# Gamma Radiation from Certain Nuclear Reactions*

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The gamma radiation from five nuclear reactions has been studied with a single NaI crystal. Three new resonances in the emission of 12-Mev radiation from the reaction $F^{19}(p,\gamma)Ne^{20}$ have been found at 1092-kev, 1324-kev, and 1431-kev bombarding energy. The widths are, respectively, <1.2 kev, 4.0 kev, and 15.7 kev, and the cross sections at resonance are >0.05 mb, 0.081 mb, and 0.19 mb, respectively. The first resonance corresponds to one in the reaction $F^{19}(p,\alpha\gamma)O^{16}$, whereas the last two do not. All the transitions are to the 1.63-Mev level in $Ne^{20}$ or to a nearby level. Possible values of the spin and parity of the excited levels in $Ne^{20}$ are discussed.

A search was made for gamma radiation from the bombardment of lithium by 650-kev deuterons. Upper limits for the production of 5-, 6-, and 7-Mev gamma rays are <2 mb, <1 mb, and <0.5 mb, respectively.

A search was made for the radiative capture of deuterons in the bombardment of deuterium, helium, and oxygen. No capture gamma rays were observed, and upper limits for the cross section for these reactions are: $D_2$, <0.05 $\mu$b at a deuteron energy of 1260 kev; He, <0.1 mb at 1055 kev; and $O_2$, <0.5 mb at 1100 kev.

## I. RADIATIVE CAPTURE OF PROTONS BY FLUORINE

### Introduction and Experimental Procedure

In the proton bombardment of fluorine, a likely mode of decay of the compound nucleus is by the reaction

$$F^{19}+p\rightarrow(Ne^{20*})\rightarrow O^{16}+\alpha. \quad (1)$$

An alternative though less likely reaction is radiative capture of the proton

$$F^{19}+p\rightarrow(Ne^{20*})\rightarrow Ne^{20}+\gamma. \quad (2)$$

Reaction (1) can leave the oxygen nucleus in the ground state, the pair-emitting state, or one of the three gamma-emitting states of excitation energy 6.13, 6.9, and 7.1 Mev. The resonances in the $(p,\alpha\gamma)$ reaction leading to these last three states and in the $(p,\alpha\pi)$ and $(p,\alpha)$ reactions have been the subject of careful study,[1–4] and considerable information concerning the levels in $Ne^{20}$ and $O^{16}$ is now available.[5] Recent work[6] has shown that the level in $Ne^{20}$ formed by incident protons of 669-kev energy decays by reaction (2) about 2 percent of the time. The observed decay[7] is not to the ground state but to the first excited state at 1.634 Mev.[8]

Reaction (2) has been studied in this laboratory, with protons accelerated by the Rice Institute 2-Mev Van de Graaff generator. The energy of the proton beam was measured with a 90° analyzing magnet, and the spread in beam energy was ~0.1 percent of the average proton energy. Targets, together with a blank for background readings, were mounted in a holder so designed that any one of five targets could be rotated into the beam without breaking the vacuum. A single NaI(Tl) crystal, $1\frac{1}{2}$ in. diam.×$1\frac{1}{2}$ in. long, was used as the gamma-ray detector and was placed at 0° to the proton beam. Figure 1, curve $A$, shows the differential pulse-height curve obtained with the scintillation spectrometer at the 669-kev resonance. The three gamma rays from reaction (1) are not resolved but appear as a single peak. The 12.1-Mev capture gamma ray appears as a second peak at slightly more than double the pulse height of the first. Excitation curves were then obtained for reactions (1) and (2) by counting the radiation from each reaction separately. The base line and channel width of the pulse-height analyzer were set to cover either the interval marked "high" or that marked "low"; the first interval counted the 12-Mev radiation whereas the second interval detected almost completely the radiation from the $(p,\alpha\gamma)$ reaction. It was necessary to keep the counting rate with the "low" interval below about 320 counts per second to avoid a pileup of counts in the high interval. This was done by placing the crystal further away from the target at the more intense $(p,\alpha\gamma)$ resonances.

