output pulses from the multiplier obtained for the case of 47-Mev deuterons from Cu, the first peak being protons, the second, deuterons.

Particles of energy greater than 45 Mev were measured by placing absorbers in front of the two-crystal telescope. With absorber in place, the protons detected are of slightly different energy than the deuterons. To obtain the ratio for protons and deuterons of the same energy, the known[3,4] proton spectrum was used.

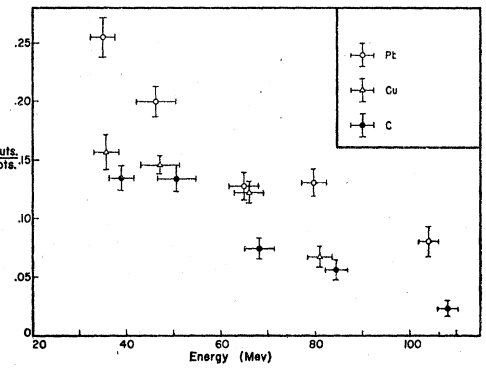

FIG. 3. The ratio of deuterons to protons produced by 310-Mev *bremsstrahlung* at 90° in the laboratory. The abscissa represents the energy of the product particles. The statistical errors are shown.

Figure 3 shows the ratio of the number of deuterons to protons per unit energy interval at various energies at 90° in the laboratory system. The A and Z dependence and the energy dependence of these ratios is suggestive of a (γ,n) or (γ,p) reaction followed by a pickup process.

* Work supported by the U. S. Office of Naval Research.
1 Wolfe, DeWire, and Silverman, 1953 Washington meeting of the American Physical Society [Phys. Rev. 91, 22 (1953)]. We are preparing a more detailed description of this apparatus for publication in *The Review of Scientific Instruments*.
2 It should be pointed out that if the product $E^{0.8}dE/dx$ were used, there would be no energy dependence.
3 C. Levinthal and A. Silverman, Phys. Rev. 82, 822 (1951).
4 J. C. Keck, Phys. Rev. 85, 410 (1952).

Elastic Photoproduction of π^0's from Deuterium*

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We have investigated the reaction $\gamma+D\rightarrow\pi^0+D$ for γ-ray energies between 250 Mev–300 Mev and π^0 mesons emitted at 90°–120° in the laboratory. Figure 1 shows the experimental arrangement. The deuteron detector is described in the previous letter.[1] The γ-ray counter detects one of the decay γ rays from the π^0. An event is recorded by a deuteron-γ-ray coincidence. Measurement of the energy and angle of the recoil deuteron determines the energy of the γ ray and the energy and angle of the π^0.

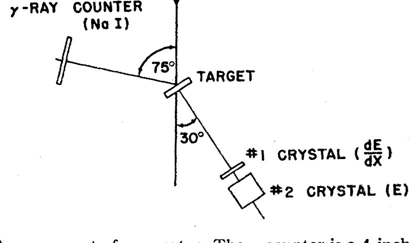

FIG. 1. Arrangement of apparatus. The γ counter is a 4-inch NaI crystal in front of which is placed a ¼-inch lead convertor and a 2-inch carbon absorber.

The experiment is performed by taking a D_2O-H_2O difference. The distribution of pulse heights from the multiplier[1] for both D_2O and H_2O are shown in Fig. 2. With the D_2O target, the distribution shows two peaks corresponding to protons and deuterons, whereas the results for H_2O show only a proton component.

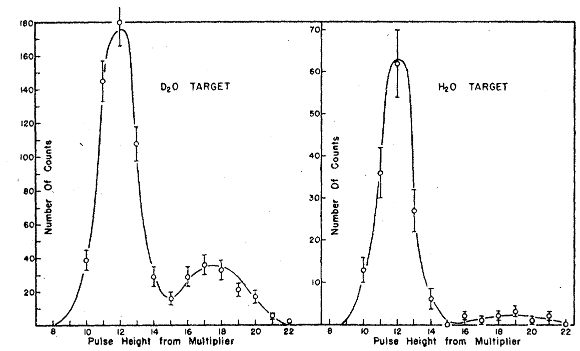

FIG. 2. Comparison of the multiplied pulse distribution for D_2O and H_2O targets, showing the large number of deuterons from D_2O. The D_2O run was for an integrated beam intensity of $7.63\times10''Q$ while the H_2O run was for $3.72\times10^{11}Q$.

