$T(p,\gamma)He^4$ Reaction*

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The $T(p,\gamma)He^4$ reaction has been studied over the proton energy range 0.1 to 6.2 Mev, by detecting the gamma rays with a sodium iodide scintillation counter. The 90° excitation function rises to a maximum in the region of 4 to 5 Mev and drops off slightly at higher energies. The angular distribution, measured at four energies, shows that in addition to the $\sin^2\theta$ distribution previously reported there is a small asymmetry about 90° of the form $\sin^2\theta\cos\theta$, which increases with proton bombarding energy. This asymmetry has been studied over the entire energy range. Absolute yield measurements of the reaction give a 90° differential cross section at 1 Mev at 3.65×10^{-30} cm² per steradian, which is considerably lower than has been previously reported.

I. INTRODUCTION

THE capture of protons by tritons to form He^4 leads to capture radiation with an energy above 19.8 Mev. The reaction cross section, the yield curve, and the angular distribution of the gamma rays are of interest. Theoretical interpretation of the experimental results should yield some information on the properties of the interaction states, and should give evidence on the radius of the alpha particle and its wave function.

Since the discovery[1] of this reaction several experiments covering various aspects of the reaction have appeared in the literature. Rochlin,[2] using a magnetic pair spectrometer, measured the energy of the gamma ray and stated that it was probably monoenergetic. However, other features of the reaction have been obscured by divergent experimental results. The shape of the yield curve as a function of proton energy has been in doubt.[1,3–6] There has been serious disagreement in the absolute cross section of the reaction,[1,2,4,7] and the angular distributions have been inconsistent.[1,4,7] The possibility of a narrow excited state[1] of He^4, as exhibited by this reaction, does appear to have been ruled out.[3,4,6]

An approach to predicting the characteristics of the $T(p,\gamma)$ reaction has been made by calculating the photodisintegration of He^4, and applying the principle of detailed balance.[8,9] Comparison of theory with experiment has been difficult because of the uncertainty of the available experimental data. Recent experimental results of $He^4(\gamma,p)T$ obtained by Fuller[10] agree with the results of this paper within the experimental errors. The combined results of both experiments agree with the general predictions of the theory.

The salient features of this experiment are that the reaction occurred in a tritium gas target and that the gamma rays were detected by sodium iodide scintillation counters. Throughout the experiment it has been assumed that only transitions to the ground state of He^4 have been measured.

II. EXPERIMENTAL DETAILS

General features of the experimental arrangement are shown in Fig. 1. An analyzed beam of protons from an electrostatic generator entered the target of tritium gas through a thin window of 0.05-mil nickel or 0.2-mil aluminum foil. The reaction gamma rays were incident along the axis of a cylindrical NaI(Tl) scintillation counter. Various crystals were used, with the dimensions given in Table III. The differential pulse height distribution from the crystal was observed with a multichannel pulse height analyzer (Los Alamos Model 100),[11]

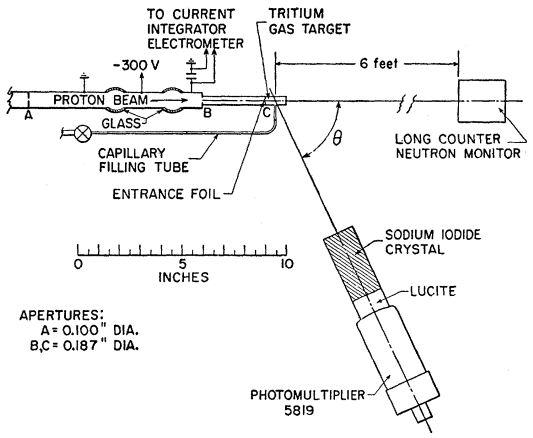

FIG. 1. Schematic drawing of the experimental arrangement. For angular distributions the NaI crystal was rotated about the middle of the gas target as a center.

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] Argo, Gittings, Hemmendinger, Jarvis, and Taschek, Phys. Rev. **78**, 691 (1950).
[2] R. S. Rochlin, Phys. Rev. **84**, 165L (1951).
[3] C. E. Falk and G. C. Phillips, Phys. Rev. **83**, 468L (1951).
[4] J. E. Perry, Jr. and S. J. Bame, Jr., Phys. Rev. **90**, 380A (1952).
[5] R. W. Birge and J. Jungerman, University of California Radiation Laboratory Report, UCRL-2109, February, 1953 (unpublished).
[6] Willard, Bair, and Kington, Phys. Rev. **90**, 865 (1953).
[7] J. B. Warren and G. M. Griffiths, Phys. Rev. **92**, 1084(A) (1953).
[8] B. H. Flowers and F. Mandl, Proc. Roy. Soc. (London) **A206**, 131 (1951).
[9] J. C. Gunn and J. Irving, Phil. Mag. **42**, 1353 (1951).
[10] E. G. Fuller, Phys. Rev. **96**, 1306 (1954).
[11] C. W. Johnstone, Nucleonics **11**, 36 (1953).

and served as the basis for computing the gamma-ray yield. Throughout most of the experiment a Los Alamos Model 250 preamplifier and a 250 amplifier[12] were used. A model 500 pulser[13] served to check the amplifier linearity and to calibrate the pulse-height scale of the analyzer. The photomultiplier voltage was provided by a well-regulated supply, and the over-all gain of the system was frequently checked with a Cs^{137} radioactive source.

