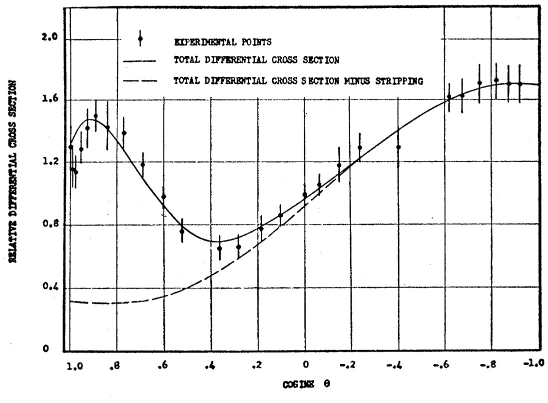

FIG. 1. Comparison of long range proton differential cross section from $Be^9(d, p)Be^{10}$ with calculated stripping curve for $l_n = 1$.

are such unusually large ratios of the matrix elements to compensate for the decreased penetrability of the necessary higher orbital angular momenta can be avoided by considering the possibility of a stripping process for the deuteron. In a stripping process neither the incoming deuteron nor the outgoing proton need penetrate as far into the potential barrier, and higher orbital angular momenta can participate.

The angular distribution of the protons from a deuteron stripping process has been calculated by Butler[3] neglecting the effects of the Coulomb potential. The distribution obtained depends, in addition to the energies involved, on the angular momentum l_n which the absorbed neutron adds to the initial nucleus. The alpha-particle model for the Be nuclei under consideration has recently been discussed by Haefner,[4] and provides the assumption that the angular momentum quantum number of the additional neutron which is added to Be^9 to give Be^{10} in this reaction must be 1, since this, together with the neutron spin, provides for the change from spin 3/2 to 0 and for the parity change. Calculation of the proton angular distribution curves by Butler's methods for the values of the energy and Q involved, and for $l_n = 1$, gives curves which have a characteristic maximum at a small forward angle and agree well with the initial peak observed in the curves obtained by Canavan. Using an arbitrary constant multiplicative factor the calculated stripping curve can be subtracted from the experimental points and the resulting smooth remainder curve shows a marked decrease in complexity from the sixth to the fourth power of the cosine. Figure 1 shows a comparison between the curve obtained by adding the calculated stripping curve to the smoothed-out remainder curve, designated as Total Differential Cross Section, and the experimental points. The agreement is good and it may be noted that the maximum of the experimental curve is shifted towards larger angles by a few degrees.

A recent investigation of the same reaction by Black[5] at much higher energies confirms the result that the angular momentum quantum number of the added neutron is 1 and also shows a shift between the calculated and observed maxima which may be interpreted as the effect of the Coulomb repulsion neglected in the calculations. It may, therefore, be concluded that the forward peak observed in the angular distributions even at low energies is due to the stripping reaction and that the remaining curve, which represents a sum of a term referring only to compound nucleus formation and one due to interference between compound nucleus formation and stripping, is lowered in complexity and therefore not as severely affected by penetrability difficulties.

---

[1] F. L. Canavan, S. J., thesis, Catholic University of America (1952); Phys. Rev. **87**, 136 (1952).
[2] L. Diesendruck, thesis, Johns Hopkins University (1950); C. N. Yang, Phys. Rev. **74**, 764 (1948).
[3] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951).
[4] R. R. Haefner, Revs. Modern Phys. **23**, 228 (1951).
[5] C. F. Black, Phys. Rev. **87**, 205 (1952). The value $l_n = 0$ for the ground state of the $Be^9(d, p)Be^{10}$ reaction given in this abstract is a misprint. Private communication confirms that $l_n = 1$ is the correct result.

Neutrons from Deuteron Bombardment of N^{14}†

WILLIAM B. ROSE AND EMMETT L. HUDSPETH,
University of Texas, Austin, Texas,
AND
N. P. HEYDENBURG,
Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.

(Received May 12, 1952)

THE neutron spectrum from the reaction $N^{14}(d, n)O^{15}$ has been recently studied by Gibson and Livesey,[1] who found only one group of neutrons from this reaction at a bombarding energy of 930 kev. Earlier work[2,3] had led to the conclusion that two groups of neutrons were emitted in this reaction, corresponding to Q-values of 5.1 and 1.1 Mev. Subsequently, it was concluded by Hudspeth and Swann[4] that the low energy group reported by them was actually produced by deuteron bombardment of aluminum, and the neutrons from $N^{14}(d, n)O^{15}$ were found to be associated with only one Q-value for Q greater than a few tenths of a Mev. The value of this reaction as a source of neutrons intermediate in energy to those produced in the $d-d$ and $d-t$ reactions has been emphasized.[5]

We have now made a more complete study of this reaction, utilizing the statitron at the Carnegie Institution of Washington. Targets of NH_4NO_3 of thickness about 300 kev were bombarded with deuterons for approximately 15,000 microcoulombs at 1.7 Mev. The neutrons produced in the reaction were recorded in Ilford C-2 photographic emulsions, which were placed at 0° and at 90° to the bombarding beam. The plates were developed and analyzed with a microscope in the conventional manner; all recoil proton tracks within 12° of the direction of the neutrons emitted by the target were counted. Corrections were applied for the variation of the $n-p$ cross section with energy, for the probability that tracks remain in the emulsion over their entire lengths, and for inverse square decrease of track density with distance from target. The resulting data are shown in Fig. 1. The errors indicated are probable errors based on number of tracks observed in the corresponding energy interval.

