompanying deuterons is similar to the inclusive proton spectrum. Part of the loss of efficiency is due to protons with momenta outside our accepted range of 0.30–1.15 GeV/c.

Folding in this approximate efficiency, we predict 30 events containing 2 protons, with 31 observed, and 142 events containing 1 proton, with 118 observed, as summarized in Table IV. Within the limits of our uncertainties and assumptions, our data is consistent with baryon number conservation occurring with roughly equal probabilities for accompanying \( pp, pn, np, \) or \( nn \).

It is also interesting to look for compensation of an antideuteron by a deuteron; this is found to occur at the 1\% level. Figure 6 shows one of our four possible \( ddX \) events, which is nearly fully reconstructed. Inspection of these four \( dd \) candidate events reveals that one of them is consistent with a through-going deuteron track (presumably from a cosmic-ray interaction) faking a \( dd \) pair. The remaining three are consistent with true \( dd \). Through-going deuterons might constitute a non-negligible background to our antideuteron yield, if the inward deuteron track passed our antideuteron cuts, but the outgoing deuteron fails. Therefore, we have searched for such events with relaxed cuts. We find none in the \( \Delta r \) and \( \Delta z \) sidebands, nor do we find any antideuteron candidate events where there is a lower-quality track candidate failing our cuts back-to-back with our candidate track. We conclude that this faking mechanism is rare and the one event seen was a somewhat unlikely occurrence for our data sample size.

**D. \( \bar{d} \) production in 2S, 4S, and continuum**

We now summarize results from other \( Y \) resonances and the continuum.

In \( Y(2S) \) data, 69 antideuteron events are observed. This sample has the same background sources as the \( Y(1S) \) data, but contains several possible sources of antideuteron signal. These include: (i) \( Y(2S) \rightarrow Y(1S)X \), followed by \( Y(1S) \rightarrow dX' \), (ii) \( Y(2S) \rightarrow gg, \ g_g, \) and (iii) \( Y(2S) \rightarrow \chi_{cJ}X \), followed by \( \chi_{cJ} \rightarrow dX' \). We may subtract process (i) based on known branching ratios. Separating (ii) and (iii), for example, by looking for the transition \( \gamma \) in (iii), is not feasible with our limited statistics. However, we can assume that the rate for the direct decay (ii) is equal to the analogous \( Y(1S) \) process, and look for any excess from \( \chi_{cJ} \) decays. This is interesting since the \( \chi_{cJ} \) decay via \( gg \) for \( J = 0, 2 \) and via \( gg \) for \( J = 1 \) and thus access distinct hadronization processes.

After background subtractions analogous to the \( Y(1S) \) case, we find \( 58.3 \pm 8.6 \) signal events, which translates to

\[
\mathcal{B}(Y(2S) \rightarrow \bar{d} + X) = (3.37 \pm 0.50 \pm 0.25) \times 10^{-5}.
\] (7)

To isolate this rate, we subtract contributions from the processes \( e^+ e^- \rightarrow Y(2S) \rightarrow \pi \pi Y(1S) \) and \( e^+ e^- \rightarrow Y(2S) \rightarrow \gamma \gamma Y(1S) \) (two-photon transitions via the \( \chi_{cJ} \) states) assuming that these processes dominate inclusive \( Y(1S) \) production. We must further assume that direct \( ggg \), \( g_g \gamma \) decays of the \( Y(2S) \) produce antideuterons at the same rate as the \( Y(1S) \). We are left with an insignificant excess, and extract a 90\% C.L. upper limit for a weighted average of the \( \chi_{cJ} \) states of
\[ \sum \mathcal{B}(Y(2S) \rightarrow \gamma \chi_{bJ}(1P)) \]

\[ \times \mathcal{B}(\gamma \chi_{bJ}(1P) \rightarrow \bar{d}X) / \sum \mathcal{B}(Y(2S) \rightarrow \gamma \chi_{bJ}(1P)) \]

\[ < 1.1 \times 10^{-4}. \]  

(8)

This limit is not stringent enough to draw firm conclusions on antideuteron production in these distinct gg and gjq̅ hadronization processes in contrast to gjgg, ggγ.

In Y(4S) data, 3 \( \bar{d} \) candidates are observed. Based on \( \Delta r \) and \( \Delta z \) sidebands and the continuum data, we expect 5.2 background events. For both this limit and the following continuum production limit, we ignore any possible backgrounds in the \( \chi_d \) distribution. We obtain a 90% C.L. upper limit, using the Feldman-Cousins method [17], of

\[ \mathcal{B}(Y(4S) \rightarrow \bar{d}X) < 1.3 \times 10^{-5}. \]  

(9)

This limit is not very stringent in view of the dominance of \( B \bar{B} \) decays of the Y(4S).

A 90% C.L. upper limit for continuum production is also obtained, based on 6 events with 1.5 expected background:

\[ \sigma(e^+e^- \rightarrow \bar{d}X) < 0.031 \text{ pb}, \quad \text{at } \sqrt{s} = 10.5 \text{ GeV}. \]  

(10)

Given that the continuum hadronic cross section at \( \sqrt{s} = 10.5 \) GeV exceeds 3000 pb, we see that fewer than \( 1 \times 10^5 \) gjq̅ hadronizations result in antideuteron production, noticeably less than for gjgg, gjgγ hadronization.

VI. CONCLUSIONS

Using CLEO data, we have studied antideuteron production from \( Y(nS) \) resonance decays and the nearby continuum. Y(1S) and Y(2S) production rates are presented separately for the first time and combined to limit antideuteron production from \( \chi_{bJ}(1P) \) states. First limits on production from the Y(4S) and an improved continuum production limit are given.

The results confirm a small but significant rate from hadronization of \( Y(nS) \rightarrow gjq̅, gjgγ \) decays, for \( n = 1, 2 \). However, no significant production from gjq̅ hadronization is observed; our gjq̅ limit is more than 3 times smaller than the observed rate from gjgg hadronization. Thus, the results indicate that antideuteron production is enhanced in gjgg, gjgγ hadronization relative to gjq̅.

We observe that baryon number conservation is accomplished with approximately equal amounts of accompanying \( pp, pn, np, nn \). We also found three \( \bar{d}d \) events; it is not immediately clear if double coalescence from initial baryons and antibaryons can accommodate this rate, or if this is evidence for a more primary sort of (anti)deuteron production in the hadronization process.

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