EXPLANATORY PHYSICS NOTES FOR NON-SPECIALISTS

Antideuterons

The nucleus of an atom of deuterium is referred to as a deuteron. It consists of one proton and one neutron. Like any atomic nucleus it is positively charged, its charge being carried by the proton. An antideuteron is a nucleus of antimatter. It contains an antiproton and an antineutron. The antideuteron is negatively charged, since the antiproton is negatively charged and the antineutron is neutral. If this nucleus finds a positron, it forms an atom of antideuterium. This process has not as yet been observed.

The antideuteron is the first complex nucleus of antimatter to be artificially made and observed. In 1968, soon after the new Soviet accelerator of 76 GeV, located at Serpukhov, became operational, antihelium-3 was produced. In analogy with the helium isotope He^3, it consists of two antiprotons and one antineutron.

The concept of "antiparticles" was originated by Dirac who, in establishing the relativistic equations for the electron, noted that there were "unwanted solutions" corresponding to particles with the same mass as electrons but with unit positive charge. Anderson's discovery of the positron* provided experimental confirmation of Dirac's prediction and was the first antimatter to be observed.

* Anderson, C. D., "The Positive Electron", Phys. Rev., 43, 492 (1933).

All elementary particle theories feature sets of solutions representing "charge conjugate" particles. These antimatter particles have opposite charge from their matter counterparts. Otherwise they have very similar properties including a mass identical to that of their particle complements. Thus one expects the antideuteron to be precisely as massive as the deuteron.

Antiparticles can never be produced alone. Conservation of the number of nucleons (baryon number) requires that an antiparticle can only be produced along with its particle counterpart. For example:

$$P + P \rightarrow P + P + \bar{P} + P$$

or

$$P + P \rightarrow P + P + \bar{D} + D \quad (D = \text{deuteron})$$

Hence the initial proton energy needed to produce one antinucleus must be enough to produce a net center of mass energy of twice the nucleus mass. For antiproton production, the laboratory energy of the incident proton must be 5.63 GeV. It was with this fact in mind that the Berkeley Bevatron was designed to reach energies of 6 GeV.

Antideuterons were also observed at about the same time by Zichichi and co-workers at CERN's (European Organization for Nuclear Research) proton-synchrotron (P.S.) in Geneva, Switzerland.

Their report is reproduced next. □

T. MASSAM, *et al.*
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Experimental Observation of Antideuteron Production.

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CERN - Geneva

(ricevuto il 13 Marzo 1965)

Summary. — The results of an experiment which show the existence of antideuterons in the production process proton-beryllium are reported.

We report here the results of an experiment on the production of antideuterons in proton-beryllium collisions. The beam used for the investigation was the high-intensity, partially-separated negative beam of the CERN Proton-Synchrotron. The beam layout is shown in Fig. 1 and its caracteristics are summarized in Table I. The details of the beam are described elsewhere (1), so we will mention only the points relevant to the detection of antideuterons

TABLE I. – *Basic parameters of the beam.*

Production angle	111 mrad
Target	Be; ∅ 1×20 mm; at 100 mrad
Horizontal angular acceptance	± 32 mrad
Vertical angular acceptance	± 6.2 mrad
Maximum momentum band	± 2%
Total length	61 m
Beam size in the experimental area	horizontal 3 cm; vertical 2.2 cm

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(1) G. BRAUTTI, G. FIDECARO, T. MASSAM, M. MORPURGO, TH. MULLER, G. PETRUCCI, E. ROCCO, P. SCHIAVON, M. SCHNEEGANS and A. ZICHICHI: *Nuovo Cimento*, **38**, 1861 (1965). See also report presented by A. ZICHICHI at the *International Conference on High-Energy Physics* (Dubna, August 1964): « *A high-intensity, partially-separated, beam of antiprotons and* K-*mesons* ».