It is believed that two groups of neutrons were observed at our bombarding energy which may be ascribed to $N^{14}(d, n)$. These correspond to Q-values of approximately 5.1 and 0.2 Mev, indicating an excited state in O^{15} at approximately 4.9 Mev. (The lowest excited level in the mirror nucleus N^{15} is at 5.5 Mev.) The low energy group which we found would not have been observed by Gibson and Livesey[1] at their bombarding voltage.

The lowest energy group found at both 0° and 90° is thought to come from the reaction $C^{12}(d, n)$, since this is the expected energy of the neutrons from this reaction and since carbon is apparently a universal contaminant in such systems. In a separate experiment, we checked this point by bombarding a pure carbon target of known thickness and observing the density of recoil proton

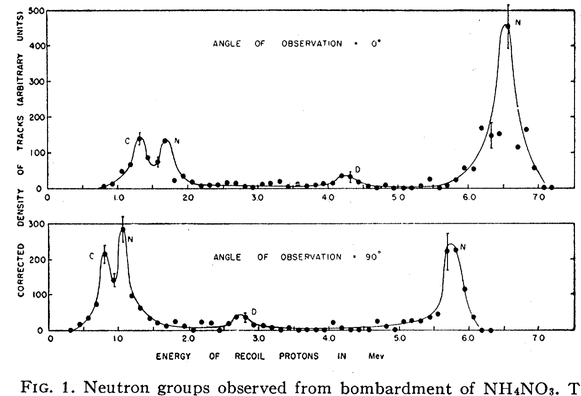

FIG. 1. Neutron groups observed from bombardment of NH_4NO_3. The groups marked C, N, and D are thought to arise from $d-n$ reactions in carbon, nitrogen, and deuterium, respectively.

tracks produced in photographic plates; the N^{13} activity of the bombarded target was also quantitatively followed. When targets of NH_4NO_3 were bombarded, the N^{13} activity (produced by bombardment of carbon contaminant) was again followed. The activity found in the latter case was in satisfactory correspondence to the density of the proton recoil tracks in the lowest energy group shown at 0° and at 90° in Fig. 1. We therefore conclude that our assumptions are correct regarding carbon.

A group of tracks was also observed with maximum energy of 4.5 Mev in plates placed at 0° and at approximately 3.0 Mev in plates at 90°. These apparently represent neutrons which come from the $d-d$ reaction. A deuterium target is of course built up during bombardment, but absorption of deuterium on the surface of the silver plate is probably more important. The "effective bombarding voltage" can be computed by assuming the 4.5-Mev group in the 0° plate does arise from $d-d$; this implies an effective bombarding voltage of 1.3 Mev (which is nearly equal to our bombarding voltage less the target thickness). Using this value, one may compute the energy of the neutrons from $d-d$ which should be observed at 90°; this is 2.8 Mev, in satisfactory agreement with our observations at this angle. The error associated with the number of tracks which we observed in this region make angular distribution comparisons of little value.

We conclude that the Q-values associated with $N^{14}(d, n)$ are 5.1 and 0.2 Mev, and that no other Q-value which leads to neutron yields of more than about 5 percent of the yield corresponding to $Q=5.1$ Mev is present.

Frequent changing of the easily prepared NH_4NO_3 targets would probably enable one to reduce considerably the neutron yield from both carbon and deuterium. Further studies regarding yield and angular distribution are planned with the statitron at the University of Texas.

† Assisted by the AEC.

[1] W. M. Gibson and D. L. Livesey, Proc. Phys. Soc. (London) 60, 523 (1948).

[2] Stephens, Djanab, and Bonner, Phys. Rev. 52, 1079 (1937).

[3] E. L. Hudspeth and C. P. Swann, Phys. Rev. 76, 464 (1949).

[4] Unpublished progress report from Bartol Research Foundation to ONR (1949).

[5] Hanson, Taschek, and Williams, Revs. Modern Phys. 21, 635 (1949).

The Reactions $p+d\rightarrow\pi^++H^3$ and $p+d\rightarrow\pi^0+He^3$†

M. Ruderman
Radiation Laboratory, Department of Physics, University of California, Berkeley, California

(Received June 2, 1952)

THE production of positive and neutral mesons from the bombardment of deuterons by protons is a sensitive test of the charge independence hypothesis.