A preliminary excitation curve covering the proton energy range 620 kev to 1650 kev detected the pressure of four resonances for the emission of 12-Mev gamma rays. Figures 2 and 3 show the detailed excitation curves obtained in the neighborhood of these resonances for radiative capture at 669 kev, 1092 kev, 1324 kev, and 1431 kev. Results in the region of the 1292-kev resonance (shown for comparison) and the other resonances for 6-Mev radiation showed no capture radiation. Each radiative capture resonance was detected with three different $ZnF_2$ targets, and data taken showed no evidence of target contamination. Differential pulse-

* This work was supported by the U. S. Atomic Energy Commission.
† Now with Westinghouse Research Laboratories, East Pittsburgh, Pennsylvania.
[1] Bennett, Bonner, Mandeville, and Watt, Phys. Rev. **70**, 882 (1946).
[2] T. W. Bonner and J. E. Evans, Phys. Rev. **73**, 666 (1948).
[3] Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).
[4] Willard, Blair, Kington, Hahn, Snyder, and Green, Phys. Rev. **85**, 849 (1952).
[5] J. Seed and A. P. French, Phys. Rev. **88**, 1007 (1952).
[6] S. Devons and H. G. Hereward, Nature **162**, 331 (1948).
[7] G. A. Jones and D. H. Wilkinson, Proc. Phys. Soc. (London) **A65**, 1055 (1952).
[8] Donahue, Jones, McElliston, and Richards, Phys. Rev. **89**, 824 (1953).

height curves were obtained at these radiative capture resonances and are shown in Fig. 1. All four curves show the 12-Mev gamma ray. Although the energy of the gamma ray was not measured too accurately, the transition in each case seems to be to the 1.63-Mev level or another level nearby but not to the ground state.

### Discussion of Results

The target thickness was taken equal to the experimental width of the very narrow resonance at 1092 kev.[9] The target used to obtain Figs. 2 and 3 was 3.7 kev thick at this energy. The thickness at other energies and the number of fluorine nuclei per $cm^2$ were calculated. The efficiency (effective solid angle times probability of a photon interacting in the NaI) of the scintillation spectrometer for 6- and 7-Mev radiation was calculated to be 0.0096, with the crystal 8 mm from the target. This was found from the observed counting rate at the 669-kev resonance and the calculated yield, using the value of $2.5\times10^{-26}$ $cm^2$ for the cross section at this energy.[2] The efficiency for detection of the 12-Mev gamma rays was then calculated from the latter by correcting for the greater probability of a 12-Mev photon scattering in the crystal and for the different fraction of the total number of pulses from the crystal that fell within the analyzer window. The yield of 12-Mev gamma rays relative to the yield of gamma rays following alpha emission could then be found from the observed counting rates at each resonance. The absolute cross sections for reaction (2) at the 669-kev and 1092-kev resonances were calculated from the known cross sections for reaction (1) at these energies.[2,9] The cross section in the neighborhood of the 1324-kev and 1431-kev resonances was described by a Breit-Wigner single level formula,[10] and the cross sections at resonance found from the observed widths and target thickness. This treatment assumes that the gamma radiation is emitted isotropically, which is known to be the case at the 669-kev resonance.[6,11] Table I lists the parameters of the four radiative capture resonances. The value of 1.8 percent found for the yield at the 669-kev resonance is in good agreement with the value of $1.72\pm0.25$ percent given by Carver and Wilkinson.[12]

TABLE I. Resonances in the reaction $F^{19}(p,\gamma)Ne^{20}$.

| Proton energy (kev) | Resonance width (kev) | Yield[a] (percent) | Cross section (mb) |
|---|---|---|---|
| 669 | 7.5 | 1.8 | 0.48 |
| 1092 | <1.2 | 1.3 | >0.05 |
| 1324 | 4.0 | >1.5 | 0.081 |
| 1431 | 15.7 | >1.5 | 0.19 |

[a] Yield of 12-Mev gamma radiation relative to yield of 6- and 7-Mev radiation at each resonance.

