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PRODUCTION OF ANTIDEUTERONS IN ANTIPROTON RINGS

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The reaction $\bar{p}\bar{p} \to \bar{d}\pi^-$ is proposed for the production and storage of $\bar{d}$. The conversion yield from two stored $\bar{p}$ to one stored $\bar{d}$ should exceed 10^{-3}.

In the near future, intense $\bar{p}$ beams will be available from the low-energy antiproton ring (LEAR) at CERN [1]. For various purposes (antinuclear atoms, antinucleus–nucleus annihilation in flight) it may be desirable also to produce heavier antinuclei. A first step in this direction is the production of antideuterons. A separated $\bar{d}$ beam has been constructed at the IHEP accelerator at Serpukhov [2]. However, its pion contamination is 10^6, its momentum of 12.2 GeV/c is too high for many interesting experiments, and there are only seven $\bar{d}$ for 10^{13} primary protons. One may think of accumulating $\bar{d}$ in the same way as $\bar{p}$ [3], but it appears that the $\bar{d}$ beam intensity is too low, at least for accelerators such as the CERN Proton Synchrotron (PS) [4]. It has already been suggested to produce low-energy antideuterons in the reaction $\bar{p}\bar{p} \to \bar{d}\pi^-$ by colliding antiproton beams of equal momenta [5] with a total c.m.s. energy close to the maximum of the reaction cross-section. Monoenergetic $\bar{d}$ would emerge isotropically from the collision region and could be used directly for low-energy and stop experiments. Here, however, we propose a scheme, where $\bar{d}$ synthesized in this reaction are successively accumulated and stored. We first discuss the relevant cross-sections and then the $\bar{d}$ accumulation rate.

The cross-section for $\bar{p}\bar{p} \to \bar{d}\pi^-$ should be identical with that of $pp \to d\pi^+$, which has been studied in some detail. It has a maximum of about 3.2 mb at a proton lab. kinetic energy $T_p \approx 620$ MeV (c.m.s. energy $s^{1/2} = 2.16$ GeV). The total pp cross-section at this energy is 38 mb, i.e. deuterons are produced in 8.4% of all pp collisions. The only other inelastic reactions are $pp \to pn\pi^+$ (≈ 10 mb) and $pp \to pp\pi^0$ (3 mb). The maximal storage probability occurs at somewhat lower energy, however, as we shall see. Rather precise cross-section measurements at the relevant energies have recently been published by Hoftiezer et al. [6]. The unpolarized differential centre-of-mass cross-section has the form

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi}\left[a_0 + a_2 P_2(\cos\theta) + a_4 P_4(\cos\theta)\right]. \tag{1}$$

We shall only need $d\sigma/d\Omega$ near $\theta = 0°$, where eq. (1) simplifies to

$$\frac{d\sigma}{d\Omega} = \frac{1}{4\pi}(a_0 + a_2 + a_4). \tag{2}$$

The essential trick for producing and storing $\bar{d}$ is to choose the momenta p_1 and p_2 of the colliding antiprotons such that the $\bar{d}$ momentum p_d is equal to the larger $\bar{p}$ momentum, which we call p_1. The stored $\bar{d}$ can then be cooled to perfect beam quality and their energy can be changed. One needs two $\bar{p}$ rings as indicated in fig. 1, the $\bar{d}$ being accumulated in the larger ring 1. For given p_1, the p_2 must be taken as

$$p_2 = \pm\tfrac{1}{2}\left[(E_d - E_1)^2 + (m_p^2 - m_\pi^2)^2 (E_d - E_1)^{-2} - 2m_p^2 - 2m_\pi^2\right]^{1/2}, \tag{3}$$

$$E_1 = (m_p^2 + p_1^2)^{1/2}, \qquad E_d = (m_d^2 + p_1^2)^{1/2}.$$

The function $p_2 = p_2(p_1)$ is shown in fig. 2, with c.m. energy $s^{1/2}$ as a parameter. Positive p_2 correspond to the parallel motion of the two antiprotons, negative p_2 to antiparallel motion. As the ring accepts virtually only

