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Abstract

We report a measurement of the production of antideuterons $\bar{d}$ in e^+e^- annihilation at centre-of-mass energies around 10 GeV using the ARGUS detector at the DORIS II storage ring. We observe an enhancement of $\bar{d}$ production in direct hadronic $\Upsilon(1S)$ and $\Upsilon(2S)$ resonance decays. From 21 events with a $\bar{d}$ candidate the inclusive cross section $1/\sigma^{had}_{dir} \cdot d\sigma/dp$ and the production rate of antideuterons are determined. A production rate of $(6.0 \pm 2.0 \pm 0.6) \cdot 10^{-5}$ $\bar{d}$ per direct hadronic Υ decay and a 90% CL upper limit of $1.7 \cdot 10^{-5}$ $\bar{d}$ per $e^+e^- \to q\bar{q}$ continuum event are obtained. These results are related to antiproton production through a simple model.

Baryon production in e^+e^- interactions has been extensively studied by several experiments at different centre-of-mass energies, ranging from 10 GeV to 30 GeV [1,2]. In the 10 GeV centre-of-mass region it is possible to study and compare baryon production in gluon fragmentation from hadronic decays of the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances with quark fragmentation in the continuum process $e^+e^- \to q\bar{q} \to hadrons$. In general, it is observed that baryons are more abundantly produced in direct hadronic Υ decays than in the continuum process at comparable centre-of-mass energies [1,2]. This enhancement in gluon fragmentation might be considered as an indication of differences between the fragmention processes of quarks and gluons.

In a previous paper [3], the ARGUS collaboration reported the first observation of antideuteron production in e^+e^- annihilation. Here, based on a much larger data sample, we present a more detailed study of antideuteron production, with emphasis on differences between the production in direct hadronic decays of the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonances and in the nearby $q\bar{q}$ continuum. Note that the measurement of deuteron production as compared to $\bar{d}$ production is prevented by a huge background of deuterons originating from beam-gas and beam-wall interactions.

The data were collected with the ARGUS detector at the e^+e^- storage ring DORIS II at centre-of-mass energies between 9.4 GeV and 10.6 GeV. The analyzed event samples correspond to integrated luminosities of 31.6 pb^{-1} on the $\Upsilon(1S)$, 38.2 pb^{-1} on the $\Upsilon(2S)$, 104.5 pb^{-1} on the $\Upsilon(4S)$, and 47.1 pb^{-1} in the nearby continuum. The ARGUS detector, its trigger, and particle identification capabilities are described in detail elsewhere [4].

The search for multihadronic events with antideuteron candidates was performed in several steps. Multihadronic events were selected by requiring at least three tracks with either a common main vertex or a total energy deposition in the shower counters of more than 1.7 GeV. To suppress background from radiative Bhabha events with converted photons, we required $N_{tot} \geq 5$, where $N_{tot} = N_{ch} + N_\gamma/2$. Here, N_{ch} is the number of all charged particles pointing to the main vertex, and N_γ is the number of photons. Only photons with an energy deposition in the shower counters of at least 50 MeV were considered. After this preselection we obtained a data sample of 1.2 million multihadronic events.

The subsequent search for antideuteron candidates relies on the particle identification capabilities of the detector provided by the momentum and energy loss (dE/dx) measurements in the main drift chamber and the time-of-flight (TOF) measurement. From the dE/dx measurement antideuterons can be well identified for momenta below 1.7 GeV/c, where the deuteron band is clearly separated from the other hypotheses. To ensure a good energy loss determination we used only those negatively charged tracks with at least 15 samplings for the dE/dx measurement after truncation [4]. The measured dE/dx value for each track which fulfilled the above criteria was tested against the charged particle hypotheses e, μ, π, K, p, and d. If the likelihood [4] for the antideuteron hypothesis normalized to the sum of the likelihoods of all particle hypotheses exceeded 0.95, the track was accepted as an antideuteron candidate. The necessary knowledge of the expected dE/dx for particles of antideuteron mass, unit charge and momentum p was obtained by studying and calibrating the detector response with a large data sample of deuterons produced in beam-gas and beam-wall interactions.