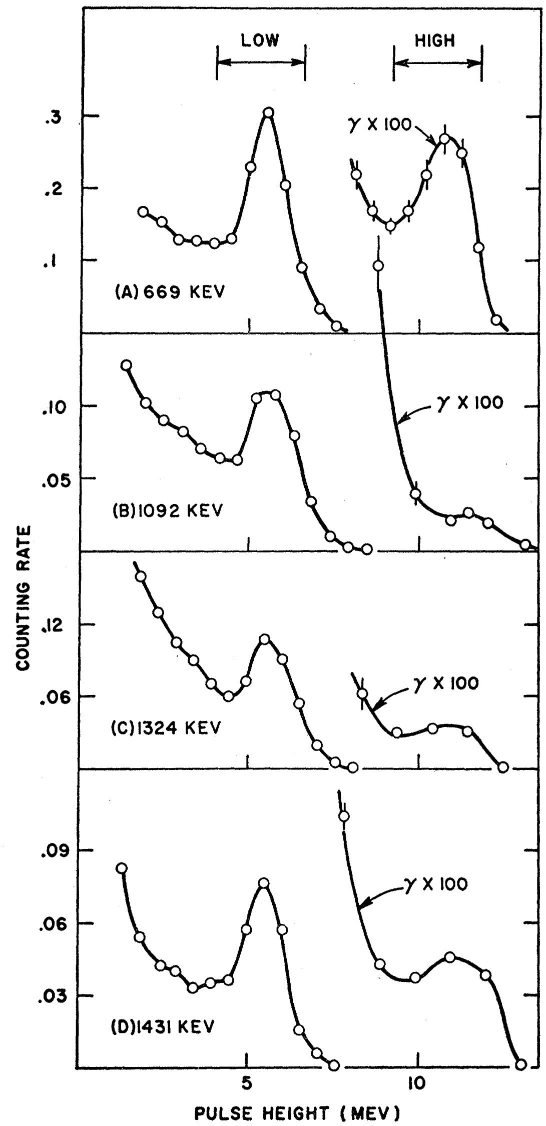


FIG. 1. Pulse-height distributions obtained at the four resonances for radiative capture of protons. Each curve is labeled with the corresponding proton energy.

No difference in the excitation curves for the two reactions was detected at the 669-kev resonance, confirming the work of other investigators.[5] It thus seems probable that the same level in $Ne^{20}$ is involved in both reactions. Since this level is (1,+),[5,13] the observed decay scheme is explainable in terms of an $M1$ transition to the (2,+) level at 1.634 Mev.[14] No reason is apparent why this transition is so much stronger than the $M1$ transition to the $Ne^{20}$ ground state or why other (1,+)

[9] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).
[10] G. Breit and E. P. Wigner, Phys. Rev. **49**, 519 (1936).
[11] S. Devons and M. G. N. Hine, Proc. Roy. Soc. (London) **A199**, 56 (1949).
[12] G. H. Carver and D. H. Wilkinson, Proc. Phys. Soc. (London) **A64**, 199 (1951).
[13] C. Y. Chao, Phys. Rev. **80**, 1635 (1950).
[14] J. Seed, Phil. Mag. **44**, 921 (1953).

