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 (*C*I), 1.7 (*C*II), 1.6 (*B*I), 1.2 (*B*II) 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 $p+\mathrm{D}\rightarrow\mathrm{T}+\pi^+$ 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.

* This work was assisted by the joint program of the ONR and AEC.
† 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.
[6] F. Cartwright, Ph.D. thesis, University of California Radiation Laboratory Report No. 1278 (1951).

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.

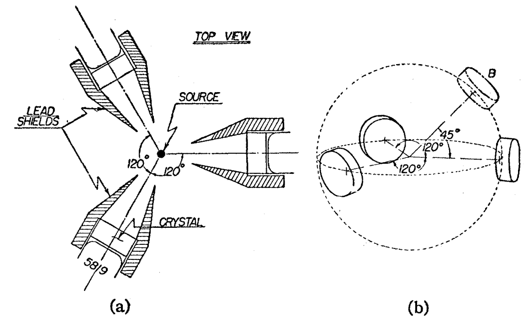

FIG. 1. Arrangement of the three counters for the detection of three-quantum annihilation.

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

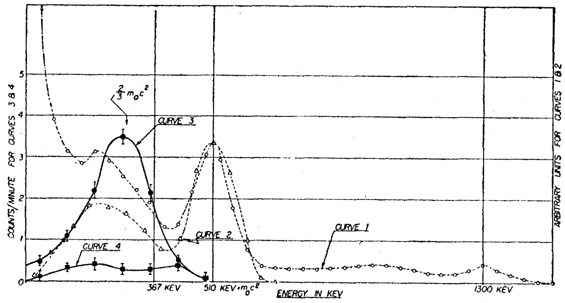

FIG. 2. Pulse-height distributions: (1) single counts from Na^{22}; (2) coincident pulses from two-quantum annihilation; (3) coincident pulses from three-quantum annihilation; (4) background for three-quantum annihilation.

atmospheres pressure. With this source the counting rates observed were as follows:

Counters coplanar	11.85 ±0.43 counts/min
Counters not coplanar	1.33 ±0.15 counts/min
Difference	10.52 ±0.46 counts/min

The tenfold increase of the effect confirms the stability of positronium in freon.

Finally, Fig. 2 shows the results of the study of pulse-height distribution. Curve 1 shows the distribution of pulses from a single counter exposed to the γ-radiation from a source of Na^{22}. The photopeaks of the 1.3-Mev nuclear γ-ray and of the 0.510-Mev annihilation line are used to calibrate the *DPHS* scale; another calibration point is provided by the position of the photopeak of the 0.367-Mev γ-rays from I^{131}.

Curve 2 was obtained with a double coincidence arrangement responding to two-quantum annihilation; it shows the pulse-height distribution of the coincident pulses from one of the two counters. It is evident that only the effect of the mc^2 γ-rays is present here. Curve 3 was obtained with the triple coincidence setup of Fig. 1 responding to the triplet annihilation of the source in freon, and shows the distribution of the coincident pulses in any one of the three counters. The single peak at $\frac{2}{3}$ mc^2 is further evidence for the three-quantum effect. Curve 4 is the corresponding background measured as described above.

Further studies of the effect in solids and gases are in progress.

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† AEC Predoctoral Fellow.
1 A. Ore and J. L. Powell, Phys. Rev. **75**, 1696 (1949).
2 J. A. Rich, Phys. Rev. **81**, 140 (1951).
3 M. Deutsch, Phys. Rev. **82**, 455 (1951); Phys. Rev. **83**, 866 (1951); M. Deutsch and E. Dulit, Phys. Rev. **84**, 601 (1951).

Negative Ion Formation in Oxygen*

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We have made measurements of ionization currents in O_2 which clarify certain points in connection with the Townsend coefficient and the attachment cross section in this gas. These measurements used plane-parallel electrodes separated as far as 40 mm and pressures from 11 to 40 mm of Hg in a range of E/p from 27.5 to 75 volts/cm/mm. Plotting, in the conventional way, log i against electrode separation, we find at each pressure a family of curves markedly different from the ordinary. Although the initial slope of such graphs has been reported as strictly linear for all gases investigated previously[1,2] we find O_2 exhibits an initial curvature followed by a more or less linear portion. The initial curvature becomes less prominent as E/p increases and is imperceptible for $E/p > 65$ at these pressures. We have observed similar curves in another gas, CF_3SF_5,[3] but will confine this discussion to the case of O_2. To check our apparatus we made careful measurements in H_2 but found no trace of a departure from linearity.

