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PRODUCTION OF DEUTERONS AND ANTIDEUTERONS IN
PROTON-PROTON COLLISIONS AT THE CERN ISR

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ABSTRACT

The inclusive production of deuterons and antideuterons at 90° in the c.m.s. has been measured at the CERN ISR. The measurements for antideuterons extend over $0.15 < p_T < 0.75$ GeV/c and for deuterons from 0.25 - 0.75 GeV/c for $\sqrt{s} = 45$ and 53 GeV. In the overlapping p_T region the average ratio $d/\bar{d} = 4.1 \pm 1.2$ at both energies. The invariant cross-section for $\bar{d}$ shows a p_T and energy dependence similar to those observed for $\bar{p}$.

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Inclusive single-particle spectra of low momentum charged hadrons have been measured at 90° in the c.m.s at the CERN ISR. Data on pion, kaon and proton production have been previously published ^{1,2)}.

The data were collected with a magnetic spectrometer installed at 90° to the intersecting beams, as shown in fig. 1. The details of the apparatus are described in ^{1,2)}. It was designed to detect particles of low transverse momenta and the triggering particle had to traverse only $\sim 0.6 \text{ g cm}^{-2}$. The spectrometer was placed so that the c.m. velocity of the beams was directed towards the equipment.

A trigger was defined as the coincidence $\text{SC1} \cdot \text{SC2} \cdot (\text{SC3} + \text{SC6})$ with a timing requirement between the counters so as to reject particles with a velocity $\beta > 0.85$. This timing requirement improved the detection of heavier particles, including deuterons and antideuterons, which is the subject of the present paper.

The acceptance of the apparatus along the beams was limited so that, in general, only a fraction of the interaction region could be seen. The previously published data on the production of hadrons were taken during special runs, called Terwilliger (TW) runs, when the horizontal extent of the beams was reduced, decreasing the length of the interaction region so that the full source could be seen. In that case an absolute normalization could be obtained using calibrated monitor counters around the beam pipes. In the search for rare events, e.g. those including deuterons, the full intensity of the machine was required and the TW scheme could not be applied. A region of good acceptance was defined by imposing a cut of $\pm 10 \text{ cm}$ along the bisector of the beams. The deuteron data are therefore normalized to the yield of antiprotons, which are produced without noticeable background.

The momentum acceptance was calculated using a Monte Carlo program. The proton and deuteron acceptances as a function of p_T are very similar except that the deuteron acceptance at low p_T is reduced by about 20% because of multiple scattering. The nuclear interaction including stripping of (anti)deuterons is negligible in both cases. The data were collected with alternate positive and negative magnet currents. The quality of the tracks was judged on the basis of the linking between the track segments before and after the magnet, i.e. a cut was imposed on the deviation between the extrapolated positions of the track segments at the magnet centre. This requirement removes less than 10% of the signal while removing most of the background.

The deuterons and antideuterons were identified using momentum and time-of-flight measurements, by imposing the mass cut $1400 < M_d < 2500$ MeV. The limits chosen correspond to $\geq 3 \sigma$ of the observed distribution for the anti-proton peak. In addition, the pulse height recorded in SC1 + SC2 was required to be higher than for protons of the same momentum. Events with one particle in each arm of the spectrometer were eliminated as in that case the pulse height information from SC1 + SC2 was ambiguous. The pulse height distributions in the back dE/dx (SC3 or SC6), total E (SC4 or SC7) and veto (SC5 or SC8) counters were found to be consistent with the assumed identification. For positive particles the identification poses no problem, as the number of deuterons produced was significant, but for negative particles the check on dE/dx versus E is not useful since the particles interact in the total energy counter. Nearly all antideuteron candidates produce a secondary interaction where fast particles are emitted penetrating the veto counter and generating a larger number of hits in the back MWPC. The resultant mass distributions are shown in Fig. 2a.

In order to obtain a clean sample of beam-beam events, a coincidence was required between two large scintillation counter hodoscopes surrounding the two downstream beam pipes. These hodoscopes recorded 25 mb of the proton-proton cross section. The beam-beam requirement reduces the sample to about 75% for $\bar{p}$, 60% for d and 80% for $\bar{d}$. The reason for the larger rejection of deuterons is the contribution of background from beam-gas or beam-wall interactions which is not present for antiprotons or antideuterons. The distributions of the vertical position at the origin of the event are shown in fig. 2b. There is essentially no background for antideuterons, i.e. the vertical height of the beams is reproduced. For deuterons on the other hand the beam-beam peak is superimposed on a broad distribution which is due to secondary nuclear interactions in the wall of the beam tube. The beam-wall background is eliminated by the beam-beam coincidence requirement. The width of the whole distribution is related to the spectrometer acceptance, i.e. mainly to the height of the first scintillator (60 mm). The amount of background is strongly p_T dependent, decreasing as p_T increases (see Table 1).

In order to estimate the background under the beam-beam peak (the region $|Z| < 12$ mm) a linear fit to the events on either side of that region was made and the average level was subtracted.

