Gamma Yield from the Proton Bombardment of Tritium*

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The Livermore 90-in. variable-energy cyclotron has been used to measure the excitation function for the $T(p,\gamma)He^4$ reaction for proton energies between 5.8 and 9.2 Mev at a laboratory angle of 90°. The γ radiation was produced in a 0.12-Mev-thick tritium gas target and detected in a 5-in.-diam by 6-in.-long NaI(Tl) crystal. Gamma-ray angular distributions were measured at $E_p=5.8$, 6.4, 7.7, 8.4, and 9.2 Mev and were found to be peaked at angles less than 90°, the asymmetry increasing with proton energy. No evidence was found for excited states of He^4 previously reported by Milone.

INTRODUCTION

THE low-energy proton spectrum from the photodisintegration of He^4 has been measured by several authors.[1–3] The most recent work was done by Milone,[3] using 31- and 32-Mev bremsstrahlung spectra from the Turin University betatron. Milone examined the proton spectra in nuclear emulsions with an energy resolution of 0.133 Mev and found several peaks, the most prominent of which were located at excitation energies in He^4 of 24.7 and 26.1 Mev, which correspond to proton energies of 6.5 and 8.4 Mev. It was pointed out that these resonances, with widths less than 0.5 Mev, would not have been found by the previous experimental work which had been done with relatively broad resolution. The resonances were interpreted as excited states of He^4.

The $T(p,\gamma)He^4$ reaction is related to the photoproton production in He^4 by the principle of detailed balance and thus the excitation function for this reaction would be expected to show the same resonance behavior. The previous measurements of this reaction, culminating in the work of Perry and Bame[4] at Los Alamos, had been made with good energy resolution but were restricted to proton energies below 6.2 Mev. For this reason it was decided to extend the measurements of the $T(p,\gamma)He^4$ excitation function to the energy region observed by Milone.

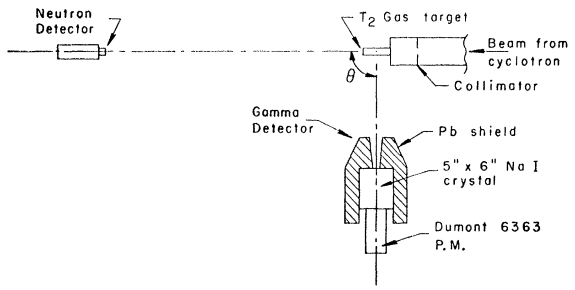

FIG. 1. Geometry.

METHOD

The 90-in. variable-energy cyclotron at Livermore was used as a source of protons, with the experimental arrangement shown in Fig. 1. The proton beam entered the tritium gas target through a 12.9-mg/cm² Ta foil, which was strengthened by a gold grid. The target was 4 in. long by $\frac{7}{8}$ in. diam and was filled to 1 atm pressure. The beam was stopped by a Ta liner at the end of the target.

The gamma radiation was detected by an NaI(Tl) crystal, 6 in. long by 5 in. diam. It was viewed by a Dumont 6363 photomultiplier, mounted in a matched-window assembly. The crystal was inserted in a Pb shield, 2-in. thick around the crystal and formed into a collimator as shown in Fig. 1. The collimator was 5 in. long and was tapered from a 2-in. diameter at the opening to a 1-in. diameter at the face of the crystal. The detector was mounted on an angle changer and is shown (Fig. 1) positioned at 90° to the proton beam. The crystal face was 17 in. from the center of the gas target.

The neutron production from the $T(p,n)He^3$ reaction was monitored by a neutron detector placed at 0° to the proton beam, 68 in. from the gas target. It consisted of a plastic scintillator viewed by an RCA 6655A phototube. The time-of-flight technique was used to separate background neutrons and gamma rays from neutrons produced in the tritium gas.[5]

A block diagram of the electronics associated with the γ detector is shown in Fig. 2. After initial preamplification, the pulses from the detector were clipped by a delay line to about 0.5-μsec full width, which decreases the number of pile-up pulses, although at some sacrifice in resolution. A biased diode discriminator was used to keep the large flux of low-energy pulses from reaching the pulse-height analyzer.

One of the pulse-height spectra from the γ detector is shown in Fig. 3. This spectrum was obtained with 7.1-Mev protons, which corresponds to a 25.1-Mev γ ray.