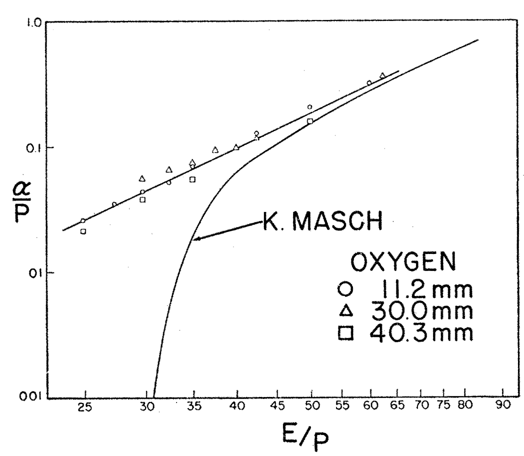

Fig. 1. Values of ionization coefficient α/p *vs* E/p in O_2 given by Masch (see reference 4) compared with those of the present experiment.

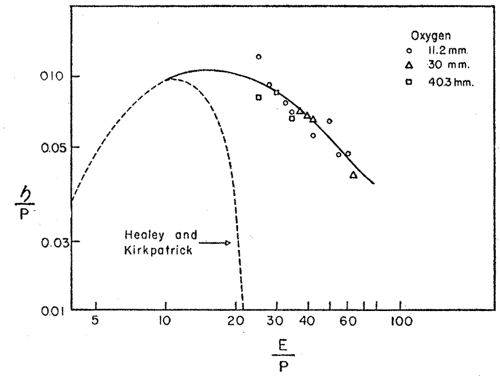

Fig. 2. Values of attachment probability η/p in O_2 given by Healey and Kirkpatrick (see reference 6) compared with those of the present experiment.

If ionization occurs in the gas at the mean rate α per cm and attachment forms negative ions (O_2^- and/or O^-) at the mean rate η per cm, the steady-state current is given by

$$i = i_0[\alpha \exp(\alpha-\eta)\delta - \eta]/[\alpha-\eta],$$

where δ is the plate separation and i_0 is the photoelectric current liberated at the cathode by an external source. This equation can be fitted closely to our experimental points. The process of curve-fitting on a basis of the foregoing assumptions yields values of both α/p and η/p.

The only published data with which to compare the present values of α/p are those of Masch[4] reproduced in Fig. 1. Masch attributed the rapid drop below $E/p \sim 40$ to attachment but did not attempt to analyze its effect. It can be seen from Fig. 1 that if due allowance is made for attachment in computing α/p, this drop, which does not appear in other gases, is not found in O_2.

Attachment probabilities in O_2 have been measured by Bradbury[5] and Healey and Kirkpatrick.[6] The curves submitted by these authors are similar in shape but differ by a factor of about 2 in magnitude. It is likely that this discrepancy arises only from differences in the values of drift velocity used to compute probabilities from the directly measured values of η/p. Figure 2 shows the values of η/p quoted by Healey and Kirkpatrick, which therefore are probably close to those (not quoted directly) found

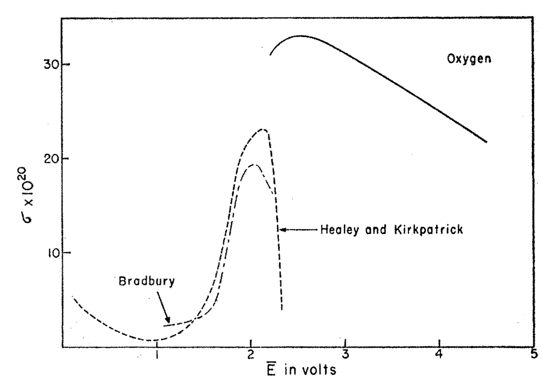

Fig. 3. Attachment cross section *vs* mean electron energy. Dashed curve—Healey and Kirkpatrick; dot-dashed curve—Bradbury; solid curve—present results computed from our η/p using thermal and drift velocities of Healey and Kirkpatrick.