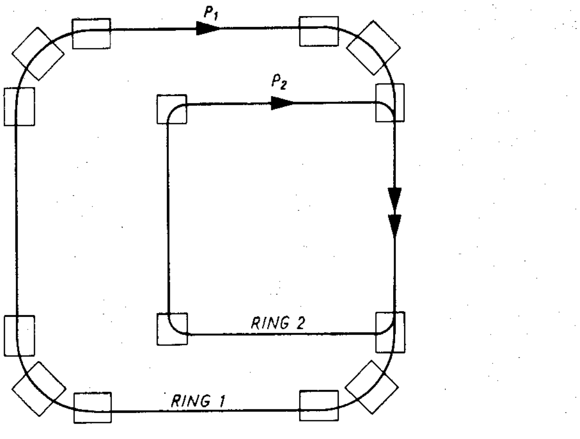

Fig. 1. Schematic view of the double ring collider for $\bar{d}$ production. The $\bar{p}$ in rings 1 and 2 overlap in a common straight section. Here $\bar{d}$ are produced and stored in ring 1.

forward-produced $\bar{d}$, parallel motion is an order of magnitude better than antiparallel motion: because of the Lorentz transformation from the c.m. to the lab. system, all possible lab. angles are confined in a rather small forward cone for parallel collisions. (At the reaction threshold $s^{1/2} = 2.0152$ GeV, all π^- and $\bar{d}$ emerge at zero lab. angle, but here the production cross-section vanishes.) This is why fig. 1 has $\boldsymbol{p}_1$ parallel to $\boldsymbol{p}_2$ in the collision region.

Three possible combinations of p_1 and p_2 are examined in table 1. We have assumed rather conservative acceptance limits of $\Delta\theta = 1°$ and $\Delta p/p = \pm 0.001$ for each ring. With these values, the losses due to $\bar{p}\bar{p}$ Coulomb scattering arise primarily from the angular acceptance of ring 2. (They rise when the acceptance shrinks.) They are collected in column 7 of table 1. The last column contains the $\bar{d}$ yield y per $\bar{p}$ pair,

$$y = \frac{d\sigma}{d\Omega}\Delta\Omega / \left(\sigma_{pp}^{tot} + \Delta\sigma_C\right), \qquad (4)$$

which tells us the number of $\bar{p}$ pairs needed to produce one stored $\bar{d}$. Eq. (4) shows how larger acceptances improve the $\bar{d}$ yield.

We obtain the maximal $\bar{d}$ current $J^{\bar{d}}_{max} = \frac{1}{2} J^{\bar{p}}_{max} \cdot y$ when the set-up is able to use up the available $\bar{p}$ current $J^{\bar{p}}_{max}$. This occurs at a characteristic luminosity