Relative cross sections were computed from the pulse-height spectra by obtaining an energy calibration using a pulser, shown in Fig. 2. Measurements of pulser

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[1] E. R. Gaerttner and M. L. Yeater, Phys. Rev. **83**, 146 (1951).
[2] E. G. Fuller, Phys. Rev. **96**, 1306 (1954).
[3] Carmelo Milone, Phys. Rev. **120**, 1302 (1960).
[4] J. E. Perry and S. J. Bame, Phys. Rev. **99**, 1368 (1955).
[5] M. D. Goldberg, J. D. Anderson, J. P. Stoering, and C. Wong, Phys. Rev. **122**, 1510 (1961).

voltage vs channel number confirmed the linearity of the system, and comparisons of pulser voltages corresponding to various gamma rays of known energy showed that zero pulser voltage corresponded to zero gamma-ray energy. Thus the energy of any channel can be found by determining the full-energy peak position of the gamma ray in a given spectrum. In this manner, the channel corresponding to $\frac{3}{4}\,E_\gamma$ was found for each spectrum and relative cross sections were obtained by summing all counts above this channel. It was found that the $\frac{3}{4}\,E_\gamma$ position could be determined to within ± 2 channels which leads to an uncertainty of $\pm 2\%$ in the sum. The $\frac{3}{4}\,E_\gamma$ point was chosen for convenience; it was low enough in energy to produce good statistics (about 6000 counts in the sum) but safely above the point at which pile-up pulses were noticeable (about $\frac{1}{2}\,E_\gamma$). The flat cosmic-ray background observed above the gamma ray was extrapolated under the spectrum and subtracted from the sum. It amounted to 2.3 counts/min Mev for all runs.

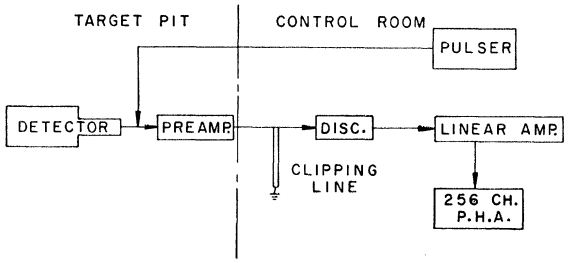

FIG. 2. Electronics block diagram.

Absolute cross sections were obtained with reference to known $T(p,n)He^3$ zero-degree cross sections,[5] from the formula

$$\left(\frac{d\sigma}{d\Omega}\right)_{p,\gamma}(\theta)=\left(\frac{d\sigma}{d\Omega}\right)_{p,n}(0^\circ)\left[\frac{N_\gamma}{\Omega_\gamma\epsilon_\gamma}\right]\left[\frac{\Omega_n\epsilon_n}{N_n}\right].$$

In this expression, N_γ and N_n refer to the observed counts; Ω_γ and Ω_n, the solid angles; and ϵ_γ and ϵ_n, the efficiencies of the gamma and neutron counters.

N_γ and N_n were recorded for each run, Ω_n was determined from the geometry, and previously measured[6] values of ϵ_n were used. The solid angle Ω_γ was computed by a numerical integration which included transmission of the gamma rays through the Pb collimator. This collimator correction increased the apparent solid angle by 28% and took into account the finite length of the tritium gas target. The gamma-ray efficiency ϵ_γ was found by computing a total efficiency using known gamma-ray absorption coefficients, corrected by the ratio of counts above $\frac{3}{4}\,E_\gamma$ to the total number of counts in the spectrum. For this purpose, the low-energy tail on the line shape was assumed to be flat down to zero energy. This assumption is partially justified by previous measurements of the line shape,[7] which found the tail to be flat down to $\frac{1}{4}\,E_\gamma$, and by the calculations of Starfelt.[8] This extrapolation is, however, a source of uncertainty in the absolute value of the cross sections, to which it contributes an error of about $\pm 10\%$.

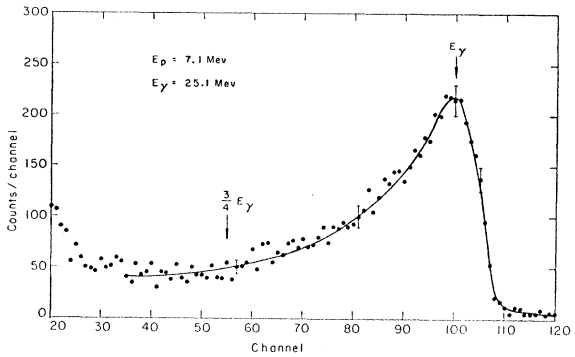

FIG. 3. Typical spectrum.

RESULTS

The 90° absolute cross section for the $T(p,\gamma)He^4$ reaction for 6.15-Mev protons is 11.4 μb/sr, with an absolute error of about $\pm 15\%$. The major uncertainties are the line-shape extrapolation to zero energy, the absolute value of the $T(p,n)He^3$ cross section, and uncertainties in Ω_γ and ϵ_n.