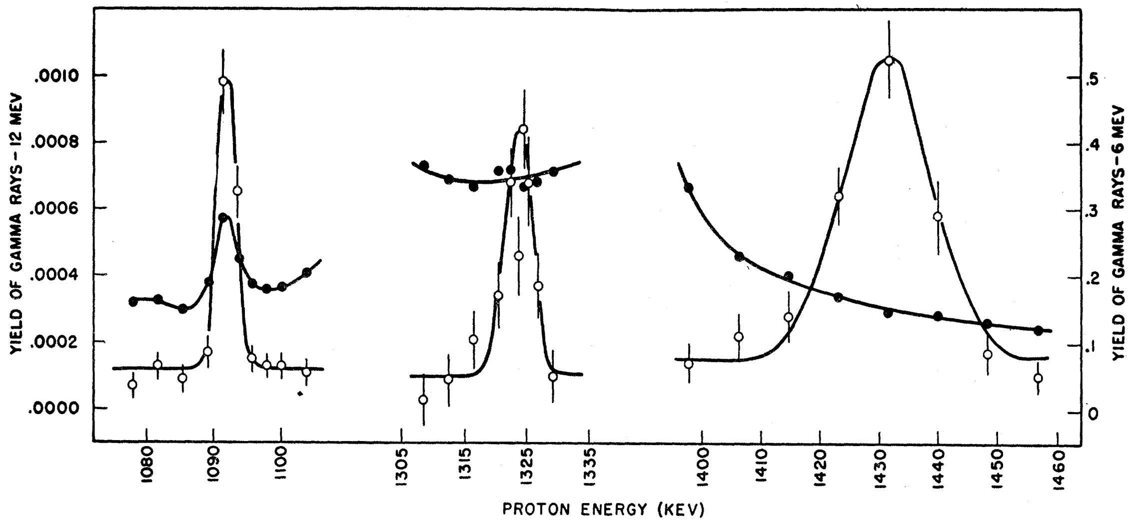


FIG. 2. Yield of 6-Mev gamma rays (solid circles) and 12-Mev gamma rays (open circles) as a function of the energy of the bombarding protons near the resonances at 1092 kev, 1324 kev, and 1431 kev.

levels formed at 340-kev and 935-kev bombarding energy[5] do not show a detectable emission of 12-Mev radiation.

No difference in the excitation curves was detected at the 1092-kev resonance; again, therefore, it seems likely that the same level is involved in both modes of decay. The calculations of Bonner and Evans[2] for this resonance predicted a high angular momentum for the incoming proton ($\sim$4) and emitted alpha particle ($\sim$4), assuming alpha emission is not strongly inhibited by the isotopic spin assignment $T=1$. These values would require a large value of $J$, the angular momentum of the compound nucleus. Since no resonance in the long-range alpha particles has been observed at this energy, we would expect the parity to be either even for odd $J$, or vice versa.[5] A possible assignment for the level formed at this resonance is $(5,+)$, $T=0$, this being the least value of $J$ that requires the alpha particles to the $(3,-)$ level in $O^{16}$ to carry off three units of angular momentum. If this assignment is correct, it is unlikely the transition to the ground state or to the 1.63-Mev state of $Ne^{20}$ would occur because of the high polarity order of the radiation. On the other hand, radiation to another level with $J\geqslant 4$ would be possible. There is evidence for a level in $Ne^{20}$ at 2.2 Mev,[15,16] and if, for example, it were a $(4,+)$ level, the gamma radiation would be magnetic dipole and might compete with alpha emission. This would be in keeping with the observed trend of even-even nuclei to have the first excited state $(2,+)$ and the second $(4,+)$.[17] If, however, the level formed by 1092-kev protons had $T=1$, $J$ might be much less than the value of five predicted above.

[15] C. F. Powell, Proc. Roy. Soc. (London) **A181**, 344 (1942).
[16] Heitler, May, and Powell, Proc. Roy. Soc. (London) **A190**, 180 (1947).
[17] G. Scharff-Goldhaber, Phys. Rev. **90**, 587 (1953).

The radiative capture resonances at 1324 kev and 1431 kev do not correspond to known $(p,\alpha\gamma)$ resonances; therefore, the yields of 12-Mev gamma rays given in Table I are lower limits which are calculated from the estimated height of a $(p,\alpha\gamma)$ resonance that would just escape detection. Since these lower limits for the percentage yields are comparable to the observed percentage yield of 12-Mev radiation at the 669-kev resonance, the possibility that weak resonances for alpha-emission occur cannot be ruled out. The alternative conclusion is that either or both of these levels in $Ne^{20}$ cannot emit an alpha particle. A possible assignment for such a level is $(0,-)$ which would forbid alpha emission to all states of $O^{16}$ as well as an electromagnetic transition to the ground state of $Ne^{20}$. An allowed decay would then be to the 1.63-Mev level, as observed. The observed width of 15.7 kev or 4.0 kev would then be equal to the proton width, which is compatible with the calculations of Christy and Latter[18] and Chao.[13]