Several auxiliary experiments were done to check that the observed deuterons were recoils from the reaction $\gamma+D\rightarrow\pi^0+D$. (a) A 0.040-in. Cu absorber was placed in front of the deuteron detector which was just sufficient to make the detector insensitive to the highest-energy deuteron expected from the reaction; (b) the deuteron detector was moved to 70° where no recoils from the above reaction can occur; (c) the maximum energy of the synchrotron was reduced to 250 Mev so that no deuteron could have sufficient energy to be recorded. In each of these experiments, the deuteron peak disappeared and there was no detectable D_2O-H_2O difference.

This reaction is of special interest because the cross section depends rather sensitively, through interference effects, on the relative sign of the neutron and proton π^0 coupling constants, g_p and g_n. There have been several calculations of this process using the impulse approximation.[2] All of these calculations arrive at approximately the same result and may be roughly summarized as follows: Where the impulse approximation is good, the cross section for the elastic production can be written as

$$\sigma_{\text{elastic}}=|A_n+A_p|^2|I(\mathbf{k}/2)|^2. \quad (1)$$

A_n is the amplitude for π^0 production from the neutron and A_p is the same for the proton. I is an integral that depends only on the wave function of the ground state deuteron and is written as

$$I(\mathbf{k}/2)=\int|\psi_D(\mathbf{R})|^2e^{i\mathbf{k}\cdot\mathbf{R}/2}d\mathbf{R}.$$

In the same approximation, the total cross section (elastic and inelastic) can be written as

$$\sigma_{\text{total}}=A_p^2+A_n^2+2\,\text{Re}(A_p^*A_n)I(\mathbf{k}/2). \quad (2)$$

For $I(\mathbf{k}/2)\ll1$,[3] the interference term can be neglected and the total cross is just the sum of the two free cross sections:

$$\sigma_{\text{total}}=A_p^2+A_n^2.$$

Measurements at this laboratory[4] and recently confirmed at Berkeley[5] show that

$$\sigma_{\text{total}}\text{ (deuterium)}/\sigma\text{ (hydrogen)}\approx2.$$

This implies that $A_p\approx A_n$.

Returning now to the elastic cross section [Eq. (1)] and setting $A_p = A_n$, we obtain $\sigma_{\text{elastic}} \approx 0$ for destructive interference ($g_n = +g_p$) and $\sigma_{\text{elastic}} \approx 4A_p^2 |I(\mathbf{k}/2)|^2$ for constructive interference ($g_p = -g_n$).[6] $I(\mathbf{k}/2)$ is evaluated by Chew and Lewis[2] using Hulthén functions for the ground state of the deuteron. Using their results and previously measured cross sections for hydrogen,[4,7] we obtain the calculated result:

$$\frac{d\sigma_{\text{elastic}}}{d\Omega}(\pi/2, E_\gamma = 275 \text{ Mev}) \approx 5 \times 10^{-30} \frac{\text{cm}^2}{\text{sterad}}.$$

The experimental result is $d\sigma/d\Omega = 3.5_{-1}^{+2} \times 10^{-30}$ cm^2/sterad for γ rays between 250–300 Mev. The error shown includes estimates of what we believe to be all the uncertainties involved in measuring the absolute cross section.

This result offers rather strong evidence that the neutron and proton are oppositely coupled to the $\pi^0 (g_p = -g_n)$ as required by the "symmetrical theory." The strength of this conclusion depends on the validity of the impulse approximation for this calculation. Chappalear and Brueckner[8] have recently attempted to evaluate the effect of multiple scattering. They find that the multiple scattering tends to reduce the difference between the two cases. However, the calculations are not yet complete and no quantitative information is yet available.

We are continuing this experiment in an attempt to measure the angular and energy dependence of this cross section.

* Work supported by the U. S. Office of Naval Research.
[1] DeWire, Silverman, and Wolfe, preceding Letter [Phys. Rev. 92, 519 (1953)].
[2] G. F. Chew and H. W. Lewis, Phys. Rev. 84, 779 (1951); N. C. Francis and R. F. Marshak, Phys. Rev. 85, 496 (1952); Heckrotte, Henrich, and Lepore, Phys. Rev. 85, 490 (1952); N. C. Francis, Phys. Rev. 89, 766 (1953).
[3] $I(\mathbf{k}/2)$ is in general small. It becomes comparable to unity only near threshold or in the extreme forward direction for the π^0. None of the experimental results correspond to either of these cases.
[4] G. Cocconi and A. Silverman, Phys. Rev. 88, 1230 (1952).
[5] W. K. H. Panofsky (private communication).
[6] More precise calculations by authors quoted in reference 2 show that the ratio of cross sections for the two cases may be of the order of 30:1 rather than ∞.
[7] A. Silverman and M. Stearns, Phys. Rev. 88, 1225 (1952).
[8] J. Chappalear and K. A. Brueckner (private communication).