III. ABSOLUTE DIFFERENTIAL CROSS SECTION AT 90° AND 1 MEV

Seven determinations of absolute 90° differential cross section were made at various energies below the neutron threshold of the reaction $T(p,n)He^3$. These were made at different times throughout the course of the experiment, with slightly differing geometries, different samples of tritium, and different NaI counters. The results are presented in Table I. Values in column three are cross sections for the reaction at 1 Mev, extrapolated from the foregoing data in accordance with the shape of the 90° relative yield curve (see Sec. IV and Fig. 3).

The average value of the differential cross section[14] for the $T(p,\gamma)He^4$ reaction at 90° and 1 Mev was found to be 3.65×10^{-30} cm²/steradian. Since the angular distribution of the gamma rays is nearly $\sin^2\theta$ (Sec. V), the total cross section of the reaction is very nearly $8\pi/3$ times the 90° differential cross section, i.e., 3.05×10^{-29} cm² at 1 Mev. We believe the standard errors of these values to be ±7%.

Table II contains a list of the sources and sizes of error associated with a determination of the absolute cross section at 90° and 1 Mev. Various comments pertaining to the items of Table II are given below.

The number of incident protons was measured to ±1% by a current integrator.[15] The density of target atoms was known to about ±4 percent. Heating of the target gas by the passage of the beam through the entrance foil and the gas itself necessitated a correction of about 3%±1.5%. The tritium content of the target gas was determined by mass spectrographic analysis. Five analyses were done for the seven cross-section determinations.

The product (counter solid angle)×(counter efficiency) was computed by evaluation of the integral

$$d\omega\times\text{eff}=\int_V \frac{\exp(-\mu l/\cos\varphi)}{r^2}\mu dV,$$

where μ is the total absorption coefficient of the gamma rays in NaI.[16] dV is a volume element located at distance r from the gamma source, at angle φ from the counter axis, and at depth l from the front face of the counter. The over-all uncertainty in (solid angle)×(efficiency) is considered to be ±3%.

The absorption coefficient μ appearing in the integral is based on the total interaction cross section per molecule of NaI. With this basis an absolute yield of gamma rays can only be obtained by counting the total number of pulses produced by the gamma rays in the crystal. This number is equal to the area of the differential pulse height distribution.

Pulse-height distributions obtained with two counters are shown in Fig. 2. At very low pulse heights the shapes of the curves become unreliable because of subtraction

TABLE I. Differential cross section of the $T(p,\gamma)He^4$ reaction at 90° and 1 Mev.[a]

E_p Mev	$\sigma(90°)_{E_p}$ 10^{-30} cm²/sterad	$\sigma(90°)_{1\text{ Mev}}$ 10^{-30} cm²/sterad	Crystal length, inches
0.806	3.036	3.815	3.3
0.949	3.598	3.802	3.3
0.751	2.556	3.464	1.5
0.640	2.505	3.718	3.3
0.640	2.435	3.613	1.5
0.732	2.559	3.563	3.3
0.732	2.500	3.481	1.5

Average $\sigma(90°)_{1\text{ Mev}}=3.637\times10^{-30}$ cm²/steradian.

[a] The cross sections were measured at the listed energies (E_p) and extrapolated to 1 Mev by means of the 90° relative yield curve (Fig. 3).

TABLE II. Errors in $T(p,\gamma)He^4$ differential cross section at 90° and 1 Mev.

Item	Error in percent
I. Incident protons, ±1%	1
II. Density of target atoms, ±4%	
Target length, pressure, room temperature	2
T_2 gas analysis	3
Target heating due to beam	1.5
III. Counter (solid angle)×(efficiency), ±3%	
Numerical integration	0.5
Geometry of counter	1
Effects of absorption coefficient μ	2
IV. Observed gamma count, ±5%	
Statistics and extrapolation	5
V. Energy extrapolation to 1 Mev, ±1%	1
VI. Miscellaneous, ±2%	
T_2 absorbed in target walls	1
Room-scattered gamma rays	0.5
Thallium activator in crystal	1
Conversion in aluminum light reflector	0.5
Σ error=	20%
$[\Sigma(\text{error})^2]^{\frac{1}{2}}=$	±7%

[12] C. W. Johnstone, Los Alamos Report LA-1878, 1955 (unpublished). See also R. J. Watts, Part 9, Institute of Radio Engineers National Convention Record, New York Meeting, March, 1954.

[13] O. L. Stone, Los Alamos Report LA-1330, 1953 (unpublished). See also reference 12.

[14] Throughout this paper the notation $\sigma(\theta)$ is used to represent differential cross section in cm²/steradian.

[15] Worthington, McGruer, and Findley, Phys. Rev. **90**, 899 (1953).

[16] The values of μ were obtained from G. R. White, National Bureau of Standards Report 1003 (unpublished).