For tracks with well measured time-of-flight information we required, in addition, that the likelihood ratio from TOF for the antideuteron hypothesis be greater than 0.01. This cut suppresses background from minimum ionizing particles, where two tracks overlap and fake a single track with an energy loss expected from a slow antideuteron. To avoid electron misidentification on the basis of the dE/dx measurement alone, information from all detector components is used and combined into an overall likelihood [4]. For accepted antideuteron candidates this likelihood from dE/dx, TOF, the observed energy deposition, and its lateral distribution in the shower counters, had to be less than 0.25 for the electron hypothesis.

After applying all cuts 21 events remained, each containing one antideuteron candidate. In fig. 1 we plot the measured energy loss dE/dx of the 21 $\bar{d}$ candidates versus their momenta, together with a solid line showing the expected momentum dependent energy loss of antideuterons. The experimental points follow the $\bar{d}$ curve and are separated from other particle hypotheses.

In the momentum region above 1 GeV/c, where the dE/dx bands come close together, particle misidentification becomes more likely. In this region, background contamination of our $\bar{d}$ sample is possible, since only half of all measured $\bar{d}$ tracks are supplied with good time-of-flight information. A reduced acceptance for a good TOF measurement arises from backscattered tracks originating from the antideuteron annihilation process in the shower or TOF counters. The amount of background in our $\bar{d}$ sample from overlapping tracks was studied using deuteron candidates with a good time-of-flight measurement. A low TOF likelihood ratio for the deuteron hypothesis indicates overlapping tracks. From the ratio of deuteron tracks, which are identified as deuterons through dE/dx but have a likelihood ratio

from TOF of less than 0.01, to all deuterons with good TOF information, the background rate from overlapping tracks is estimated. Scaling this ratio to the number of $\bar{d}$ candidates without a TOF measurement yields a background estimate of three events. The fake rate from particle misidentification was determined by applying all $\bar{d}$ selection criteria to samples of well identified antiprotons from $\bar{\Lambda}$ decays, π^- from K^0_S, and e^- from converted photons. In total we estimate five background events in our final sample of 21 antideuteron candidate events.

Baryon number conservation provides a check on the purity of our final $\bar{d}$ sample, by counting the number of baryons in an antideuteron event. As neutrons (n) cannot be identified with the ARGUS detector, we looked for well identified protons (p) with momenta below 1.2 GeV/c. In the 21 $\bar{d}$ events we observe 8 events containing one proton and 3 events with two protons. The proton detection efficiency, including the affect of the momentum cut, has been determined from Monte Carlo studies to be 0.6. Therefore, assuming that the baryon number of the antideuteron is balanced by either a (pp)-, (pn)-, (np)-, or (nn) pair with equal probability, we expect 8 events with one proton and 2 events with two protons. These numbers are in good agreement with the observed numbers of events.

In fig. 2 we show a projection on a plane perpendicular to the beam axis of an antideuteron candidate event taken at an e^+e^- centre-of-mass energy of the $\Upsilon(1S)$ resonance. Besides an antideuteron the event contains two protons, three π^-, two π^+ and four photons. One of the photons converted into an e^+e^- pair in the main drift chamber. Several observations support our interpretation that this event contains an antideuteron. We first note that all charged tracks are identified with a likelihood ratio from dE/dx and TOF measurements of at least 0.75 for their respective hypotheses. Secondly, the charged tracks fulfil baryon number and charge conservation, and the quark flavour content of the event is balanced. Finally, the difference of the energy sum of the chosen particle assignments to the centre-of-mass energy of $\Delta E = (130 \pm 72)$ MeV shows that the event is nearly completely reconstructed.

The 21 antideuteron candidate events consist of 12 events from data on the $\Upsilon(1S)$, 7 events from the $\Upsilon(2S)$, and two events from the $\Upsilon(4S)$ resonance. No antideuteron candidates are observed in the pure $q\bar{q}$ continuum sample. The two events recorded at the $\Upsilon(4S)$ energy are kinematically incompatible with $\bar{d}$ production in B meson decays. Therefore they are either background or originate from the continuum underneath the $\Upsilon(4S)$ resonance. Scaling the total expected background according to the number of preselected multihadronic events of the combined data sample of $\Upsilon(4S)$- and continuum events results in an expected background of three events, consistent with the observed number of events.