Radioactive Copper Nuclides Produced by Slow Negative Pions and Muons from Zinc*

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ISOTOPES of copper are made when negative pions and muons are absorbed by zinc nuclei and only neutrons are emitted. Such events correspond to the "0-prong" stars in photographic emulsions that are a good fraction (~25 percent) of all slow π^--meson interactions with complex nuclei,[1] and are the predominant mode of interaction of slow μ^- mesons with nuclei.[2] This letter reports the preliminary results of the use of radiochemical methods to get more detailed information on such events.

Zinc, in the form of kilograms of zinc chloride, was exposed to magnetically analyzed 122-Mev negative pion beam of the University of Chicago synchrocyclotron.[3] This beam is contaminated[4] with several percent of 139-Mev negative muons. The copper radioactivities formed when the beam is stopped completely in the target were determined radiochemically. Under our conditions of irradiation and chemistry, the five species listed in Table I were identified.

TABLE I. Production of copper nuclei from zinc by 122-Mev π^- beam.

Half-life	Assignment	Relative yields[a] thick target	at pion range	at muon range
10 min	Cu^{58} or Cu^{59} and Cu^{62}	1.48	1.9	1.1
25 min	Cu^{60}	0.16	0.17	0.01
3.3 hr	Cu^{61}	0.62	0.80	0.2
12.8 hr	Cu^{64}	1.00	1.0	1.0
60 hr	Cu^{67}	0.22	0.10	0.6

[a] The observed activities with an end-window proportional counter were corrected for the background activity induced when the analyzing magnet was shut off and for the fraction of electron capture in the different nuclides.

The production of three of the copper nuclides (Cu^{61}, Cu^{64}, and Cu^{67}) in a 2-in. collimated beam of pions was studied as a function of depth of penetration into a 5-in.×5-in. target of zinc chloride. Figure 1 graphs the results. The production of all three nuclides

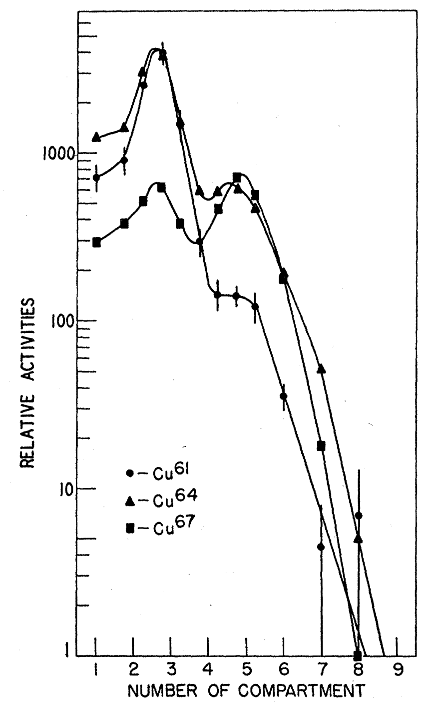

FIG. 1. Production of Cu^{61} (●), Cu^{64} (▲) and Cu^{67} (■) activities as a function of depth of penetration of a 122-Mev π^- beam (after 36.8 g/cm^2 of Cu initial absorber) into a $ZnCl_2$ target. Each compartment corresponds to approximately 6.2 g of $ZnCl_2$/cm^2.

is a maximum at the range of the pions (53 g/cm^2). In addition, there is a definite second maximum in the production of Cu^{67} and Cu^{64} at approximately the range of the muons (70 g/cm^2). The relative production of these three nuclides in the regions of the pion range and the muon range is also given in Table I.

On the assumption that all the stable zinc isotopes (Zn^{64}, Zn^{66}, and Zn^{68} compose 95 percent of the element) capture mesons equally and react in the same way, these data lead to the following conclusions:

1. The reaction $Zn(\mu^-; yn)Cu$ gives a different distribution of radioactive nuclides than does the corresponding reaction with pions. The data of column 5 of Table I, in particular, the very low yield of Cu^{60} and the relatively high yield of Cu^{67}, indicate a maximum probability for y a little greater than 1. This is in agreement with low neutron multiplicities observed[5] upon muon capture in elements near zinc.

2. The reaction $Zn(\pi^-; xn)Cu$ with slow pions has an apparent maximum probability at $x = 2-3$. A distribution with a maximum probability at $x = 5-6$ such as was found radiochemically in the reaction (π^-; p, xn) with bromine,[6] arsenic,[7] and iodine[8] and which is implied by the average neutron multiplicity upon π^- absorption in nuclei in this region of atomic number[9] is definitely excluded. The effect of the secondary neutrons born inside the target at the death of a π^- and contributing via (n; p, xn) reac-