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.

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

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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

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

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

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

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]

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

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:

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

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

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

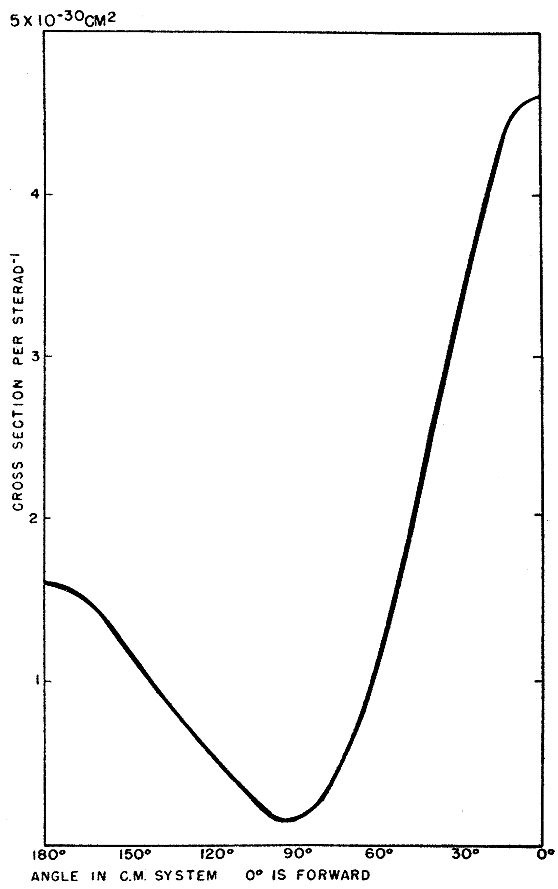

Fig. 1. Differential cross section for meson in the center-of-mass system for $p+d\rightarrow H^3+\pi^+$ with 345-Mev incident protons.

should be evaluated for d-states between 1 and 2 since the predominantly $\cos^2\theta$ angular distribution from the $(p+p\rightarrow\pi^++d)$ interaction shows that the final nucleons are mostly in d-states. In the calculations, s-state wave functions were used for simplicity in view of the crude nature of other approximations.

If one assumes that the deuterium neutron does not influence the production except for the momentum distribution it gives to the deuterium proton[6] and the interactions among the three nucleons in a triton, the cross section $\frac{d\sigma}{d\Omega}(p+d\rightarrow H^3+\pi^+)$ can be estimated in terms of $\frac{d\sigma}{d\Omega}(p+p\rightarrow\pi^++D)$ as

$$\frac{1}{3v_{PD}}\left|\int d\mathbf{x}\frac{\psi_T(0,x)}{\psi_D(0)}\exp\left[i\left(\frac{\mathbf{k}}{2}-\frac{\mathbf{q}}{3}\right)\cdot\mathbf{x}\right]\psi_D(x)\right|^2\frac{E_T}{E_\pi+E_T}\times\left[\frac{d\sigma}{d\Omega}(p+p\rightarrow\pi^++D)\frac{v_{PP}(E_\pi+E_D)}{E_D}\right]. \quad (5)$$

E is the total energy in the center-of-mass system including rest mass; $\mathbf{k}$ is the momentum of the incident proton in the center of mass system; $\mathbf{q}$ is the meson momentum. The quantities in the bracket are evaluated at that energy which gives mesons of momentum $\mathbf{q}$. The factor 1/3 arises from the various spin sums.

We choose for the spatial part of the wave functions:

$$\psi_D(r)=\frac{e^{-\beta r}-e^{-\gamma r}}{r}\left(\frac{\beta\gamma(\beta+\gamma)}{2\pi(\beta-\gamma)^2}\right)^{\frac{1}{2}} \quad (6)$$

and[7]

$$\psi_T(0,r)=(\alpha^3/8\pi)e^{-\alpha r}, \quad (7)$$

with $\gamma=6\beta$, $\beta=0.32/\lambda$, $\alpha=1.6/\lambda$, $\lambda=1.4\times10^{-13}$ cm.