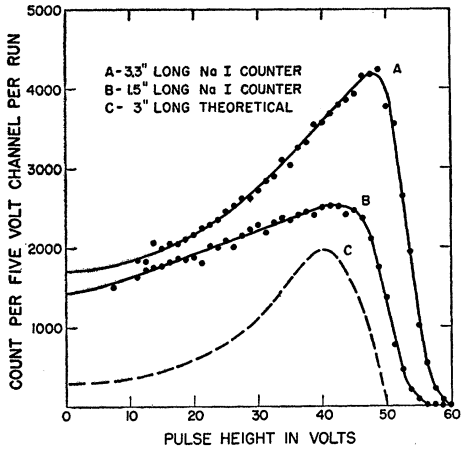

FIG. 2. Differential pulse height distributions produced by tritium gamma rays in NaI crystals. The proton bombarding energy is below the T(p,n) neutron threshold. Curve C is due to Campbell and Boyle (reference 17).

of rising backgrounds. Campbell and Boyle[17] have made an approximate Monte Carlo calculation of the differential pulse height distributions produced by gamma rays of various energies in NaI crystals. Their calculations indicate that in the region of small pulse height there should be no abrupt increase or decrease of the distributions. We have accordingly extrapolated the distributions smoothly to zero pulse height in the manner shown in Fig. 2. The areas of the distributions are considered uncertain by $\pm 5\%$, due in part to counting statistics, but mostly to the necessary extrapolation.

The errors of the "miscellaneous" items of Table II were estimated. Because of the uncertainties of the estimates no corrections were made and the cross section was merely considered in error by the amounts shown.

As an over-all check of the system the gamma-ray yield from the $F^{19}(p;\alpha,\gamma)O^{16}$ reaction in a thick CaF_2 target was measured at 1-Mev proton energy. The result, 7.3×10^{-7} gammas per proton, agrees well with other published values.[18]

The cross-section error of ± 7 percent, compounded quadratically from the many individual errors of Table II, is really the error associated with one determination of the absolute cross section. However, because the major errors are probably systematic, we do not feel justified in reducing the over-all error by virtue of having made several determinations. We believe that there is a 70% chance that the true cross section lies within ± 7 percent of the value 3.65×10^{-30} cm^2/steradian.

TABLE III. 90° excitation curve data.

Energy range Mev	NaI counter	Electrostatic generator Mev	Number of data points
0.15 to 2.6	1.5 in. diam×2 in. long, and 1.5 in. diam×3.3 in. long	2.6	37
2.2 to 3.9	1.5 in. diam×3.3 in. long	6	14
0.6 to 4.3	1.5 in. diam×3.3 in. long	6	33
0.10 to 1.00	1.5 in. diam×2 in. long	2.6	16
1.0 to 4.0	1.5 in. diam×3.3 in. long, and 3 in. diam×3 in. long, collimated by 1 in. diam hole in lead brick	6	4
0.8 to 6.2	1.5 in. diam×3.3 in. long, and 1.5 in. diam×1.5 in. long	6	17

IV. 90° EXCITATION CURVE

The yield of gamma rays emitted at 90° to the proton beam was measured at proton energies ranging from 0.10 Mev to 6.2 Mev. Approximately 300 individual yields were measured at 80 different energies in six series of runs. Details of these series are given in Table III.

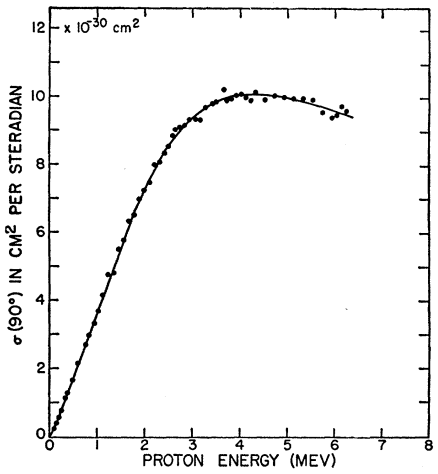

FIG. 3. 90° excitation function of T(p,γ)He^4. This is a composite of the sets of data mentioned in Table III.

The results of the six series form the smooth yield curve given in Fig. 3, normalized to pass through 3.65×10^{-30} cm^2/steradian at 1 Mev. No sharp resonance structure is evident in the excitation function over the entire proton energy range. The shape of the curve agrees very well with that found by Willard *et al.*[6]

Two characteristics of the differential pulse height distribution influenced the measurement of the 90° yield curve as a function of energy. (1) Figure 2 shows a peak in the distribution followed by a sharp linear decrease in the number of high-energy pulses. This slope was extrapolated to the abscissa axis to obtain an extrapolated pulse height, P_x. Figure 4 shows that the extrapolated pulse height was linear with proton bom-

[17] J. G. Campbell and A. J. F. Boyle, Australian J. Phys. **6**, 171 (1953); and **7**, 284 (1954).

[18] R. B. Day and R. L. Walker, Phys. Rev. **85**, 584 (1952). See also Chao, Tollestrup, Fowler, and Lauritsen, Phys. Rev. **79**, 108 (1950).

barding energy. Since the increase of gamma energy is linear with proton energy, this establishes the proportionality of sodium iodide pulse height to gamma energy in the range 20 to 24 Mev. (2) At energies above the $T(p,n)$ threshold there was a large number of neutron pulses ranging in size up to about half of the maximum tritium gamma-ray pulse height. Figure 5 is a typical distribution taken at 1.9-Mev proton energy. It is not possible here to extrapolate the tritium distribution to zero pulse height by subtracting out a neutron background.

