[10] See references 8, 9, 10, and 11 in preceding Letter [Phys. Rev. Letters 14, 999 (1965)] (Columbia-Princeton-Lawrence Radiation Laboratory collaboration).

[11] P. Franzini, B. Leontić, D. Rahm, N. Samios, and M. Schwartz, Phys. Rev. Letters 14, 196 (1965).

OBSERVATION OF ANTIDEUTERONS*

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(Received 4 May 1965)

Using a high-transmission mass analyzer designed to search for unitary-symmetry triplets,[1] we have observed the production of antideuterons in 30-BeV proton-beryllium collisions.

The search was made in a $4\frac{1}{2}$-deg beam described in the preceding Letter. This communication also described the logic designed to suppress $\beta = 1$ particles and their residue while recording beam-defined particles of $0.81 < \beta < 0.96$. To bring antideuterons into the sensitive velocity band, the beam was tuned to momenta between 4.5 and 6 BeV/c. We also report on a search for antitritons in the momentum interval near 9.0 BeV/c.

The evidence for antideuterons is contained in the graphs of Fig. 1. Table I summarizes all the negative-beam runs. Events which satisfy the logic have the velocity recorded in two time-of-flight systems, S_1S_{10} (210 ft) and S_2S_9 (170 ft). In S_1S_{10} there is the additional requirement of constant velocity across each of three

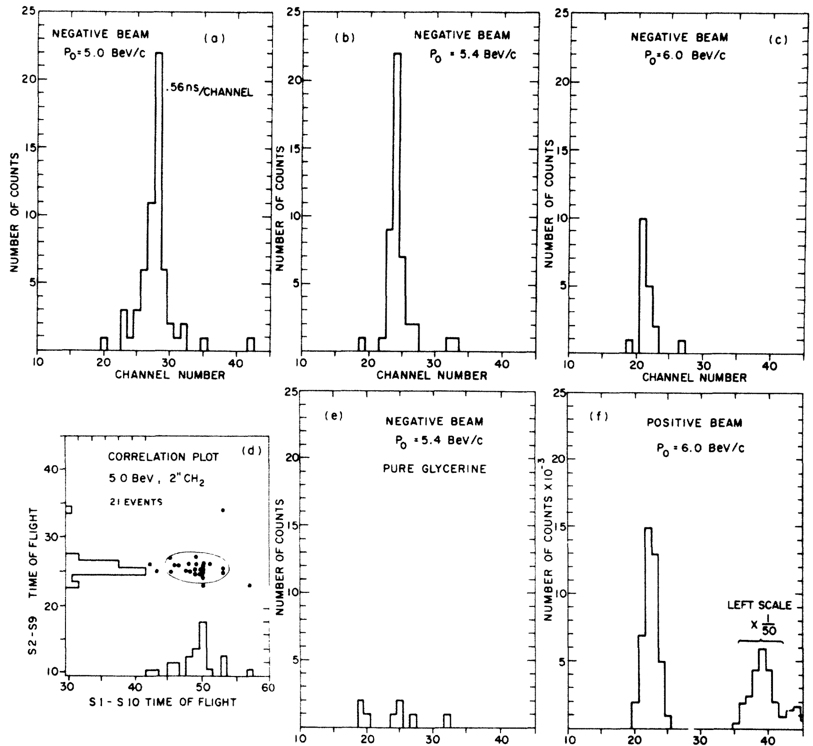

FIG. 1. Time-of-flight spectra between counters S_2 and S_9 (180 ft) for particles of the indicated momenta. The data of Figs. 1(a), 1(b), 1(c), 1(e), and 1(f) were taken in consecutive runs during which the time-to-channel calibration was ~0.55 nsec channel. The normalizations are given in Table I, except for 1(e) which should be divided by two to compare with 1(b). The resolution oval indicated in 1(d) is obtained from graphs like 1(f).

Table I. Summary of negative-beam runs.

Momentum (BeV/c)	No. of events	$\bar{d}/\pi^-$ yield[a]
4.5	41	$(3.0\pm1.5)\times10^{-8}$
5.0	118	$(3.9\pm0.8)\times10^{-8}$
5.0[b]	21	$(2.0\pm0.5)\times10^{-8}$
5.4	55	$(2.4\pm1.0)\times10^{-8}$
6.0	17	$(6.0\pm3.0)\times10^{-8}$
9[c]	2 ± 2	$(1\pm1)\times10^{-10}$[d]

[a] Uncorrected for $\bar{d}$ absorption and π-μ decay.

[b] CH_2 in beam.

[c] See Table I of reference 1.

[d] $\bar{t}/\pi^-$ yield.

pairs of counters separated by 100 ft. Figure 1(d) indicates how the two pulse-height analyzer outputs are used to reduce background. Calibration is done on the positive-polarity beam [Fig. 1(f)] where a copious source of deuterons and tritons was used to establish the position and resolution of the mass peaks for these particles.