The 12 and 7 observed antideuteron events from the $\Upsilon(1S)$ and $\Upsilon(2S)$ data samples cannot be accounted for by the expected total background of two events or by the continuum process $e^+e^- \to q\bar{q}$. Scaling the two selected antideuteron candidate events of the combined $\Upsilon(4S)$ and continuum sample by the luminosities of the $\Upsilon(1S)$ and $\Upsilon(2S)$ data sample, and correcting for the energy dependence of the hadronic continuum cross section, results in predictions of 0.5 events each for the $\Upsilon(1S)$ and $\Upsilon(2S)$ data samples. Furthermore, the ratio of the number of $\bar{d}$ events from $\Upsilon(1S)$ and $\Upsilon(2S)$ data agrees with the ratio of the corresponding hadronic resonance cross sections times the integrated luminosities of both data samples. Such a scaling result is expected for antideuteron production in hadronic $\Upsilon(1S)$ and $\Upsilon(2S)$ resonance decays, since the amount of three gluon decays from the $\Upsilon(1S)$, and the sum of direct $\Upsilon(2S)$ and $\Upsilon(2S) \to \Upsilon(1S)$ cascade decays, are comparable. Therefore we conclude that the observed excess of antideuteron events from the $\Upsilon(1S)$ and $\Upsilon(2S)$ data samples is produced in direct resonance decays.

Given the small number of antideuterons from $\Upsilon(1S)$ and $\Upsilon(2S)$ decays and the similarity in the decay mechanism of both resonances, we combine the event samples to determine the differential cross section $1/\sigma_{dir}^{had} \cdot d\sigma/dp$ for antideuteron production in direct Υ resonance decays. The cross section σ_{dir}^{had} for direct hadronic $\Upsilon(1S), \Upsilon(2S)$ decays was calculated [5] from the measured hadronic cross section at the $\Upsilon(1S)$ and $\Upsilon(2S)$ resonance, respectively, by subtracting the continuum cross section and correcting for the vacuum polarization contribution, $\Upsilon \to q\bar{q}$.

In fig. 3 we show the background subtracted and acceptance corrected momentum spectrum of antideuterons observed in $\Upsilon(1S), \Upsilon(2S)$ resonance decays. The overall acceptance of the $\bar{d}$ selection is slightly momentum dependent and decreases from 0.76 at $p = 0.4$ GeV/c to 0.65 at $p = 1.7$ GeV/c. In table 1 we list the corresponding values of the inclusive cross section $1/\sigma_{dir}^{had} \cdot d\sigma/dp$ for each momentum bin. The systematic errors take into account uncertainties in acceptance correction, in background subtraction, and in the determination of σ_{dir}^{had}. The latter two are the dominant sources of error.

The measured momentum distribution of antideuterons is well described by a Maxwell distribution as used in fire ball models [6]:

$$f(p) = a \cdot \beta^2 \cdot e^{-E/b}, \tag{1}$$

where $\beta = p/E$. Here, a and b are free parameters, the first for normalization and the second an effective temperature. The result of a fit of this function to the data yields $b = (0.20 \pm 0.09)$ GeV. Using the fitted curve to extrapolate into the unmeasured region of the momentum spectrum, indicated by the solid line in fig. 3, we determine a total production rate of $(6.0 \pm 2.0 \pm 0.6) \cdot 10^{-5}$ antideuterons per direct hadronic $\Upsilon(1S), \Upsilon(2S)$ resonance decay. The fit gives 15% of the production rate for $\bar{d}$ momenta above 1.7 GeV/c and below 0.4 GeV/c. Assuming the same fraction of 15% outside the $\bar{d}$ momentum range used, and not correcting for any background, we derive from the two observed antideuteron events of the combined continuum data sample an upper limit at the 90 % confidence level of $1.7 \cdot 10^{-5}$ $\bar{d}$ per $q\bar{q}$

continuum event.

