Table I summarizes the approximate amount of the various modes of decay and the calculated partial half-lives for each.

TABLE I. Branching ratios and partial half-lives for various modes of decay in Np^{235}.

Mode of decay	Branching ratio (% of total disintegrations)	Partial half-life
Alpha	0.005	2×10^4 yr
K-capture	<10	>12 yr
L-capture	>90	<450 days
Total	100	410 days

The authors are indebted to Professor Glenn T. Seaborg under whose direction this problem was undertaken, and to G. B. Rossi and the 60-inch cyclotron crew for the excellent U^{235} bombardment.

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Charged π-Meson Production from Deuterium*

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EXPERIMENTAL RESULTS.—The $\pi^{\pm}$ meson production cross sections from deuterium at $90°\pm5°$ to a 381-Mev proton beam have been obtained. The technique utilizing nuclear emulsions embedded in a tapered copper absorber, exposed to the internal circulating beam of the Nevis cyclotron, has been described previously.[1] The experimental arrangement has been modified to obtain better energy resolution. The target is now placed radially, and a copper "clipper," to define the beam energy, is placed $\frac{1}{4}$ inch radially behind the leading edge of the target, and located 90° from the target in azimuth, to prevent neutrons scattered from the "clipper" from striking the emulsions (see Fig. 1).

The target, 60 mils thick, was made from deuterated paraffin, whose composition was analyzed to be ~96 percent $(CD_2)_n$.[2] It was exposed for 7 minutes to an average proton beam current of $\sim10^{-10}$ ampere, at an energy of 381 ± 5 Mev. The deuterium contribution to meson production was obtained by subtracting the known carbon differential cross section[1] from the observed spectrum of CD_2, and halving this result. The deuterium positive meson spectrum, $d^2\sigma/d\omega dE$, obtained from $174\pi-\mu$ decays is shown in Fig. 2. It has a maximum in the region between 30 and 50 Mev of about 4.5×10^{-30} cm² Mev⁻¹ sterad⁻¹ D-nucleus⁻¹. The integrated cross section $d\sigma^+/d\omega$ is $(2.9\pm1.2)\times10^{-28}$ cm² sterad⁻¹ D-nucleus⁻¹. In the same regions scanned for the positives, only $6\pi^-$ meson stars were observed from $(CD_2)_n$. The statistical errors are too large to permit the drawing of a spectrum but an estimate of the total 90° negative cross section, $d\sigma^-/d\omega$, is $(1.1\pm0.9)\times10^{-29}$ cm² sterad⁻¹ D-nucleus⁻¹.

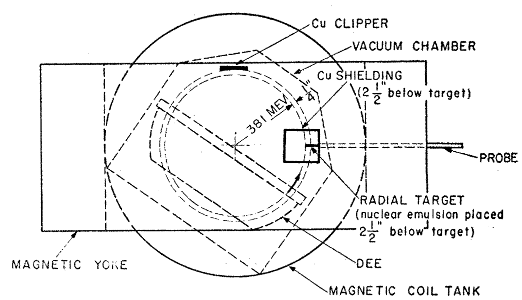

FIG. 1. Floor plan of Nevis cyclotron, showing experimental arrangement for proton bombardment of radial target.

Analysis.—In analyzing the production of mesons in the bombardment of deuterium by highly energetic protons, we have used the impulse approximation;[3] that is, we have assumed that π-mesons are produced by collisions between an impinging proton and a single nucleon in the loosely bound deuteron. The second nucleon in the deuteron serves only to impart a deuteron momentum distribution to the struck nucleon prior to the collision, and satisfies conservation laws by carrying off the complimentary momentum.

The possible modes of producing mesons in nucleon-nucleon collisions between the incident proton and the proton or neutron of the deuteron are: (a) $p+p\rightarrow\pi^++d$ (or $p+n$); (b) $p+n\rightarrow\pi^++n+n$; (c) $p+n\rightarrow\pi^-+p+p$.