The mass peaks seen in Figs. 1(a), 1(b), and 1(c) are interpreted as being due to antideuterons. The evidence is based upon the following:

(1) In each case, the location of the peak agrees with that of the corresponding d^+ peak observed in the positive beam to within ±1 channel. This corresponds to ±0.56 nsec and is consistent with combinations of magnet hysteresis and pulse-height analyzer drifts. The resulting mass difference between the negative and positive peaks averaged over all three momentum intervals is less than 3%.

(2) The $\bar{d}$ peak moves from channel 21.5 at $p=6$ BeV/c to channel 23.5 at 5.4 BeV/c to channel 26 at 5.0 BeV/c, corresponding to a slope $\Delta\beta/\Delta p=(1.6\pm0.4)\times10^{-2}$ $(\text{MeV}/c)^{-1}$, in agreement with the value

$$d\beta/dp=\beta^3m^2/p^3=1.7$$

computed with $m=1.86$ BeV. This also ties the peak to a real particle rather than a spurious collection of counts defined by some gate edge in the complex logic.

(3) With the momentum set at 5.4 BeV/c, the Fitch Čerenkov radiator, normally 75% glycerine and 25% H_2O, and defining a velocity band $\beta=0.81\rightarrow0.955$, was replaced by pure glycerine having a cutoff at $\beta=0.91$. The efficiency of this counter for pions is thereby reduced from ~10 to ~5%. However, the resulting counts in the $\bar{d}$ peak were reduced by a factor ~10 [Fig. 1(e)], indicating that this independent verification of velocity is satisfied.

(4) As a final check, 5 gm/cm^2 of CH_2 were inserted in the beam to measure the transmission relative to pions. At 5.0 BeV/c, the multiple scattering of a particle with $\beta=0.95$ would differ only slightly from that of a pion ($\beta=1$), and should not reduce the overall beam transmission by more than ~10%. In fact, the ratio of $\bar{d}/\pi$ changed by a factor of 1.6 ± 0.5 (see Table I), suggesting a larger absorption cross section, typical of $\bar{p}$ in this momentum interval.[2]

In summary, the counts we observe have been shown to correspond to real particles of negative charge and mass within ±3% of that of the deuteron. Of course, we cannot rigorously rule out a new particle, accidentally coinciding in mass with the deuteron. However, the stability as evidenced by its survival through a flight time of ~10^{-7} sec and its typically large absorption cross section argue strongly against this possibility.

The rate of production of $\bar{d}$ relative to pions is found to be

$$\bar{d}/\pi^-=(5.5\pm1.5)\times10^{-8}\ (5\ \text{BeV}/c). \tag{1}$$

A correction has been applied for the relatively higher absorption of $\bar{d}$ in counters and air as well as for $\pi\rightarrow\mu$ decay. This corresponds to a cross section, at 4.5° and 5.0 BeV/c, of

$$d^2\sigma/d\Omega dp=120\times5.5\times10^{-8}\ \text{mb/sr BeV},$$
$$\cong7\times10^{-33}\ \text{cm}^2\ \text{sr}^{-1}\ (\text{BeV}/c)^{-1}$$
$$\text{per Be nucleus}, \tag{2}$$

based on pion production data.[3] The ratio $\bar{d}/\bar{p}$ at this momentum is of the order of 10^{-6}. Table I also shows that $\bar{t}$ production could be as high as ~1% of $\bar{d}$ production, although no unambiguous evidence for $\bar{t}$ was obtained in the available time.

There has been one attempt to predict the rate of antideuteron production: This assumes direct $\bar{d}$ production in a quasifree nucleon-nucleon collision, and calculates the yield, using the statistical model.[4] The authors anticipate that the model will overestimate the actual rate due to experience with statistical model calculations of $\bar{p}$ production, and, indeed, the observed rate is ~2000 times lower than the statistical theory predicts.

We have, therefore, attempted to understand the order of magnitude of the production on the basis of simple, semiempirical considerations. To do this we must intrude on the lively discussion[5-7] found in the literature of d^+ and heavier particle production at BeV energies.[8-10] One learns that the production mechanism is a sensitive function of d^+ momentum and angle of production. For example, although a very small fraction of the d^+ observed at large angles and low energies (<2 BeV/c) are made in nucleon-nucleon collisions,[11] this contribution becomes very important at ~5-10 BeV/c and forward angles.[12] However, the significant aspect for our results is the apparent success in fitting high-energy d^+ production without the important requirement of particle "pick-up" processes. That is to say, most of the effect can be accounted for by the finite probability of two outgoing high-energy nucleons having small enough relative momenta to fit the deuteron wave function.[13] Whether these are produced on quasifree nucleon-nucleon collisions[6] or in a nucleonic cascade,[7] one can use the observed nucleon momentum distribution emerging from proton-beryllium (say) collisions to compute the overlap of two such particles to form an outgoing deuteron. The same considerations should then be valid for $\bar{d}$ production if we assume that the antinucleons are produced independently in 30-BeV collisions. We can then directly estimate the 5-BeV $\bar{d}$ rate as