## II. GAMMA RADIATION FROM DEUTERON BOMBARDMENT

### Deuteron Bombardment of Lithium

There is evidence the reaction $Li^7(d,n)Be^{8*}$ leaves the residual nucleus in several excited levels.[19–21] The purpose of the present experiment was to look for gamma emission from any such levels. A combination evaporator-target unit was used to prepare metallic lithium targets (natural isotopic mixture) in the accelerator vacuum system. All parts of the system

[18] R. F. Christy and R. Latter, Revs. Modern Phys. **20**, 185 (1948).
[19] H. T. Richards, Phys. Rev. **59**, 796 (1941).
[20] L. L. Green and W. M. Gibson, Proc. Phys. Soc. (London) **A62**, 407 (1949).
[21] W. D. Whitehead, Phys. Rev. **79**, 393 (1950).

struck by the beam were carefully cleaned of carbon and other deposits to reduce spurious sources of gamma radiation. The NaI crystal was placed 4.7 cm from the target, with 1.1 cm of graphite between crystal and target. This absorber, together with the thickness of the target unit, was just sufficient to stop the $Li^8$ beta rays. A deuteron energy of 650 kev was used to bombard targets about 64 kev thick. At this energy the cross section for the $Li^7(d,n)$ reaction has almost the maximum value obtainable over the available energy range,[22] whereas the 325-kev protons in the weak $HH^+$ beam will give little high-energy gamma radiation from the reaction $Li^7(p,\gamma)Be^8$ because of the low cross section for this reaction below the 440-kev (proton energy) resonance.[2]

Figure 4, Curve $A$, shows the pulse-height curve obtained with the crystal from the reaction Li+D. There is no indication of gamma radiation between widely separated states of $Be^8$, which would result in gamma rays of at most several discrete energies. The counting rate immediately after the beam was taken off the target indicated that no more than ~20 percent of the counts above 1.5 Mev were from the effects of 0.9-sec $Li^8$, and no more than ~0.9 percent of these counts were from the decay of 25-min $I^{128}$ produced by radiative capture of neutrons. The counts in the pulse-height range above 4 Mev can thus be ascribed almost completely to the interaction of neutrons in the crystal and to any gamma radiation from $Be^{8*}$. The most important means of interaction of the fast neutrons from Li+D will be inelastic scattering.[23] Curve $B$

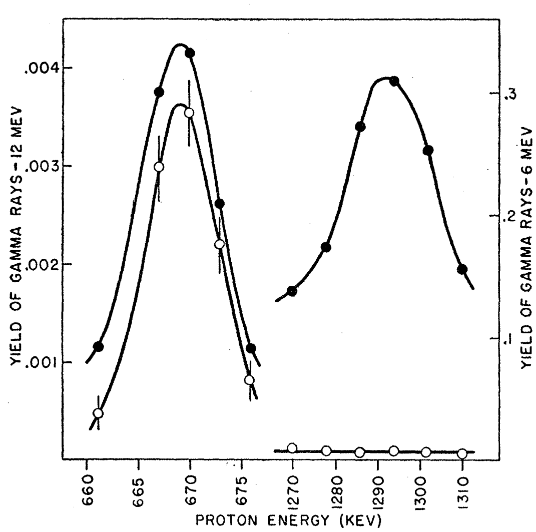


FIG. 3. Yield of 6-Mev gamma rays (solid circles) and 12-Mev gamma rays (open circles) as a function of the energy of the bombarding protons near the resonances at 669 kev and 1292 kev. The 1292-kev resonance for 6-Mev gamma rays is not accompanied by a detectable resonance for 12-Mev gamma rays.