With these production rates we conclude that antideuteron production is distinctly enhanced in gluon mediated Υ decays with respect to that from the continuum reaction $e^+e^- \to q\bar{q}$. This observation is in agreement with the general behaviour of enhanced baryon production in Υ decays [1,2] and seems to support distinctions between gluon and quark fragmentation.

To investigate a possible production mechanism, we relate our measured antideuteron production cross section to that of antiproton production in direct hadronic $\Upsilon(1S)$ decays by slightly modifying a model for deuteron production in high energy nucleus-nucleus collisions [7]. The basic idea is that antiprotons and antineutrons are independently produced in e^+e^- annihilation and coalesce into an antideuteron if their momenta lie close enough in momentum space. The antideuteron cross section can then be expressed by the product of the single particle production cross sections for antiprotons and antineutrons:

$$\frac{1}{\sigma_{dir}^{had}} \frac{d^3\sigma(\bar{d})}{d^3p} = \frac{4\pi}{3} p_0^3 \gamma \cdot \left(\frac{1}{\sigma_{dir}^{had}} \frac{d^3\sigma(\bar{p})}{d^3p} \right) \cdot \left(\frac{1}{\sigma_{dir}^{had}} \frac{d^3\sigma(\bar{n})}{d^3p} \right). \tag{2}$$

Here, p denotes the momentum per nucleon, $\gamma = [1 + (p^2/m_n^2)]^{1/2}$ is a Lorentz factor, and m_n the nucleon mass. To form an antideuteron the difference of the momentum vectors of both antibaryons has to lie within a momentum sphere, whose effective radius is p_0. Physically the coalescence volume $4\pi/3\, p_0^3$ is related to the spatial size of the antideuteron wave function and the size of the fragmentation region emitting the particles. In the following we use an effective momentum $p_0 \simeq 130$ MeV/c, which successfully describes the data on deuteron production obtained in high energy hadron collisions [7,8]. Since experimental results on antineutron production in e^+e^- annihilation are not available, we assume equal probabilties for antineutron as for antiproton production. For isotropic particle production, and with the assumptions stated above, equation (2) yields the following relation between the antideuteron cross section $1/\sigma_{dir}^{had} \cdot d\sigma(\bar{d})/dp_{\bar{d}}$ at momentum $p_{\bar{d}}$ and the antiproton cross section $1/\sigma_{dir}^{had} \cdot d\sigma(\bar{p})/dp_{\bar{p}}$ at antiproton momentum $p_{\bar{p}} \approx p_{\bar{d}}/2$:

$$\frac{1}{\sigma_{dir}^{had}} \frac{d\sigma(\bar{d})}{dp_{\bar{d}}} = \frac{1}{6} \gamma \frac{p_0^3}{p_{\bar{p}}^2} \cdot \left(\frac{1}{\sigma_{dir}^{had}} \frac{d\sigma(\bar{p})}{dp_{\bar{p}}} \right)^2_{p_{\bar{p}} \approx p_{\bar{d}}/2}. \tag{3}$$

In table 1 we list the estimated antideuteron production cross section according to expression (3), where we used as input an interpolation of the measured antiproton cross section in direct $\Upsilon(1S)$ decays from ref. [2]. The statistical errors on the measured antiproton cross section contribute a 14% uncertainty in the estimated $\bar{d}$ cross section. Comparing our experimental results with this estimation, we conclude that the suppression of antideuteron production relative to antiproton production by roughly four orders of magnitude can be understood on the basis of this simple coalescence model. This conclusion is supported by applying this model to $\bar{d}$ production in the continuum. The estimated antideuteron production rate of $0.6 \cdot 10^{-5}$ $\bar{d}$ per $q\bar{q}$ continuum event is in good agreement with the given upper limit.

Within this model, a better match between experimental and estimated values can be achieved by a somewhat larger coalescence radius p_0 in e^+e^- annihilation compared to that in nucleus-nucleus collisions. A softer momentum spectrum for the data might be expected due to the limited amount of phase space, for which the model does not account. However, from the present number of events it cannot be decided whether this model reproduces the correct momentum dependence of the $\bar{d}$ cross section. Although the model is a nonrelativistic approach with minimal relativistic modifications and does not take into account any correlations in particle production, it may provide some insight into the antideuteron production mechanism.