6575

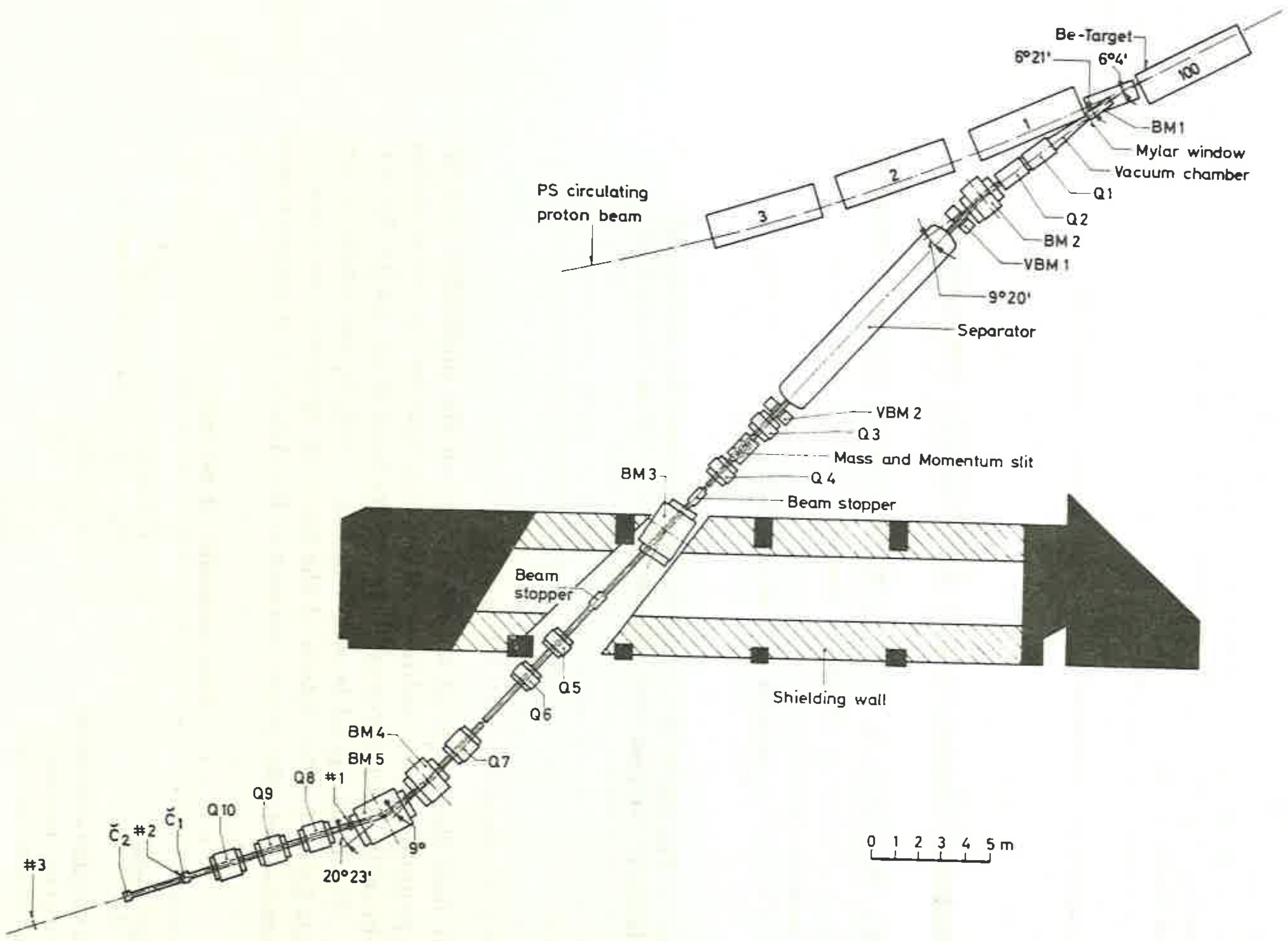


Fig. 1. – Beam layout and set-up. BM are bending magnets; VBM are two vertical bending magnets which compensate the deflection produced in the electrostatic separator; Q are quadrupoles; 1, 2, 3 are scintillation counters of $(12.5 \times 16.5 \times 0.8)$ cm^3 used for the time-of-flight measurements; $\check{C}_1$ and $\check{C}_2$ are gas Čerenkov counters filled with 5 kg/cm^2 of ethylene; they are 7.40 m and 2.50 m long respectively.