The technique used for the 90° yield curve was to plot the differential pulse height distribution for each energy, determine the extrapolated pulse height, P_x, and compute the area of the distribution above 0.7 P_x.[19] This technique appropriately varies the lower bias of the counter in accordance with change of gamma-ray

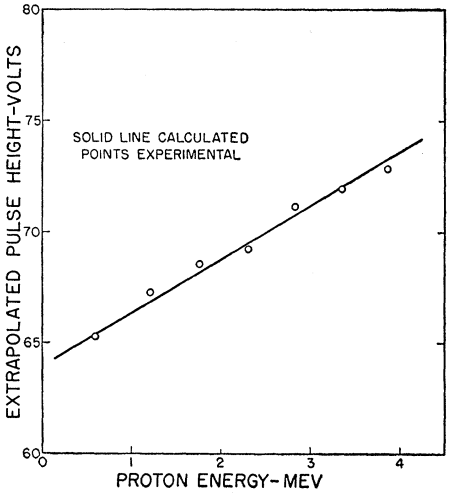

FIG. 4. Energy increase of gamma rays with increasing bombarding energy. The solid line is calculated on the assumption that the maximum pulse height is proportional to the gamma-ray energy in sodium iodide.

energy, and makes the yield independent of slow amplifier gain shifts. It has, however, the clear disadvantage that the yield so measured is based only on the peak region of the distribution.

The visible part of the pulse height distribution lies above about 0.55 P_x at all energies. Study of this part of the distribution showed that it was gradually smeared out with increasing proton energy. Clearly then the area above 0.7 P_x represents a slowly decreasing fraction of the distribution area, as the proton energy is increased. By estimating the behavior of the *invisible* part of the distribution (below 0.55 P_x) as a function of energy, we have computed and applied an increasing "shape correction" of 2.5% per Mev proton energy.

[19] The value 0.7 P_x was chosen because of encroachment of neutron pulses onto the feeble gamma-ray yields at 0°, 15°, and 30° in the angular distribution work of Sec. V. At these angles the pulse height distributions were useless below 0.7 P_x.

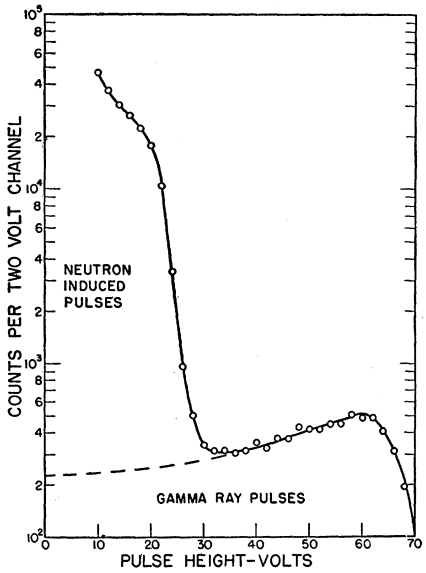

FIG. 5. Differential pulse height distribution produced by tritium gamma rays *and* neutrons in NaI. The proton bombarding energy is 1.9 Mev.

This correction must be considered uncertain by 50 to 100% of itself. Hence, if the yield curve of Fig. 3 is considered correct at 1-Mev proton energy, then at 5 Mev there must be a relative uncertainty of ±5 to 10% caused by this correction alone. Extension of the calculations of Campbell and Boyle[17] to 24 Mev would allow this particular correction to be made with considerably greater certainty.

Appropriate corrections were made for the increase of gamma-ray absorption coefficient with increasing gamma-ray energy.

The accuracy of the 90° yield curve at proton energies above 1 Mev rests mainly on the validity of the "shape correction." This correction was estimated independently for each crystal used (see Table III for crystal dimensions) and all crystals then gave a consistent yield curve. In one case a 3 in.×3 in. crystal was used with a lead collimator (1 in. diameter hole through a 2 in. thick lead brick). Here the differential pulse height distribution was markedly changed from that shown in Fig. 2. Because of reduced secondary electron and bremsstrahlung losses through the sides of the crystal, the pulse height distribution was quite peaked, with a consequent reduction in the importance of the "shape correction." Again the same yield curve resulted. It is possible that a significant increase in the accuracy of the yield curve could be obtained by using a very large crystal[20] and proper collimator.

V. ANGULAR DISTRIBUTION OF THE GAMMA RAYS

One of the interesting features of this reaction is the pronounced anisotropic angular distribution of the gamma rays, which is essentially $\sin^2\theta$. However, our

[20] R. S. Foote and H. W. Koch, Rev. Sci. Instr. 25, 746 (1954).