$$L_{max} \sim \frac{J^{\bar{p}}_{max}}{2(\sigma_{tot} + \Delta\sigma_C)}.$$

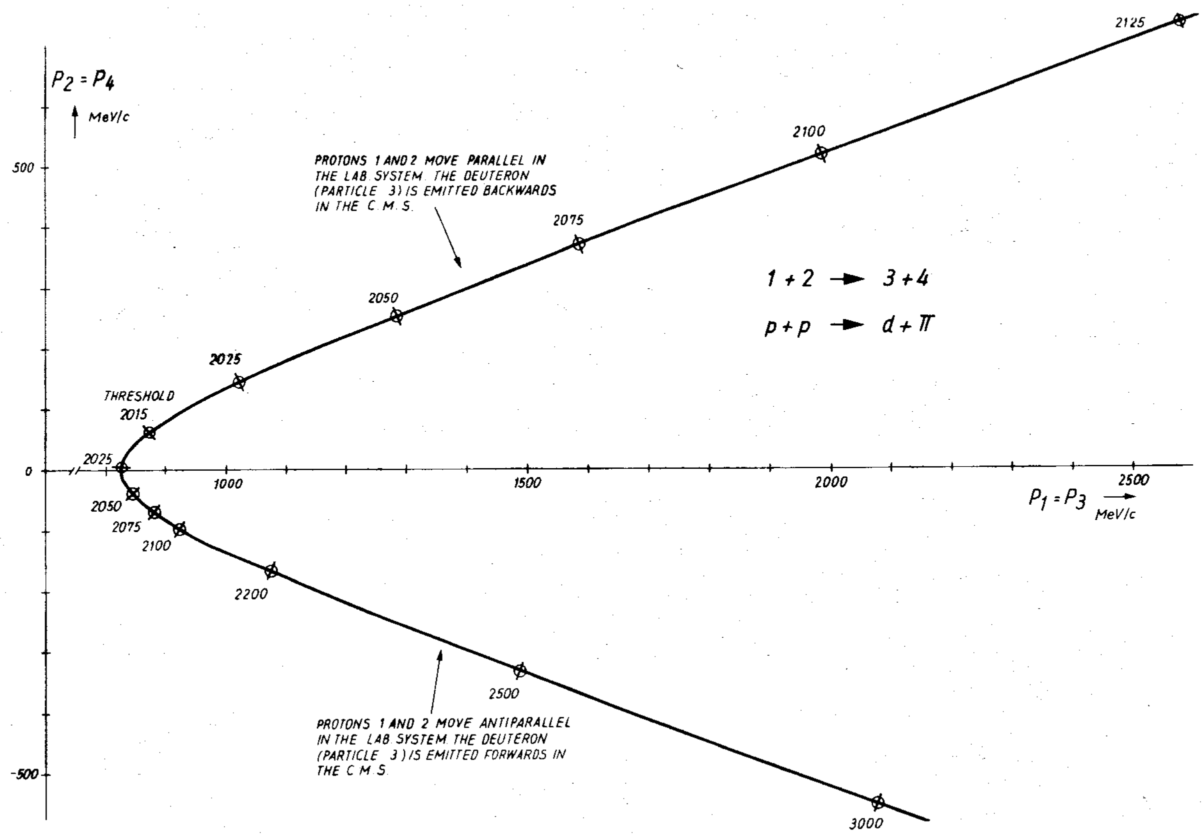

Fig. 2. Combinations of (anti)proton momenta p_1 and p_2 which produce, in collinear collisions, (anti)deuterons with the momentum p_1. Considered is the two-body reaction $pp \to d\pi$. Positive (negative) p_2 correspond to parallel (antiparallel) pp collisions. The parameter on the curve is the invariant mass $\sqrt{s}$ in MeV.

Table 1
Antideuteron yield $y=[(\mathrm{d}\sigma/\mathrm{d}\Omega)\Delta\Omega]/(\sigma_{\bar{p}\bar{p}}^{tot}+\Delta\sigma_C)$ (number of $\bar{d}$ per $\bar{p}$ pair used) for three momentum combinations p_1 and p_2 in rings 1 and 2 and quantities relevant for calculating y: $(\mathrm{d}\sigma/\mathrm{d}\Omega)$ (0°) is the production cross-section at 0° in the c.m. system; $\Delta\Omega$ is the solid angle in the $\bar{d}$ c.m. system determined by lab. acceptances $\Delta\theta_L=1°$ and $\Delta p/p=\pm 0.001$. $\Delta\sigma_C$ describes losses due to Coulomb scattering with angles outside the acceptance of ring 2.

p_1 (GeV/c)	p_2 (GeV/c)	$\sqrt{s}$ (GeV)	$\mathrm{d}\sigma/\mathrm{d}\Omega\,(0°)_{cm}$ (mb/sr)	$\Delta\Omega_{cm}^{d}$ (sr)	σ_{pp} (mb)	$\Delta\sigma_C$ (mb)	$\bar{d}$ yield (‰)
1.5	0.3372	2.068	0.15	0.106	26	7.2	0.46
2.0	0.523	2.101	0.32	0.093	27	2.3	0.99
3.5	1.056	2.146	0.48	0.085	36	0.8	1.12

Assuming $J_{max}^{\bar{p}}\approx 10^6$ $\bar{p}$/s, we find $L_{max}\approx 1.5\times 10^{31}$ cm^{-2} s^{-1} and $J_{max}^{\bar{d}}\approx 500$ $\bar{d}$/s for $p_1\approx 2$ GeV/c and the acceptance quoted above. Smaller luminosities give correspondingly less $\bar{d}$ flux for less $\bar{p}$ consumption. The storage scheme makes it possible to accumulate the necessary amount of $\bar{d}$ before doing an experiment.