The events have been distributed in three different bins in p_{lab} . Table 1 shows the effect of the various cuts on the data. For comparison a sample of antiprotons has been included. The effect of the magnet linking cut is more pronounced for antideuterons than for the other particles indicating that the antideuteron candidates contain a larger fraction of incorrectly associated track elements.

For the normalization of the antideuteron data we used antiprotons recorded in the momentum interval $350 < p_{lab} < 400$ MeV/c, where the antiproton acceptance is large and not affected by the imposed β -cut. The antideuteron cuts (see Table 1) applied to the antiprotons gave a further reduction factor of 0.6 with respect to the initial selection. Our previously published cross-sections for antiprotons ²⁾ were used to determine the effective acceptance and the antideuteron differential cross-sections were then obtained after correcting for the difference in proton and deuteron Monte Carlo generated acceptances. The uncertainty in the normalization procedure is estimated to be less than 20%.

Systematic errors in acceptance, normalization and particle misidentification are negligible compared with the statistical uncertainty. The background subtraction for deuterons makes the signal-to-background ratio insignificant below a p_{lab} of 500 MeV/c. The invariant differential cross-sections are shown in fig. 3. For comparison, the results of a previous ISR experiment ³⁾ at $\sqrt{s} = 53$ GeV, also at 90° , are shown. In the region of overlap the two experiments are in good agreement. The measured cross-sections at $\sqrt{s} = 45$ and 53 GeV are given in Table 2. There is some indication of a rise in the cross-section between the two energies. The invariant differential cross-sections at $\sqrt{s} = 53$ GeV, including ref. 3, have been fitted using the forms

$$E \frac{d^3\sigma}{dp^3} = A_1 e^{B_1(\mu_T - m_d)} \quad \text{or} \quad A_2 e^{B_2 p_T}$$

where $\mu_T = (p_T^2 + M_D^2)^{\frac{1}{2}}$. The parameters of the fits are:

$$A_1 = 0.62 \pm 0.14, \quad B_1 = -8.4 \pm 1.5 \quad \text{with } \chi^2/\text{NDF} = 3.6/6$$

and

$$A_2 = 1.18 \pm 0.40, \quad B_2 = -2.62 \pm 0.47 \quad \text{with } \chi^2/\text{NDF} = 2.7/6$$

The values of B_1 and B_2 are very close to the values for the proton and antiproton fits ²⁾.

If (anti)deuterons are produced as the result of the overlap of two produced (anti)nucleons, one would expect⁵⁾ the $d/\bar{d}$ ratio to equal approximately the ratio $(p/\bar{p})^2$ at the same p_T per (anti)nucleon. A compilation of this and other ratios are given in ref. 6. Our result is consistent with this suggestion (fig. 4).

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TABLE 1

	Deuterons				Antideuterons				Antiproton sample
	$\sqrt{s} = 45 \text{ and } 53 \text{ GeV}$								
$P_{lab} \text{ MeV/c}$	500-700 events %	700-1000 events %	300-500 events %	500-700 events %	700-1000 events %	300-500 events %	500-700 events %	700-1000 events %	300-500 events %
Y diamond <100 mm	527 100	230 100	53 100	44 100	39 100	917 100			
Magnet linking < 5.6 mm	437 82	193 83	46 86	41 93	32 82	734 80			
Two tracks	359 68	165 71	18 33	16 36	18 46	612 66			
Z diamond <12 mm	356 67	164 71	17 32	15 34	17 43	587 64			
After background subtraction	171 32	87 37	15 28	12 27	11 28	550 59			
$\sqrt{s} = 45 \text{ GeV}$	52±17	42±11	15±4	12±4	11±3				
$\sqrt{s} = 53 \text{ GeV}$			4	3	4				
			11	9	7				

The effect of cuts applied to the raw data. The percentage of events and the actual number of events are given. The deuteron signal is significant only above 500 MeV/c. Antiprotons are available only below 500 MeV/c due to the β -cut imposed to eliminate particles with $\beta > 0.85$.

TABLE 2.

Invariant differential cross-sections of inclusive
antideuteron production at $\theta_{\text{cm}} = 90^\circ$
($\mu\text{b} / \text{GeV}^2 / \text{c}^3$).

p_T (MeV/c)	$\sqrt{s}$ (GeV)	
	45	53
150 - 300	0.35 ± 0.13	0.63 ± 0.20
300 - 450		0.41 ± 0.16
450 - 600	0.29 ± 0.15	0.28 ± 0.14
600 - 750		0.41 ± 0.21

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FIGURE CAPTIONS.

- Fig. 1. Experimental layout.
- Fig. 2a. Mass distributions of accepted particles.
- Fig. 2b. The vertical projection of the origin of the tracks at the interaction region.
- Fig. 3. Invariant differential cross-sections for the production of antideuteron (statistical errors only).
- Fig. 4. Deuteron/antideuteron ratio compared with the proton/antiproton ratio squared at half the transverse momentum.

R803 Experimental layout, elevation

Fig. 1

Fig. 2

Fig. 3

Fig. 4