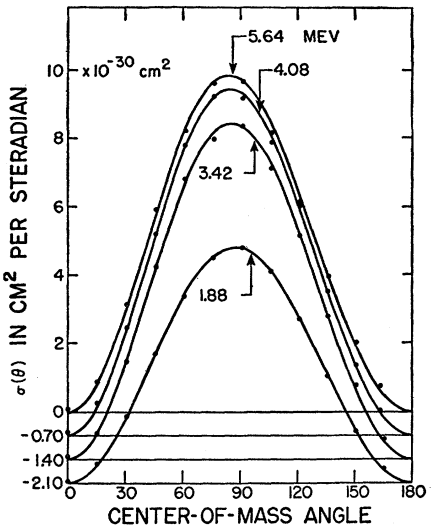

FIG. 6. Angular distributions of $T(p,\gamma)He^4$ in the center-of-mass system. The abscissa has been dropped 0.70×10^{-30} cm^2/steradian for each successive energy to prevent overlapping of data. The curves drawn through the experimental points are of the form $K(\sin\theta+a\sin\theta\cos\theta)^2$, where K is 9.77×10^{-30}, 10.1×10^{-30}, 9.79×10^{-30}, and 6.93×10^{-30}, and a is 0.110, 0.098, 0.082, and 0.051 for the respective energies 5.64, 4.08, 3.42, and 1.88 Mev.

earliest preliminary angular distributions, and indeed those of Argo *et al.*,[1] showed an asymmetry about 90°, with the yield at 45° larger than that at 135°. Moreover, this asymmetry was found to increase with energy.

To clarify the nature of the asymmetry the four angular distributions shown in Fig. 6 were measured. If the 90° yields are all normalized to unity and a $\sin^2\theta$ curve subtracted from each distribution, the resulting difference curves have the general shape $\sin^2\theta\cos\theta$, as shown in Fig. 7.

To obtain further information on the asymmetry

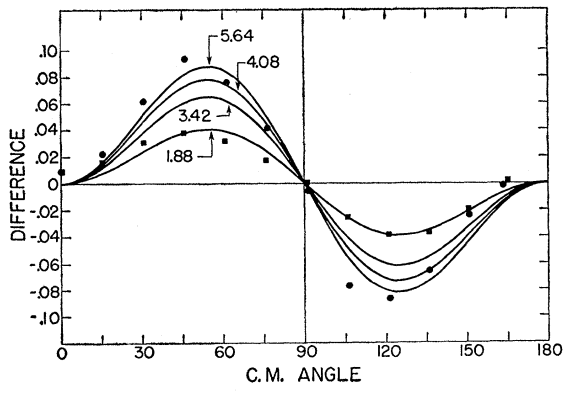

FIG. 7. Difference curves showing how the angular distributions deviate from a $\sin^2\theta$ distribution. The four angular distributions of Fig. 6 were normalized to unity at 90°, and $\sin^2\theta$ was subtracted to yield the difference values. The smooth curves have the form $2a\sin^2\theta\cos\theta+a^2\sin^2\theta\cos^2\theta$, with the values of a listed for Fig. 6. The round and square experimental points are for the 5.64- and 1.88-Mev distributions, respectively. Points for the 4.08- and 3.42-Mev distributions show similar deviations from their smooth curves.

about 90°, the ratio of 60° yield to 120° yield was taken as a function of energy from 600 kev to 5.7 Mev. Appropriate energy-dependent corrections (Sec. IV) were made to this ratio, and it was transformed to the center-of-mass system. With the assumption that the angular distribution has the analytical form $(\sin\theta+a\sin\theta\cos\theta)^2$, the asymmetry coefficient a was calculated, and is shown as a function of energy in Fig. 8.

In taking the angular distributions and 60°/120° ratios, the 3.3 in. long NaI counter was always used, at a distance of 7 in. from the gas target. The center of rotation of the rotating table was located relative to the center of the target to within 0.015 in. in 7 in., and the angular scale was set to ±0.3° by requiring the observed distribution to be symmetric about zero degrees. Then the final data were taken at angles on both sides of the beam tube. A current integrator served as primary monitor. The target gas pressure was

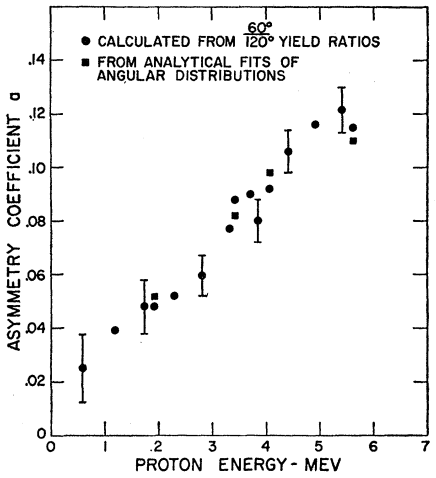

FIG. 8. Asymmetry coefficient a as a function of proton energy, where angular distributions are assumed to have the form $(\sin\theta+a\sin\theta\cos\theta)^2$. The rms statistical uncertainties in a shown for several points do not include the possibility of a small isotropic component in the angular distributions.

measured directly at intervals during the runs and over-all operation was monitored by use of a long counter[21] counting the copious neutrons from the $T(p,n)$ reaction. An isotropic angular distribution found with a radioactive source indicated sufficient magnetic shielding of the photomultiplier tube.