in it: the beam came from an internal beryllium target of the CERN Proton-Syncrotron and was momentum and velocity analysed by bending magnets and an electrostatic separator, thus allowing the mass spectrum of the particles produced in the internal PS target to be determined. In order to be able to detect masses produced at very low rates with respect to the pions, it was necessary to improve the mass resolution by adding gas Čerenkov counters [2] and time-of-flight counters. The position of these counters in the beam is indicated in Fig. 1. The function of the gas Čerenkov counters $\check{C}_1$ and $\check{C}_2$ was to provide a good anticoincidence for pions. These two counters were filled with 5 kg/cm² of ethylene and each had 99.99 % efficiency for the rejection of pions. Counters 1, 2, and 3 were used for time-of-flight measurements. All counters were timed to 0.3 ns using antiprotons of 2.5 GeV/c; the relative timing of the counters was then corrected for the difference in time of flight which exists between antiprotons and antideuterons of 2.5 GeV/c. This correction is obtained by adding delays of 8.2 and 3.7 ns to counters 1 and 2 respectively, while keeping counter 3 fixed in time. The full width at half height of our coincidence unit was 3.4 ns. The electronics block diagram is shown in Fig. 2.

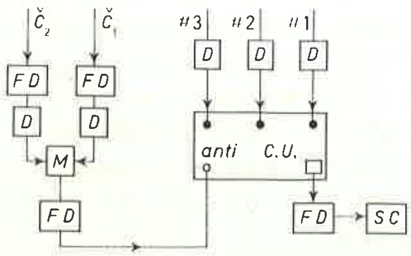
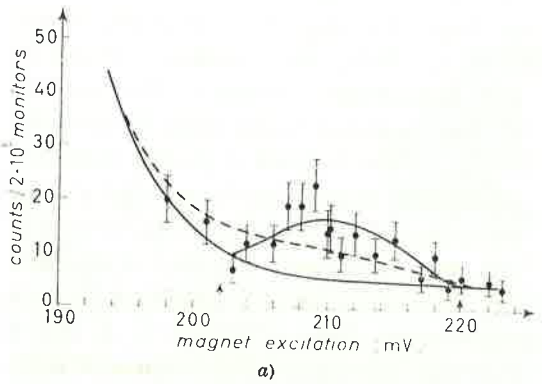


Fig. 2. – Electronics block diagram. *FD* are fast discriminators; *D* are delays; *M* is a passive mixer; *CU* is a coincidence circuit; *anti* is the input anticoincidence; *SC* is a scaler.

The Proton-Syncrotron was operated at 19.2 GeV/c with an average circulating beam of $8\cdot10^{11}$ protons/burst; the burst length was 300 ms and the repetition rate $(2.3\ \text{s})^{-1}$. About 80 % of the total circulating beam was steered onto our target (target 1) and each point of the results which are shown in Fig. 3*a* corresponds to 200 bursts. This graph shows the counting rate as a function of the excitation of the compensating magnet of the electrostatic separator. The lower curve is drawn by eye to estimate the background. The results after the subtraction of this background are shown in Fig. 3*b*. The expected shape of this curve is known from measurements which were made at the antiproton peak. The position and normalization of the curve were varied so as to find the χ^2 minimum fit. This corresponds to the curve shown in Fig. 3*b*; this curve, when added to the background, is shown in Fig. 3*a*. The position of the observed peak agrees to within one mV with the position predicted for the antideuteron peak from the experimental knowledge of the

(2) M. VIVARGENT: *Nucl. Instr. and Meths.*, 22, 165 (1963).

pion and antiproton peaks. The value of χ^2 relative to the best fit is 16.4 for 14 degrees of freedom. This corresponds to a 30% probability of obtaining a worse fit. The dashed curve shows an attempt to fit the data by eye without the antideuteron peak. This gives a χ^2 of 26 and a value of P_{χ^2} less than 3%. The variation of χ^2 with the value used for the mean of the distribution is shown in Fig. 3*c*, where the value of χ^2 obtained without the antideuteron peak is shown for reference.