In summary, we have measured antideuteron production in direct hadronic $\Upsilon(1S)$ and $\Upsilon(2S)$ decays and obtained an upper limit on $\bar{d}$ production in $q\bar{q}$ continuum events. The observed suppression of antideuteron production relative to antiproton production by about four orders of magnitude can be reproduced with a simple coalescence model.

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Table 1: The inclusive cross section $1/\sigma_{dir}^{had} \cdot d\sigma/dp$ for antideuteron production in direct hadronic $\Upsilon(1S), \Upsilon(2S)$ decays at different $\bar{d}$ momenta $p_{\bar{d}}$. The asymmetric statistical errors indicate conservative 68% confidence level intervals derived from poisson statistics. The third column contains the estimated antideuteron cross section based on equation (3). The corresponding values of the antiproton cross section $1/\sigma_{dir}^{had} \cdot d\sigma(\bar{p})/dp_{\bar{p}}$ at momenta $p_{\bar{p}} \approx p_{\bar{d}}/2$, used as input for equation (3), are listed in the last column and taken from an interpolation of ref. [2].

momentum interval $p_{\bar{d}}$ in GeV/c	antideuteron cross section $1/\sigma_{dir}^{had} \cdot d\sigma(\bar{d})/dp_{\bar{d}}$ in 10^{-5} GeV^{-1}c		$1/\sigma_{dir}^{had} \cdot d\sigma(\bar{p})/dp_{\bar{p}}$ in GeV^{-1}c at $p_{\bar{p}} \approx p_{\bar{d}}/2$
	measured	model (eq. (3))	
0.45 – 0.70	$3.7\,^{+3.6}_{-2.0} \pm 0.3$	1.2	0.05
0.70 – 0.95	$6.1\,^{+4.2}_{-2.7} \pm 0.5$	2.6	0.11
0.95 – 1.20	$5.7\,^{+4.2}_{-2.7} \pm 0.5$	3.7	0.16
1.20 – 1.45	$3.7\,^{+4.0}_{-2.4} \pm 0.3$	3.5	0.19
1.45 – 1.70	$1.0\,^{+3.8}_{-1.0} \pm 0.2$	2.7	0.19

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Figure Captions

Figure 1 Distribution of the energy loss *dE/dx* versus momentum p for the 21 antideuteron candidates (big dots), together with the expected curves for energy loss of e, μ, π, K, p, and d (solid lines). The mean *dE/dx* values of other particles, as measured in a multihadronic event sample, are also included.

Figure 2 An antideuteron candidate event viewed in a projection on a plane perpendicular to the beam axis.

Figure 3 The momentum dependence of the inclusive cross section $1/\sigma_{dir}^{had} \cdot d\sigma/dp$ of antideuteron production in direct hadronic $\Upsilon(1S), \Upsilon(2S)$ decays. The solid line represents a fit to the data using distribution (1) given in the text.