At a given proton bombarding energy, the gamma-ray energy varies with angle according to the Doppler shift relation,[22]

$$E(\theta)=E(90°)[1+(v/c)\cos\theta],$$

where θ is the laboratory angle of the gamma ray, v is the velocity of the He^{4*}, and c the velocity of light. Figure 9 shows a plot of extrapolated pulse height *vs*

[21] A. O. Hanson and J. L. McKibben, Phys. Rev. **72**, 673 (1947).
[22] S. Devons and M. G. N. Hine, Proc. Roy. Soc. (London) **A199**, 56 (1949).

angle, exhibiting clearly the Doppler effect. For the 0°, 15°, and 165° points, where the yields were very low, Doppler curves were used to determine values of P_x and hence the yield at these angles.

As in Sec. IV, the data were corrected for cosmic ray background and for energy dependent factors. Further corrections were applied for the finite angle subtended by the counter and for multiple scattering of the incident beam by the target entrance foil. Several other corrections (such as the effect of the 1-in. target length and gamma absorption and secondary electron scattering in the 0.010-in. thick target walls) were calculated but not applied because of their small size. The resulting yields were then transformed to the center of mass system through use of the equations[22]

$$\sigma_{c.m.}(\theta_{c.m.})=\sigma_{lab}(\theta_{lab})[1-(2v/c)\cos\theta_{c.m.}],$$

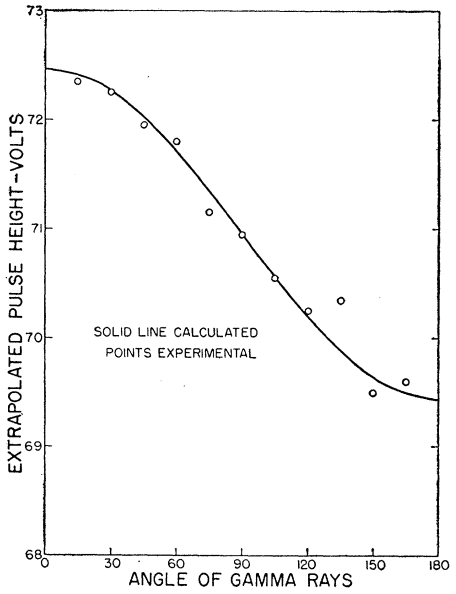

FIG. 9. Doppler shift of gamma-ray energy with angle, for proton energy of 3.42 Mev.

and

$$\theta_{c.m.}=\theta_{lab}+(v/c)\sin\theta_{c.m.}.$$

The center-of-mass corrections are quite small, the yield being changed by no more than 5 percent and angle by no more than 1.5°. However, the changes are such as to reduce appreciably the asymmetry of the distributions.

Considerable attention was given the zero-degree yield in an attempt to see if it really does vanish. As may be seen in Fig. 10, the observed yield is so small and background relatively so large, that the net yield is difficult to obtain with any accuracy. As observed, it was about 1.5%±0.5% of the 90° yield. The corrections resulting from the finite angle subtended by the counter and multiple scattering of protons by the target entrance foil reduced this to around 0.8%. It is

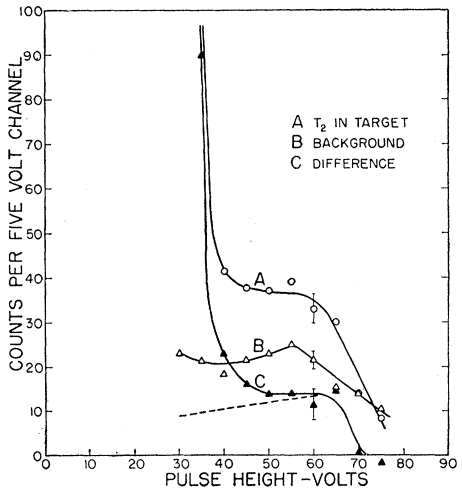

FIG. 10. Pulse-height distributions at $\theta=0°$ for proton energy of 3.42 Mev. The background curve (B) was taken with hydrogen gas replacing the tritium in the target. However, this background is entirely due to cosmic rays.

possible that this residue is caused when protons are stopping in the end wall of the target and interacting with tritium embedded there. We can only conclude that the zero-degree yield is very small, and quite possibly zero at all energies we have investigated.

VI. CONCLUSIONS

(1) Excited States of He^4

Only general conclusions about the possibility of excited states of He^4 can be made as a result of this experiment.

At all energies the gamma ray appeared to be monochromatic. The 14.7- and 17.6-Mev gamma rays from the $Li(p,\gamma)$ reaction produced a double-humped differential pulse-height distribution in the NaI counters. No "double" appearance or secondary peaks were evident in any of the tritium pulse height distributions. Cascade gamma rays would have been observed if their intensity had been 15 percent of the ground state transition and their energy had differed by at least 2 Mev from the ground state transition. Within these limits there appears to be no bound excited state of He^4.

The 90° excitation function (Fig. 3) shows no evidence of sharp resonance structure. The theoretical calculations[8,9] of the photodisintegration of He^4 predict that this yield function should have a broad maximum. Therefore, the maximum observed in this experiment does not necessarily imply a broad unbound state in He^4.

Benveniste and Cork[23] observed no inelastic groups of protons when 32-Mev protons were scattered by helium. The work of Fuller[10] on the photodisintegration of He^4 also gave no indication of excited states. There seems, then, to be no evidence of excited states of He^4

[23] J. Benveniste and B. Cork, Phys. Rev. 89, 422 (1953).