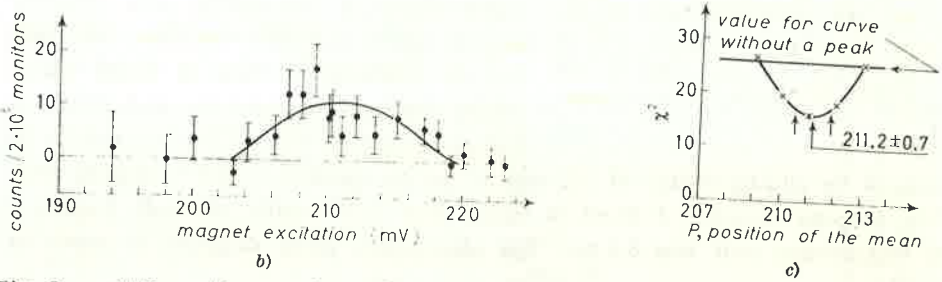


Fig. 3. – *a*) Shows the esperimental points and the fitted curves. The lower curve is an estimate of the background. The upper curve is obtained by adding the fitted curve of Fig. 3*b* to the background curve. The broken curve is drawn under the assumption that the peak does not exist. *b*) Shows the result of fitting the expected shape of antideuteron peak with the background subtracted. *c*) Shows the variation of χ^2 with the mean position of the peak.

The results reported (³) imply the conclusion that a negative particle exists with mass equal to (1867 ± 80) MeV/c² (*). The most simple interpretation of these data is to identify this particle with the antideuteron.

According to our monitor, the ratio of antideuteron flux detected to pion flux in the beam is $(8 \mp 1) \cdot 10^{-9}$. When this number is corrected for attenuation of the antideuterons in our counter system and for decays of the pions

(³) Similar investigations have been performed at Brookhaven by L. LEDERMAN, H. TING *et al.*: communication given by Prof. B. GREGORY at a CERN Seminar.

(*) An important source of error is the uncertainty in the separator calibration. The error indicated by the χ^2 curve of Fig. 3*c* would only be ± 40 MeV/c².

6577

in flight, the ratio of antideuteron to pion at the production point is $(1.2 \pm 0.2) \cdot 10^{-8}$.

Concerning the comparison of antideuteron production with Hagedorn's statistical theory (4,5) we would like to point out that: i) our data refer to the production of antideuterons from primary protons of 19.2 GeV/c, while Hagedorn's calculations (4) refer to 25 GeV/c primary momentum; ii) moreover Hagedorn's calculations are valid for nucleon-nucleon collisions while our data refer to the production of antideuterons in proton-beryllium collisions. After a detailed discussion with Prof. HAGEDORN the conclusion reached is that only an experiment on hydrogen can be decisive towards agreement or disagreement with the statistical theory.

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We would like to thank Prof. W. PAUL and Prof. P. PREISWERK for the support and interest given to the present investigation; Prof. R. HAGEDORN and Dr. H. PILKHUN for discussion on the theory of antideuteron production; our technicians, Messrs. J. BERBIERS, K. LEY and B. NICOLAI for their appreciated help.

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(4) R. HAGEDORN: *Nuovo Cimento*, 25, 1017 (1962).
(5) H. PILKHUN: CERN report 64-40.

RIASSUNTO

Si riportano i risultati di un esperimento che dimostrano l'esistenza degli antideutoni nel processo di produzione protone-berillio.

6578