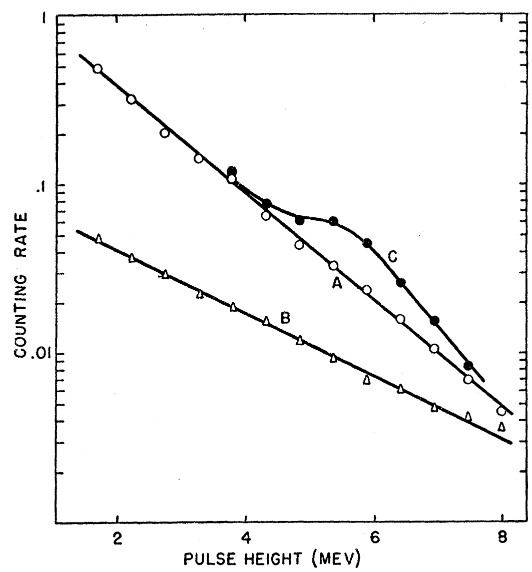


FIG. 4. Pulse-height distributions in the NaI crystal from products of the reaction Li+D (Curve $A$) and from 14-Mev neutrons (Curve $B$). Curve $C$ shows the addition to Curve $A$ of the pulse-height distribution from 6-Mev gamma radiation.

shows the pulse-height curve obtained by exposure of the crystal to a source of monoenergetic (14.1-Mev) $d$-T neutrons. The curve from Li+D has a similar shape but a steeper slope because of the proportionately larger number of low-energy pulses from the lower energy neutrons. Curve $C$ shows the addition to Curve $A$ of the pulse-height spectrum from 6-Mev gamma rays, and corresponds to an average cross section of 5 mb for the production of such gamma radiation. It was estimated that 20 percent of the deviation of Curve $C$ from Curve $A$ could be detected, setting an upper limit of 1 mb for the production of 6-Mev gamma rays. Similarly, upper limits of 2 mb and 0.5 mb can be sent for the production of 5- and 7-Mev gamma rays, respectively.

Earlier experiments[24] reported gamma radiation of 4.9±0.3 Mev, with a cross section of 14 mb for its production at 650 kev. It is now felt that these results were due to 4.47-Mev gamma radiation from $C^{12*}$, produced by the inelastic scattering of neutrons in the thick graphite absorber which was used.

### Radiative Capture of Deuterons

The deuteron beam was admitted to a gas target through a 0.0001-in. nickel foil. The NaI crystal was placed at 90° to the beam, subtending a solid angle of about 1.4 steradians. Bombardment of a 60-kev thick deuterium gas target with 1260-kev deuterons (energy at center of target) gave an upper limit of 0.05 μb for the production of 20-Mev gamma rays from the reaction

[22] L. M. Baggett and S. J. Bame, Phys. Rev. **85**, 434 (1952).

[23] *Neutron Cross Sections*, U. S. Atomic Energy Commission Report AECU-2040 (Office of Technical Services, Department of Commerce, Washington, D. C., 1952).

[24] Bennett, Bonner, Richards, and Watt, Phys. Rev. **59**, 904 (1941); **71**, 11 (1947).

$H^2(d,\gamma)He^4$, in agreement with the value of 0.1 μb obtained by Fowler *et al.*[25] at 1.2 Mev.

A 70-kev thick helium gas target was bombarded with 1055-kev deuterons (energy at center of target). This bombarding energy would form $Li^6$ in the first excited level at 2.187 Mev.[26] No gamma radiation was detected from this level, and an upper limit of 0.1 mb was sent on the cross section for the reaction $He^4(d,\gamma)Li^6$.

A 200-kev thick oxygen gas target was bombarded with 1100-kev deuterons (energy at center of target), the energy required to form $F^{18}$ in the 8.5-Mev excited state.[27] Again no capture gamma rays were detected, and an upper limit of 0.5 mb was set on the cross section for the reaction $O^{16}(d,\gamma)F^{18}$.

[25] Fowler, Lauritsen, and Tollestrup, Phys. Rev. **76**, 1767 (1949).
[26] Browne, Williamson, Craig, and Donahue, Phys. Rev. **83**, 179 (1951).
[27] G. Brubaker, Phys. Rev. **56**, 1181 (1939).