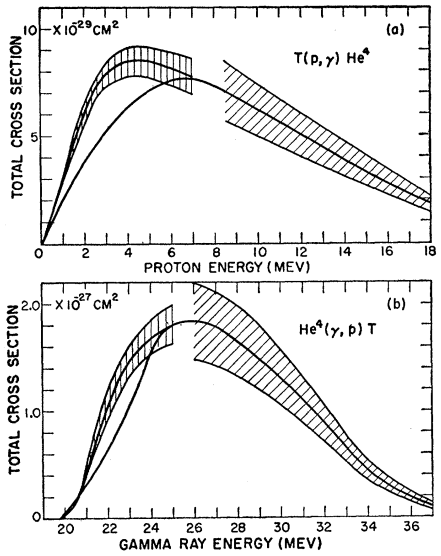

FIG. 11. Cross sections for the inverse reactions $T(p,\gamma)He^4$ and $He^4(\gamma,p)T$, based on detailed balance calculations of Fuller's data (reference 10) and the results of this experiment. The vertical shading represents the absolute error of this experiment, while the slanted shading is the error associated with Fuller's experiment. Fuller's experiment has quite large errors in the unshaded region (below 8.5-Mev proton energy or 26-Mev gamma-ray energy).

which can be produced by the $T(p,\gamma)$, $He^4(\gamma,p)$, or $He^4(p,p')$ reactions.

(2) $T(p,\gamma)$ Reaction Cross Section

The reaction cross section obtained in this experiment is in general agreement with that calculated by the principle of detailed balance from the experimental results of Fuller[10] on the photodisintegration of He^4. Figure 11 shows total cross sections for the two inverse reactions. Fuller has stated that for gamma rays below 26-Mev energy the photodisintegration cross section has rather large errors. This range covers the proton energy range 0 to 8.5 Mev for the $T(p,\gamma)$ reaction so that, unfortunately, the good region of Fuller's data does not overlap our experiment. However, by extrapolation the two results join smoothly. The combined curve has the general shape and general cross section values calculated by Gunn and Irving.[9]

(3) Angular Distributions of the $T(p,\gamma)$ Reaction

In Table IV are listed the possible interaction states of He^4 which might be formed in this reaction, together with the angular distributions of gamma rays to be expected if each state decayed individually to the ground state of He^4. The predominance of $\sin^2\theta$ distribution indicates that the reaction goes mainly by capture of p-wave protons, as pointed out initially by Christy.[24] Critchfield and Dodder[25] have explained the asymmetric deviation from $\sin^2\theta$ as the capture of d-wave protons. The states formed by the capture of p- and d-wave protons, $^1P_1$ and $^1D_2$, interfere in their decay to give a cross section of the form

$$\sigma(\theta)\sim(\sin\theta+a\sin\theta\cos\theta)^2$$
$$=\sin^2\theta+2a\sin^2\theta\cos\theta+a^2\sin^2\theta\cos^2\theta.$$

The observed asymmetry coefficient a is about 0.1 so that the deviation from pure $\sin^2\theta$ is predominantly of the form $2a\sin^2\theta\cos\theta$ (see Fig. 7). Because of barrier penetration the amount of d-wave capture is expected to increase with energy (see Fig. 8).

Plots of $\sigma(\theta)+\sigma(180°-\theta)$ *versus* $\sin^2\theta$ indicate the possibility of a small isotropic component in the angular distributions. If the cross section is assumed to have the form $\sigma(\theta)\sim b+\sin^2\theta(1+a\cos\theta)^2$, the coefficient b increases linearly from 0 ± 0.02 at zero proton energy to 0.02 ± 0.02 at 6 Mev. The fact that the experimental points lie higher than the smooth difference curves of Fig. 7 for the angles 0°, 15°, 30°, 150°, and 165° is evidence in favor of a possible isotropic or $1+\cos^2\theta$ term in the cross section. The presence of such a term would of course reduce the values of the asymmetry coefficient a given in Fig. 8. The accuracy of the present data is probably not sufficient to warrant an attempt to settle the question of an isotropic or $1+\cos^2\theta$ term in

TABLE IV. Interaction states of He^4 formed by $p+T$. States producing radiation of higher order than electric quadrupole have been omitted from the table.[a]

Spins of proton and triton	Proton ang. momentum	Transition	Angular distribution of gamma rays	Interference
1. $\uparrow\downarrow$ $S=0$	$l=0$	$^1S_0\rightarrow{}^1S_0$ Gamma rays forbidden, might be nuclear pairs		
2. $\uparrow\downarrow$ $S=0$	$l=1$	$^1P_1\rightarrow{}^1S_0$ Elec. dipole	$\sin^2\theta$	Interfere with each other
3. $\uparrow\downarrow$ $S=0$	$l=2$	$^1D_2\rightarrow{}^1S_0$ Elec. quad.	$\sin^2\theta\cos^2\theta$	
4. $\uparrow\uparrow$ $S=1$	$l=0$	$^3S_1\rightarrow{}^1S_0$ Mag. dipole	Isotropic	
5. $\uparrow\uparrow$ $S=1$	$l=1$	$^3P_0\rightarrow{}^1S_0$ Gamma rays forbidden		
6. $\uparrow\uparrow$ $S=1$	$l=1$	$^3P_1\rightarrow{}^1S_0$ Elec. dipole	$1+\cos^2\theta$	Interfere with each other
7. $\uparrow\uparrow$ $S=1$	$l=2$	$^3D_1\rightarrow{}^1S_0$ Mag. dipole	$5-3\cos^2\theta$	
8. $\uparrow\uparrow$ $S=1$	$l=2$	$^3D_2\rightarrow{}^1S_0$ Elec. quad.	$1-3\cos^2\theta+4\cos^4\theta$	