The isotopic spin of a nucleon (p, n) is 1/2; that of the meson (π^+, π^0, π^-) is 1. Charge independence is the assumption that the total isotopic spin is conserved so that all matrix elements are invariant to rotations in isotopic spin space. An immediate consequence is the charge independence of nuclear forces. Further consequences have been derived by various authors.[1]

The total isotopic spin of a deuteron is 0. Therefore, the initial state $p+d$ is $(J=\frac{1}{2}, m=\frac{1}{2})\equiv W_{\frac{1}{2}}^{\frac{1}{2}}$. For the reaction $p+d\rightarrow$deuteron (T_0^0)+nucleon $(U_{\frac{1}{2}}^{\alpha})$+meson (V_1^{β}), in order that the final state transforms like $W_{\frac{1}{2}}^{\frac{1}{2}}$, we have

$$W_{\frac{1}{2}}^{\frac{1}{2}}\rightarrow T_0^0(\sqrt{\tfrac{2}{3}}U_{\frac{1}{2}}^{-\frac{1}{2}}V_1^1+\sqrt{\tfrac{1}{3}}U_{\frac{1}{2}}^{\frac{1}{2}}V_1^0). \tag{1}$$

It follows that (as has been pointed out by Garwin[2])

$$d\sigma(p+d\rightarrow p+d+\pi^0)/d\sigma(p+d\rightarrow n+d+\pi^+)=1/2. \tag{2}$$

The isotopic spin of (H^3, He^3) is assumed to be 1/2, which is the same as the (p, d) system. Consequently,[3]

$$d\sigma(p+d\rightarrow He^3+\pi^0)/d\sigma(p+d\rightarrow H^3+\pi^+)=1/2. \tag{3}$$

A measurement of the ratio (3), which involves the ratio of H^3 to He^3 at any energy and angle, seems more feasible.

The cross section and angular distribution for the reactions (3) involve a more detailed description of meson production than is available at present. The gross features can be extracted from the known cross section for $p+p\rightarrow\pi^++d$. The smallness of the π^- yield from $p+d$ at 90°[4] and $p+C$ at 0°[5] implies that almost all of the π^+ production in $p-d$ collisions arises from $p-p$ rather than $p-n$ interactions.

With 345-Mev incident protons the π-meson will have 90 Mev in the center-of-mass system, and the triton will have 15 Mev. The exchange of momentum between the two protons engaged in the meson production will be about two times as large as the relative momentum between the two deuterium nucleons. This is because a triton will be produced only when, in the center-of-mass system, the incident and struck protons have roughtly opposite momenta, while the neutron that does not participate in the collision directly is almost at rest. The differences in the momentum transfer and hence in distance of approach imply that the incident proton interacts more strongly with the proton of deuterium than either proton interacts with the neutron. Since the final proton and neutron of the triton that participated directly in the production are so close, we can approximate the relevant triton wave function in terms of the deuteron wave function:

$$\psi_T\left(x_1-x_2, x_3-\frac{x_1+x_2}{2}\right)\sim\frac{\psi_D(x_1-x_2)}{\psi_D(0)}\psi_T(0, x_3-x_1), \tag{4}$$

where 1 and 3 are neutron coordinates. ψ_T is chosen appropriately antisymmetrized in spin and space coordinates 1, 3 in accordance with the exclusion principle. The ratio

$$\psi_T(0, x)/\psi_D(0)$$

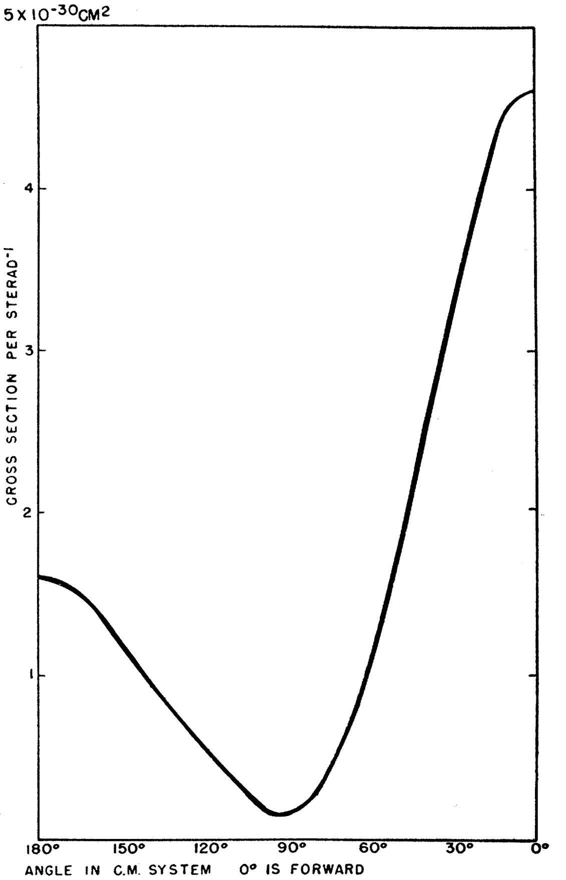

FIG. 1. Differential cross section for meson in the center-of-mass system for $p+d\rightarrow H^3+\pi^+$ with 345-Mev incident protons.