Although there is no direct experimental evidence on the relative magnitudes of processes (b) and (c), these reactions probably have comparable cross sections. This is due to charge independence of the low energy nuclear forces involved in the final state nucleon interactions of these reactions, as well as the symmetrical properties of the π^+ and π^- mesons, i.e., lifetime, mass, charge, etc. The experimental (π^+/π^-) production ratio in deuterium, measured at 90° to a 381-Mev proton beam, is very large, ~25.[4] This indicates the relative smallness of process (c) [and in turn from the above discussion, the smallness of process (b)] relative to process (a). The strong interaction of nucleons in the final state of process (a) may account for the relative importance of this mode of meson production. The small cross section for process (c) may also be the effect of the exclusion principle, since there are 3 low energy protons present in the final state when the remaining proton in the deuteron is taken into account.[5]

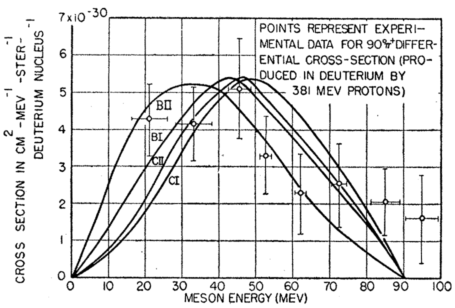

FIG. 2. Theoretical curves for the π^+ meson spectra from deuterium, labeled to indicate the energy and angular dependence used in the calculation.

With the hypothesis that process (a) is the main reaction contributing to π^+ meson production in deuterium, a theoretical calculation of this latter meson spectrum has been made based upon these assumptions:

(1) The interaction of the colliding nucleons in the final state is sufficiently large to give the meson the maximum available energy. From this it follows that the density of states is proportional to $\sqrt{T_M}$. Here T_M is the maximum energy available to the created meson in the center-of-mass system of the two colliding nucleons.

(2) The matrix elements for meson production in $p-p$ collisions are energy dependent, being proportional to $\sqrt{T_M}$ (type B), or to T_M (type C).

Assumption 2 is based upon analysis of the excitation function for meson production by protons in hydrogen.[1] Assumption 1 is consistent with the experimental evidence obtained from the spectral shape of mesons produced by protons in hydrogen.[6] It is also similar to the hypothesis used by the authors in interpreting the heavy element meson production spectra.[1]

The calculated 90° π^+ meson spectrum in deuterium was obtained by using the $p-p$ cross sections implied in assumptions (1) and (2) above, and summing over the deuterium momentum distribution derived from a Fourier transform of the deuteron ground-state wave function of the form $e^{-\alpha r}/r$. The calculations took into consideration the recoil of the third nucleon present in the collision. Two types of angular distribution were considered for the created mesons in the c.m. system, isotropic (type I) and $\cos^2\theta$ (type II).

The theoretical curves for the π^+ meson spectra from deuterium, labeled to indicate the energy and angular dependence used in each calculation and normalized to give the observed 90° cross section, are plotted in Fig. 2. Within the limited statistical accuracy of the data, the calculations are in agreement with experiment with regard to the shape and position of the maximum of the spectrum.

These calculations indicate that the proton in the deuteron has a cross section 2.2 (CI), 1.7 (CII), 1.6 (BI), 1.2 (BII) times that of a free proton for π^+ production by protons at 381 Mev. The experimentally determined 90° π^+ cross section from deuterium is (5.6±2.3) times that of the free proton cross section at 381 Mev. Therefore, unless further experiments, now in progress, show this ratio to be near the lower statistical limit given above, it is clear that it will require an excitation function of meson production greater than the $\sqrt{T_M}$ or T_M matrix element dependence used in the above calculations, or thought necessary from experiments on meson production in hydrogen, to explain the large π^+ production ratio of deuterium to hydrogen. Another possibility is that the assumption of an impulse approximation in treating the two nucleons in deuterium as independent particles for the purpose of meson production may be in error; perhaps the interaction of the proton with the deuteron as a whole must be considered. However, in this latter possibility the reaction $p+D\rightarrow T+\pi^+$ might be appreciable, with the resulting mesons coming off in a line spectrum at about 85 Mev in our experiment. No such "tritium" meson peak at the high energy end of the spectrum was observed.