[a] Angular distributions calculated from Biedenharn and Rose, Revs. Modern Phys. **25**, 729 (1953); Sharp, Kennedy, Sears, and Hoyle, Chalk River Report CRT-556, AECL 97, (Unpublished). Interference calculated from Blatt and Biedenharn, Revs. Modern Phys. **24**, 258 (1952).

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the angular distributions. In any event the predominant interaction up to proton energies of 6 Mev is the capture of p- and d-wave protons in singlet states.

The general features of these angular distributions have been observed by Fuller[10] in his photodisintegration experiment. In his experiment,[26] the asymmetry coefficient appears to be a factor of two lower than an extrapolation of the results of this experiment. The isotropic component is essentially zero at what corresponds to 6-Mev proton energy in the $T(p,\gamma)$ reaction, but rises rapidly at higher energies.

(4) Extensions of the Experiment

An independent measurement of the absolute yield of the reaction seems desirable in view of the divergence of our result from those of other experiments. More accurate angular distributions, extended to higher energy, might settle the question of interaction in triplet states. A more accurate 90° yield curve, possibly taken with a large crystal with collimator and extended to higher energy, would be of use in the theoretical interpretation of the reaction. A coincidence search might clarify the question of possible cascade gamma rays or nuclear pairs. None of these extensions is presently being considered at this laboratory.

We are particularly indebted to Dr. Robert B. Day for information on absolute gamma-ray yield measurements and for discussions on many phases of the experiment. Many members of Groups P-3 and P-9 of this laboratory helped us by discussion and criticism of the experiment, construction of the apparatus, and operation of the electrostatic accelerators. We are grateful to Dr. Thomas R. Roberts for the many tritium gas analyses.

[26] The notation used in the two experiments is unfortunately not the same. Our a is approximately $\gamma/2b$ in Fuller's notation. Our K (Fig. 6) equals his b, and our b is his a/b.

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Disintegration of Carbon into Three Alpha Particles by 12–20 Mev Neutrons*

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The reaction $C^{12}(n,n'3\alpha)$ has been studied in C-2 emulsions exposed to fifteen discrete neutron energies in the range 12.3–20.1 Mev. Measurements were made of the range and space angles of the three alpha particles for over 2000 events. The observed cross section is 78±15 mb at 12.6 Mev, goes through a broad maximum of 265±47 mb at 16.9 Mev, and is 223±40 mb at 20.1 Mev. It was found that not all the events are observed in the emulsion since (a) one prong may be too short and (b) two prongs which arise from the ground state of Be^8 may not be resolvable. A correction is made for these missed stars at four points giving: $\sigma_{corr}=190\pm50$, 230±50, 316±73, and 283±59 mb at the bombarding energies of 12.9, 14.1, 15.5, and 18.8 Mev, respectively. Evidence is found for the excitation of the 9.6-Mev level in C^{12} and the ground state and 3-Mev level in Be^8, so that at least some of the events disintegrate via the mode $C^{12}(n,n')C^{12*}(\alpha)Be^{8*}(2\alpha)$. Six events appear to involve the 7.7-Mev level in C^{12}. The center-of-mass energy spectrum of the scattered neutrons may be fitted by a four-particle phase space distribution or a Maxwellian distribution. As a result of these measurements, carbon stars in nuclear track plates may be used as a neutron monitor with an accuracy of 15% at 14 Mev and 20% elsewhere in the 12–20 Mev range.

1. INTRODUCTION

CARBON-12 has been observed to disintegrate into three alpha-particles when bombarded by neutrons or gamma rays above the threshold energy of 7.28 Mev. Hänni, Telegdi, and Zünti[1] discovered the photodisintegration reaction in nuclear emulsions exposed to p-Li gamma-rays and this reaction has since been extensively investigated.[2] The neutron-induced reaction was found in early cloud-chamber experiments of Chadwick, Feather, and Davies.[3] Green and Gibson[4] studied 168 stars produced in nuclear emulsions by d-Li neutrons and found a cross section which rises from 23 mb at 10.8 Mev to 157 mb at 14.5 Mev. Their results were further analyzed by Livesey and Smith[5] who found evidence for the excitation of the known 9.6-Mev level in C^{12}, and tentatively another level at 11.8±0.8 Mev. In the former case the breakup of C^{12*} leaves Be^8 in the ground state (the only state energetically possible) while the latter shows some indication of leaving Be^8 in the excited state at 3 Mev.

Perkin,[6] also using nuclear emulsions and d-Li neutrons with a maximum energy of 24 Mev, analyzed 485

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