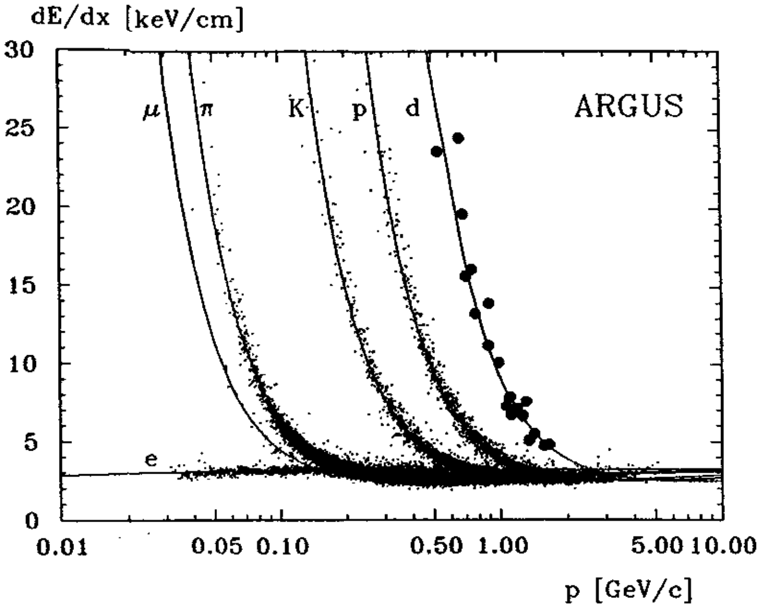
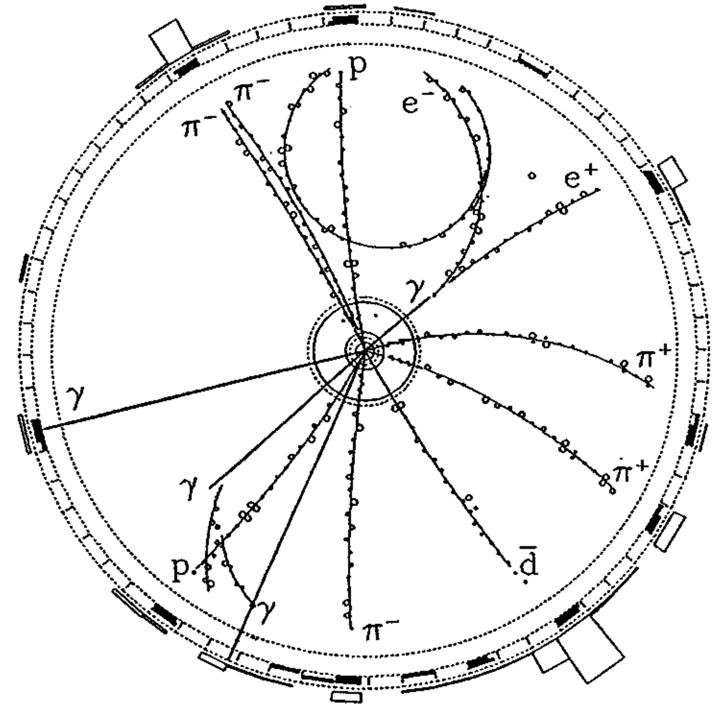
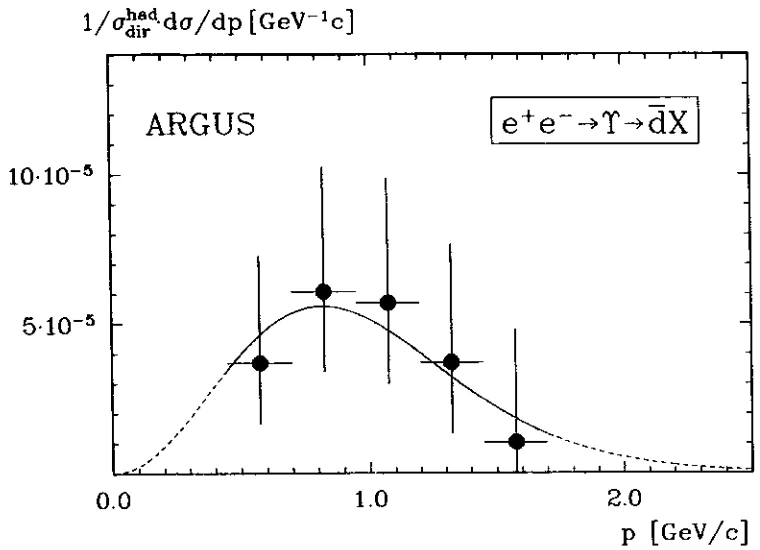


figure 1



ARGUS

figure 2



$1/\sigma_{dir}^{had} d\sigma/dp$ [$GeV^{-1}c$]
ARGUS
$e^+e^- \rightarrow \Upsilon \rightarrow \bar{d}X$
$10 \cdot 10^{-5}$
$5 \cdot 10^{-5}$
0.0
1.0
2.0
p [GeV/c]

figure 3