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# Charged Particles from the Interaction of 14-Mev Neutrons with $Li^6$ and $Li^7$†

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The angular distribution of the charged particles produced in the bombardment of $Li^6$ and $Li^7$ by 14-Mev neutrons was observed with nuclear emulsions in a multiplate camera. Metallic targets of enriched $Li^6$ and $Li^7$ were used. The following cross sections were measured: $Li^6(n,p)He^6$, 6±2 mb; $Li^6(n,d)He^5$, 89±10 mb; $Li^6(n,d)He^{5*}$, 77±9 mb; $Li^6(n,t)He^4$, 26±4 mb; $Li^7(n,t)He^5$, 55±8 mb. The reaction $Li^7(n,d)He^6$ was also observed but was not well enough resolved to give an angular distribution and total cross section. No evidence was found for the formation of $He^7$ by $Li^7(n,p)He^7$ with a cross section greater than 5 mb in the range $-1.0>Q>-7.0$ Mev. The angular distributions obtained for $Li^6(n,d)He^5$ and $Li^6(n,d)He^{5*}$ indicate these reactions proceed mainly by an inverse stripping or pick-up process. The energy spectrum of the neutrons from $Li^6(n,d)He^5(n)He^4$ and $Li^6(n,d)He^{5*}(n)He^4$ is calculated using several assumptions for the angular distribution of the $He^5$ disintegration.

## I. INTRODUCTION

THE interaction of neutrons with $Li^6$ has been studied by many investigators,[1] particularly for neutron energies of 2.5 Mev and below, where only the well-known $Li^6(n,t)He^4$ reaction is energetically possible. Recently Ribe[2] has measured this cross section as a function of energy from 0.88 to 14.2 Mev. Roberts and co-workers[3] have obtained the angular distribution of the tritons for energies up to 2 Mev using $Li^6$ loaded nuclear track plates. For the other charged particle reactions, Poole and Paul[4] used the formation of 0.8-sec $He^6$ to establish the $Li^6(n,p)He^6$ reaction for neutrons from 4 to 12 Mev. By the activation technique Battat and Ribe[5] measured the cross section for this reaction at 14.1 Mev as 6.7±0.8 mb. Also at 14 Mev Ribe[6] detected a comparatively large group of deuterons and obtained a value of ~200 mb for the cross section. For $Li^7$ the $Li^7(n,d)He^6$ process has been observed,[5] again by the activation of $He^6$, with a cross section at 14.1 Mev of 9.8±1.1 mb.

The present experiment was undertaken to determine the angular distributions of the various charged particle groups and their total cross sections at 14 Mev. The above reactions were observed, and angular distributions obtained except for $Li^7(n,d)He^6$. In addition tritons from $Li^7(n,t)He^5$ were found. The deuterons observed in the $Li^6$ experiment were established to be due to two broad groups, $Li^6(n,d)He^5$ and $Li^6(n,d)He^{5*}$. The deuteron angular distribution showed the mechanism to be predominately a pick-up process.[7]

† Work performed under the auspices of the U. S. Atomic Energy Commission.
[1] See F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952), and Hornyak, Lauritsen, Morrison, and Fowler, Revs. Modern Phys. **22**, 291 (1950) for complete references to the earlier work.
[2] F. L. Ribe, Phys. Rev. **91**, 462 (1953).
[3] Darlington, Haugsnes, Mann, and Roberts, Phys. Rev. **90**, 1049 (1953); J. H. Roberts (unpublished report).
[4] M. J. Poole and E. B. Paul, Nature **158**, 482 (1946).
[5] M. E. Battat and F. L. Ribe, Phys. Rev. **89**, 80 (1953).
[6] F. L. Ribe, Phys. Rev. **87**, 205 (1952) and private communication.

## II. EXPERIMENTAL PROCEDURE

### A. Multiplate Camera and Collimator

The experimental arrangement, shown in Fig. 1, was similar to that used previously by Allred, Armstrong, and Rosen[8] for *n-p* and *n-d* scattering. 14-Mev neutrons were furnished by the *d*-T reaction in which the 250-kev diatomic deuteron beam from the Los Alamos Cockcroft-Walton accelerator was used to bombard a tritium-zirconium target. The neutron flux was monitored by counting the accompanying alpha

[7] S. T. Butler, Proc. Roy. Soc. (London) **A208**, 559 (1951); S. T. Butler and E. E. Salpeter, Phys. Rev. **88**, 133 (1952).
[8] Allred, Armstrong, and Rosen, Phys. Rev. **91**, 90 (1953).