Phase-space cooling is essential for this scheme as it provides the long beam lifetimes necessary. It also allows for reasonable luminosity since it reduces, for the two $\bar{p}$ beams, the cross-sectional areas A_1 and A_2 which enter in the luminosity L [7]:

$$L=\tfrac{1}{4}\frac{N_1N_2}{U_1U_2}\frac{A_{min}}{A_1A_2}lc|\beta_1-\beta_2|. \qquad (5)$$

Here coasting beams are assumed in both rings; U_1 (taken to be 45 m) and U_2 (30 m) are the circumferences of the rings, l (2 m) is the interaction length, N_1 and N_2 are the number of $\bar{p}$ in rings 1 and 2, and A_{min} is the overlap area; ideally, $A_1\approx A_2\approx A_{min}$; $c\beta_{1,2}$ is the velocity of the particles. These areas are constrained by the disruptive effect of the space-charge field of one beam on the other, known as the Amman–Ritson (or beam–beam) effect [7]. For parallel beams, this effect imposes the density limit

$$\frac{N_1}{A_1}\frac{l}{U_1}\leqslant\frac{2\Delta Q}{(1-\beta_1\beta_2)r_p\beta^*}\beta_2^2\gamma_2,$$

and a similar limit for N_2/A_2. Here ΔQ is the maximum permissible beam–beam tune shift [7] ($\Delta Q=5\times 10^{-3}$ for hadron beams in the absence of strong cooling), $\beta^*\gtrsim l$ (2 m) is given by the focusing function related to the beam optics of the storage rings [7], and $r_p=1.54\times 10^{-16}$ cm.

An optimum luminosity

$$L=\frac{1}{2}\frac{\Delta Q N_2\beta_2^2\gamma_2|\beta_1-\beta_2|c}{(1-\beta_1\beta_2)U_2r_p\beta^*}\approx 1.6\times 10^{28}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

for a given N_2 (10^{11} $\bar{p}$) and ΔQ (5×10^{-3}) at $p_1=2$ GeV/c is reached for

$$N_1=N_2\frac{\beta_2^2\gamma_2U_1}{\beta_1^2\gamma_1U_2}\approx 0.22N_2=0.22\times 10^{11},$$

and for extremely small beam cross-sections

$$A_1=A_2=A_{min}\approx 0.6\ \mathrm{mm}^2.$$

This yields ~0.5 $\bar{d}$/s for a consumption of only ~1000 $\bar{p}$/s.

A standard system for electron cooling [8] would work in ring 2, and a similar system with higher-voltage electrons [9] is needed in ring 1. One could think of putting effort into a dedicated third ring for $\bar{d}$ alone. This would release the kinematical restrictions of fig. 1 only slightly, but it would allow the $\bar{d}$ to be cooled stochastically [10] and it would decouple $\bar{d}$ extraction from $\bar{p}$ handling in ring 1.

A large fraction of the produced $\bar{d}$ (which are not accepted in a storage orbit) may be continuously extracted from the interaction region for prompt use, if one is able to cope with the large momentum and angular spread given by kinematics, and if one can deal with the rather high $\bar{d}$ momenta. The production of $\bar{d}$ in flight with subsequent storage and cooling as discussed above would yield $\bar{d}$ beams of variable energy and very high phase-space density.

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References

[1] P. Lefèvre, D. Möhl and G. Plass, 11th Int. Conf. on High-energy accelerators, Geneva, 1980 (Birkenhäuser Verlag, Basle, 1980) p. 819.
[2] V.V. Vasiliev et al., ibid., p. 369.
[3] R. Billinge and M.C. Crowley-Milling, Proc. Int. Conf. on Particle accelerators, San Francisco (1979), and IEEE Trans. Nucl. Sci. NS-26 (1979) 2974.
[4] H. Koch, CERN $\bar{p}$ LEAR Note 42 (1979).
[5] H. Pilkuhn and H. Poth, CERN $\bar{p}$ LEAR Note 86 (1980), KfK-Primärbericht Nr. 11.01.02P070.
[6] J. Hoftiezer et al., Phys. Lett. 100B (1981) 462.
[7] M. Sands, Internal report SLAC 121 (1970); E. Keil, in CERN 77-13 (1977) p. 314.

[8] G.I. Budker et al., Part. Acc. 7 (1976) 197; M. Bell et al., Phys. Lett. 87B (1979) 275.
[9] G.I Budker and A.N. Skrinsky, Sov. Phys. Usp. 21 (1978) 277; R. Forster et al., IEEE Trans. Nucl. Sci. NS-28 (1981) 2386; U. Bizzarri, M. Conte and L. Tecchio, 5th European Symp. on Nucleon–Antinucleon Interactions, Bressanone (1980).
[10] D. Möhl, G. Petrucci, L. Thorndahl and S. Van der Meer, Phys. Rep. 58 (1980) 75.