The differential cross section in the center-of-mass system for 345-Mev incident protons is given in Fig. 1. $\sigma(p+p\rightarrow\pi^++D)$ for 90-Mev center-of-mass mesons was extrapolated from detailed balancing on lower energy π absorption[8] to be about $6.4(0.07+\cos^2\theta)\times10^{-28}$ cm^2 sterad^{-1}, which is 20 times $\sigma(p+p\rightarrow\pi^++D)$ for 345-Mev incident protons. Although this estimate is uncertain the very large increase of this cross section with meson energy, which is certainly present, makes $\sigma(p+d\rightarrow H^3+\pi^+)$ fairly large, approximately 1.3×10^{-29} cm^2.

† This work was performed under the auspices of the AEC.
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Some Observations on the Gamma-Radiation from Polonium

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THE gamma-radiation from polonium has been the object of a number of recent investigations,[1-5] but the present understanding of the situation is far from satisfactory. This is particularly so with regard to the soft radiation of energy about 80 kev, thought by Zajac *et al.*[2] to be nuclear in origin. Grace *et al.*[3] have recently found evidence that this component seems to be almost entirely the x-radiation of lead following the internal conversion of the well-established hard component at 800 kev, and have estimated the internal conversion coefficient by a study of the internal conversion electrons involved as being 6.7 percent.

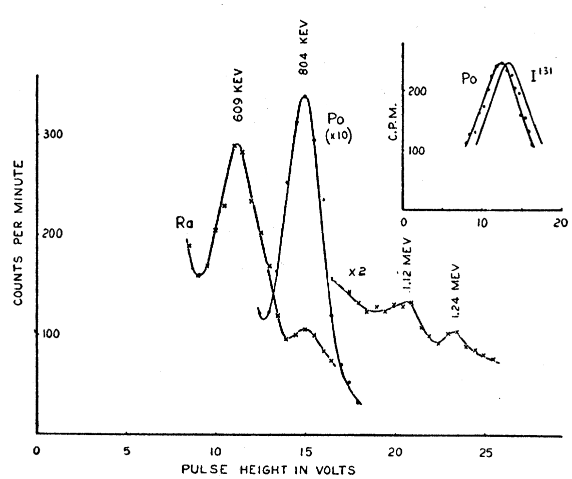

FIG. 1. Pulse-height distribution for the gamma-radiation from polonium 210.

With this interpretation the measurements of Zajac *et al.* would have given a value close to 100 percent. Further information comes from Alburger and Friedlander,[4] who investigated the secondary electrons with a beta-ray spectrometer and concluded that the conversion coefficient must lie in the range 1 to 5 percent. De Benedetti and Minton, as a result of alpha-gamma angular correlation experiments, have shown that the 800-kev component is probably $E2$, and thus imply that the conversion coefficient is less than 1 percent.

In an attempt to clarify this confusing situation certain observations have been made on the radiations involved, using a coincidence scintillation spectrometer and a weak source of polonium in solution from which all traces of Ra and RaD had been removed. Single channel pulse height distribution analysis (Fig. 1) gave a value of 804 ± 5 kev for the energy of the hard component, considerably above the Siegbahn value of 773 kev, but in excellent agreement with the Alburger and Friedlander value of 800 ± 6 kev obtained with a beta-ray spectrometer. Several standard gamma-ray energies were used for purposes of calibration, and the value of 804 kev is a mean for a number of experiments. The calibration source used for the Fig. 1 distribution was a Ra contaminated Po source, so that a residue of the Po line can be seen in the calibration curve. No evidence could be found to suggest the presence of any other component in the gamma-radiation from Po in the range 100 kev to 2 Mev.

Single channel analysis of the soft component failed to reveal any structure because of the limited resolution available at this energy in a scintillation spectrometer, but careful measurements relative to the I^{131} 80.1-kev gamma-ray gave an average energy of 77 ± 2 kev (see Fig. 1). This result is the mean of a number of determinations made with a five-channel kicksorter and also by means of the now conventional photographic storage methods employing a cathode-ray oscillograph. The value is not in disagreement with the observations of Grace *et al.*, for, although the mean energy is significantly above the value of 73 kev given by them for the main component, it agrees well with the conclusions of their critical absorption experiments that one-third of the radiation has an energy higher than 76.5 kev, and most of this is higher in energy than 78.6 kev. On the other hand, the value obtained in this investigation disagrees with the conclusion of Zajac *et al.* that no significant component of the soft radiation lies between 69.4 and 80.7 kev.

An estimate has been made of the intensity of the soft component relative to the hard component from a knowledge of the relative counting rates in the apparatus and the detection efficiencies for the two radiations. On the assumption that the soft component is entirely x-radiation following internal conversion of