$$\frac{\bar{d}}{\pi^-}=\left[\left(\frac{\text{probability of antinucleon production}}{\text{probability of nucleon production}}\right)_{2.5\text{ BeV}/c}\right]^2\left(\frac{d^+}{\pi^-}\right)_{5\text{ BeV}/c}\prod_i C_i; \tag{3}$$

and from reference 3 and Table II,

$$\begin{aligned}\bar{d}/\pi^- &= (0.01)^2\times1.5\times10^{-3}\prod_i C_i\\ &\cong 15\times10^{-8}\prod_i C_i,\end{aligned} \tag{4}$$

where C_i are correction factors whose combined effect is unlikely to be as much as $\sim\frac{1}{10}$. Thus C_1 is a correction for the difference in the shape of the $\bar{p}$ and nucleon production spectra near 3 BeV/c, C_2 relates to the occasional availability of more than two fast nucleons due to the cascade or to antiparticle production (i.e., t^+ are produced!), and C_3 accounts for extra $\bar{d}$ reabsorption in the nucleus. The reader can supply terms of $i>3$. However, the agreement with (1) is already rather good and, if not fortuitous,[14] gives strong support to the essential mechanism for high-energy d^+ production.

The existence of bound states of antiparticles is in accord with the predictions of CPT invariance of nuclear forces and suggests that even more sensitive tests could be made, if the binding energy of the $\bar{d}$ could be accurately measured.[15] The $\bar{d}$ flux in a beam of 10^{-4} sr × ($\Delta p/p$ ~ 10^{-2}) is of the order of one in several minutes, almost enough for bubble chamber observation of annihilation modes.

We would like to thank Dr. Mermod, Dr. Piroué, and Dr. Vivargent for informing us of an earlier CERN run which set a limit of $\bar{d}/\pi^-$ slightly lower than the observed yield.

Table II. Summary of positive-beam runs.[a]

Momentum (BeV/c)	Target	$d^+/(\pi^++p)\times10^3$	$t/(\pi^++p)\times10^5$
4.0	S.S.[b]	1.5 ± 0.5	1.5 ± 0.5
4.0	Be	0.8 ± 0.2	1.0 ± 0.1
5.0	S.S.[b]	0.5 ± 0.1	1.0 ± 0.4
5.0	Be	0.8 ± 0.1	0.4 ± 0.1
6.0	Be	0.5 ± 0.1	0.3 ± 0.1

[a] The normalization is done in terms of $\beta=1$ particles monitored. Beam survey data[3] indicate that the corresponding normalization to π^- flux is obtained by multiplying all numbers by ~2. Errors are due to normalization problems.

[b] Stainless steel.

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*Work supported in part by the U. S. Atomic Energy Commission.

[1] D. E. Dorfan, J. Eades, L. M. Lederman, W. Lee, and C. C. Ting, preceding Letter [Phys. Rev. Letters 14, 999 (1965)].

[2] The $\bar{p}$ absorption cross section at 6 BeV is 60 mb; the pion total cross section is 30 mb. U. Amaldi, T. Fazzini, G. Fidecaro, C. Ghesquière, M. Legros, and H. Steiner, Nuovo Cimento 34, 825 (1964).

[3] W. F. Baker et al., Phys. Rev. Letters 7, 101 (1961). See L. Lederman, Brookhaven National Laboratory Internal Report No. 8475 (unpublished), for absolute normalizations.

[4] R. Hagedorn, Nuovo Cimento 25, 1017 (1962).

[5] D. I. Blokhintsev, Zh. Eksperim. i Teor. Fiz. 33, 1295 (1957) [translation: Soviet Phys.—JETP 6, 995 (1958)].

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[7] S. T. Butler and C. A. Pearson, Phys. Rev. Letters 7, 69 (1961); Phys. Letters 1, 77 (1960).

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[12] A. N. Diddens, W. Galbraith, E. Lillethun, G. Manning, A. G. Parham, A. E. Taylor, J. G. Walker, and A. M. Wetherell, Nuovo Cimento 31, 961 (1964).

[13] See a useful review by A. Glassgold, International Symposium on Direct Interactions and Nuclear Reaction Mechanisms, Padua, Italy, 1963 (Gordon & Breach, New York, 1963).

[14] Other mechanisms for $\bar{d}$ production may surely contribute; our aim is to demonstrate that the observed yield is not unreasonable. M. Goldhaber (private communication) has suggested, for example, the production of one antiparticle by another as a reaction which could contribute to the $\bar{d}$ yield.

[15] G. C. Wick (private communication) has suggested that the angular aperture in $\bar{d}$ stripping could be a possible way of accomplishing this. This may be possible if present trends in small-angle technology continue.