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† Now at Duke University, Durham, North Carolina.
[1] Block, Passman, and Havens, Phys. Rev. 83, 167, 205 (1951).
[2] The deuterated paraffin was prepared by the Texas Oil Company, which gave a composition of (97.2±2) percent deuterium. A spectroscopic analysis of the sample used in the experiment was made by Professor T. I. Taylor of the Columbia University Chemistry Department, and he found a composition of (96±2) percent deuterium.
[3] G. Chew, Phys. Rev. 80, 196 (1950).
[4] Professor G. Bernardini has kindly informed us that his latest experiments indicate that π^- mesons interact more strongly with matter than do π^+ mesons of the same energy. Since this experiment involves a slowing down of the $\pi^\pm$ mesons in Cu absorbers, this asymmetry in nuclear interactions must be taken into account. However, the total correction factor for a geometrical nuclear absorption cross section, as previously applied, amounts to < a 25 percent increment to the total production cross section, so that the large (π^+/π^-) production ratio from D reported above is not significantly altered by the quoted results.
[5] In a more detailed theoretical analysis of the production of mesons in deuterium, H. P. Noyes [Phys. Rev. 81, 924 (1951)] indicates that the (π^+/π^-) ratio at 0° to a 345-Mev proton beam could be as large as 8.2 because of the above-mentioned effects.
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Three-Quantum Annihilation and Positronium*

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THE three-quantum annihilation of positrons and electrons in the triplet state has been studied theoretically by Ore and Powell,[1] among others, and experimentally by Rich;[2] the work of Deutsch on positronium[3] is closely related to this effect, and can be considered an implicit proof of its existence. With the present experiment we have directly detected the three γ-rays of annihilation by means of a triple coincidence method.

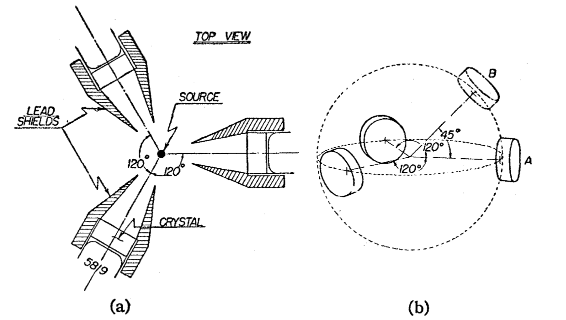

FIG. 1. Arrangement of the three counters for the detection of three-quantum annihilation.

The apparatus is shown in Fig. 1. The source used was Na^{22}. The three scintillation counters (5819 photomultipliers and NaI(Tl) crystals 4 cm in diameter and 2.5 cm thick) subtended solid angles $\Omega/4\pi=8\times10^{-3}$. They were connected to differential pulse-height selectors (*DPHS*) and to a first coincidence circuit of 10^{-7} sec resolving time. The outputs from the three *DPHS*'s and from the first coincidence circuit were connected to another quadruple coincidence circuit of $\sim2\times10^{-6}$ sec resolving time. The experiment consisted of measurements of coincidence rate with the counters coplanar with the source [A, Fig. 1(b)] and measurements of background with one of the counters rotated 45° out of this plane [B, Fig. 1(b)]. The bands accepted by the pulse height selectors were varied for a study of the energy of the coincident rays.

In a first experiment the positrons from a source of about 10^6 disintegrations/sec were allowed to stop in a solid. With the *DPHS*'s set to accept electron pulses of energy between 150 and 500 kev, the following counting rates were observed:

Counters coplanar	2.42±0.14 counts/min
Counters not coplanar	1.37±0.14 counts/min
Difference	1.05±0.19 counts/min

It seems difficult to account for this difference in any other way than by three-quantum annihilation. The magnitude of the effect agrees within a factor 2 with the theoretical expectation of one triplet annihilation per 370 singlet annihilations; however, our knowledge of counter efficiency and source strength is at present too poor for a more quantitative comparison.

In order to verify the formation of positronium in freon, as shown by the beautiful experiments of Deutsch, a source of about the same strength was deposited on thin Al and placed at the center of a bell-shaped Al container 1.2 cm in radius. The container was filled with freon 12 (dichlorodifluoromethane) at six

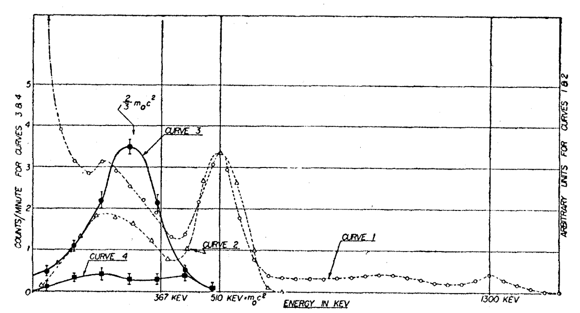

FIG. 2. Pulse-height distributions: (1) single counts from Na^{22}; (2) coincident pulses from two-quantum annihilation; (3) coincident pulses from three-quantum annihilation; (4) background for three-quantum annihilation.