Because the relative errors are considerably smaller than the absolute error, the 90° cross sections are normalized to the data of Perry and Bame and presented in Fig. 4. The vertical flags correspond to the relative errors of $\pm 5\%$ which were assigned to the excitation-function data. This uncertainty is compounded from the 2% error from determination of the $\frac{3}{4}\,E_\gamma$ point, statistics on N_γ and N_n, and relative errors in $(d\sigma/d\Omega)_{p,n}(0^\circ)$.

The energy loss of the protons in the gas target was the major factor in the energy resolution of the measure-

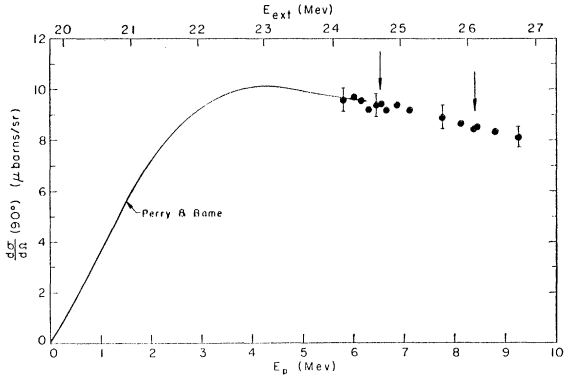

FIG. 4. $T(p,\gamma)He^4$ excitation function.

[6] C. Wong, J. D. Anderson, C. C. Gardner, J. W. McClure, and M. P. Nakada, Phys. Rev. **116**, 164 (1959).

[7] C. C. Gardner and P. C. Gugelot (to be published).

[8] J. Kokum and N. Starfelt, Nuclear Instr. and Methods **4**, 171 (1959).

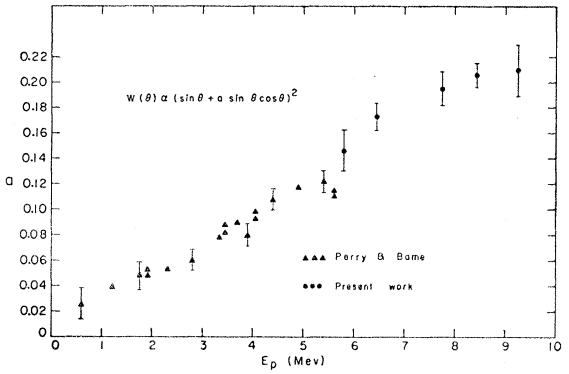

FIG. 5. Asymmetry coefficient.

ments. This energy loss changes somewhat with proton energy but amounted to about 120 kev, which is approximately indicated by the dot size in Fig. 4. The tritium purity was determined from a mass spectrographic measurement. All proton energies quoted were corrected for energy loss in the entrance foil and one-half the loss in the gas, and thus pertain to the center of the gas target.

Gamma-ray angular distributions were measured at $E_p = 5.8$, 6.4, 7.7, 8.4, and 9.2 Mev for $\theta = 30°$, 60°, 90°, and 120° and were fitted by the method of least squares to the form $W(\theta) = (\sin\theta + a \sin\theta \cos\theta)^2$. The asymmetry coefficient (a) was thus determined for each energy and is plotted in Fig. 5. The data of Perry and Bame,[4] taken at lower proton energies, are included.

Before computing the asymmetry coefficient, the angular distributions were transformed to the center-of-mass system. Although producing only a small correction at the individual points, the systematic behavior is such that the value of the asymmetry coefficient is lowered considerably by the transformation. The errors quoted are those determined by the least-squares method. The effects of absorption of the gamma rays in the target walls and the effect of the finite length of the gas target were examined and found to result in negligible corrections in a.

DISCUSSION

The results of the present experiment are in agreement with the general behavior of the reaction as summarized by Perry.[4] The excitation function gradually decreases with increasing energy, over the measured energy interval, and the absolute value of the cross sections, although higher than the work of Perry and of Fuller,[2] is within experimental errors.

The good fits obtained at the lower energies to angular distributions of the form $(\sin\theta + a \sin\theta \cos\theta)^2$ support the previous interpretation of the reaction as an interfering singlet-p and singlet-d wave interaction. At the highest proton energy, however, this form gave a poorer fit to the measured data (reflected in the larger error), which may indicate the effects of an isotropic (triplet) component. No attempt was made to look for isotropy in the angular distributions. The asymmetry found by Fuller,[2] in his work on the photodisintegration of He^4, was a factor of 2 lower than the present results. It was made with broad energy resolution, in which all protons between about 4.25 and 8.25 Mev were included.

The positions of the resonances reported by Milone are indicated by the arrows in Fig. 4. It is clear from the data that we find no evidence for these levels in He^4.