Lorentz curves. The parameters of the Gaussian curves which were used to reproduce the data, are listed in Table I, along with the 21.5- and 24.5-MeV cross section values given by the solid line in Fig. 1. Also included for comparison is the previously reported measurements using monochromatic gamma rays.[9] The two sets of data shown in Figs. 1 and 2 are consistent with each other in that the two curves yield the same value of integrated cross section from the neutron threshold up to 21 MeV: The integrated cross section under the solid line in Fig. 1 is 43 MeV-mb in good agreement with 42 MeV-mb which is the sum of four integrated cross sections listed in Table I.

The observed structure in the photoneutron cross section is compared with the available calculations[3,4] in Table II. It is seen from Table II that except for the structure at 21.5 MeV, the energy positions of the observed structure in the photoneutron cross section are in reasonable agreement with the calculations by Balashov *et al.*[4] The integrated photoneutron cross sections also agree fairly well. However, a serious discrepancy exists between our data and the theory in the relative distribution of strengths among the observed states. Our data indicate that the strength concentration above 21 MeV is much more than predicted. The structure at 21.5 MeV, which is not given by the calculations, may correspond to the pronounced peak observed at about 21 MeV in the energy spectra of the photonuetrons[10] from Ca^{40}, and also in the $K^{39}(p,\gamma_0)Ca^{40}$ reaction.[11]

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Gamma Rays from Neutron Capture in Helium-3 and Deuteron Capture in Deuterium*

R. W. Zurmühle and W. E. Stephens
University of Pennsylvania, Philadelphia, Pennsylvania

and

H. H. Staub
University of Zürich, Zürich, Switzerland

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The gamma rays from the $He^3(n,\gamma)He^4$ and the $D(d,\gamma)He^4$ reaction have been observed. The gamma detector, a 3-in.×4-in. NaI crystal, was surrounded by a plastic scintillator to eliminate the cosmic-ray background. A pileup rejection circuit was used to reduce the background from neutron induced reactions in the NaI. The cross section of the $He^3(n,\gamma)He^4$ reaction at 4 MeV is $\sigma=5\ \mu b/sr$ at 90°. The intensity ratio, $I(90°/I(45°)\approx 2$, agrees with that expected for electric dipole radiation ($\Delta M=0$). The $D(d,\gamma)He^4$ reaction at 1.35 MeV has a cross section $\sigma=2\times10^{-33}\ cm^2/sr$ at 45°.

INTRODUCTION

THE calculation of electromagnetic-transition probabilities is a good method for testing the correctness of the wave functions of the pertinent nuclear states. Some attempts have been made to calculate the excitation function of the $T(p,\gamma)He^4$ reaction,[1–4] which occurs predominantly with emission of electric dipole radiation, and to get an agreement with the experimental data. Wave functions, which give the proper binding energy of the ground state of the alpha particle, do not give an excitation function in agreement with experiments.[5] The maximum cross section always occurs at too high a proton energy. To eliminate this discrepancy, an excited state of the alpha particle has been suggested.[6]

There are two other capture reactions whose final state is an alpha particle but which has not been observed:

$$He^3+n\rightarrow He^4+\gamma,$$

$$D+D\rightarrow He^4+\gamma.$$

The calculation of their cross section also, of course, would allow some testing of the wave function of the alpha particle. This experiment was performed to obtain data on these two reactions.

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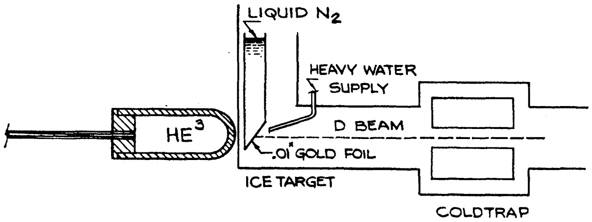

FIG. 1. Schematic drawing of the target.

EXPERIMENT

The neutrons for the neutron capture in He^3 were produced with the $D(d,n)He^3$ reaction. The deuteron beam was accelerated in the single-stage section of the University of Pennsylvania Tandem Accelerator. A layer of heavy ice on a thin gold backing and cooled with liquid nitrogen served as a target. The neutron flux was monitored with an anthracene crystal at 90° to the deuteron beam. This crystal gave a good measurement of the relative neutron yield of different runs. However, the estimation of the absolute neutron yield was inaccurate and, therefore, the deuteron beam current was integrated and the yield calculated from the known cross sections.[7] The assumption was made that the ice target (see Fig. 1) with the highest neutron yield efficiency per deuteron current was both thick enough to stop the beam completely and was free of holes. The relative yield of different targets varied between 0.5 and 1 but was, in general, close to 1. A 1.4-MeV deuteron beam produces, in such an ice target, neutrons in the energy range between 2.45 and 4.6 MeV. Only 5% of all the neutrons have an energy smaller than 3.5 MeV and less than 30% an energy smaller than 4 MeV.[8] The n,γ cross section of He^3 is not expected to vary much with energy so the nominal value of the neutron energy was taken to be 4 MeV and any uncertainty in this value will not have much effect on the accuracy of the experiment. A 50 cc high pressure cylinder was filled with 13 standard liters of He enriched to 93% of helium-3. The cylinder was placed behing the ice target. A similar cylinder without helium was used for background runs.

The gamma radiation was observed with a 3-in.×4-in. NaI(Tl) crystal and an RCA 8054 phototube. The cosmic-ray background had to be reduced and, therefore, the crystal was surrounded with a plastic scintillator which was connected to an RCA 6810 phototube. The outputs of the two phototubes were clipped with a delay line and fed into a fast coincidence circuit which used tunnel diode discriminators and had a resolution of 20 nsec. In addition, the pulse from the NaI crystal was fed into a pileup rejection circuit having approximately 30-nsec resolution. The NaI crystal pulses were analyzed with a 100-channel RIDL pulse-height analyzer. The output pulses of the cosmic-ray rejection and the pileup rejection circuits triggered an anticoincidence signal in the gated amplifier of the multichannel. (See Fig. 2.)

A 10-in.-thick lead shield on top of the gamma detector further reduced the cosmic-ray background. For gamma energies around 20 MeV the total reduction factor was about 100. Sheets of paraffin and boron carbide shielded the scintillators from neutrons. Both scintillators still had very high pulse rates due to recoil protons in the plastic and neutron capture gamma rays in the NaI crystal. This produced much pileup and many accidental coincidences in the cosmic-ray rejection circuit. Therefore, the loss of counts had to be measured. In order to do this, the pulse of the NaI crystal was delayed relative to the pulse in the plastic shield during several runs. The cosmic-ray background was no longer rejected except by accidentals, and its intensity gave a good estimate of the loss of counts. This counting loss was kept around 10% by adjustment of the beam current during the experiments.

The shape of the pulse-height distribution for the 24-MeV gamma rays of the two reactions was assumed to be the same as for the 20.5-MeV gamma rays of the $T(p,\gamma)He^4$ reaction with 1-MeV protons. The pulse-height distribution curve was extrapolated to zero on the low-energy side as recommended by Del Bianco and Stephens.[9] This tail on the low-energy side was slightly affected by the cosmic-ray rejection. The total efficiency was thereby reduced and so a correction was made.

The gamma rays from the $D(d,\gamma)He^4$ reaction in the

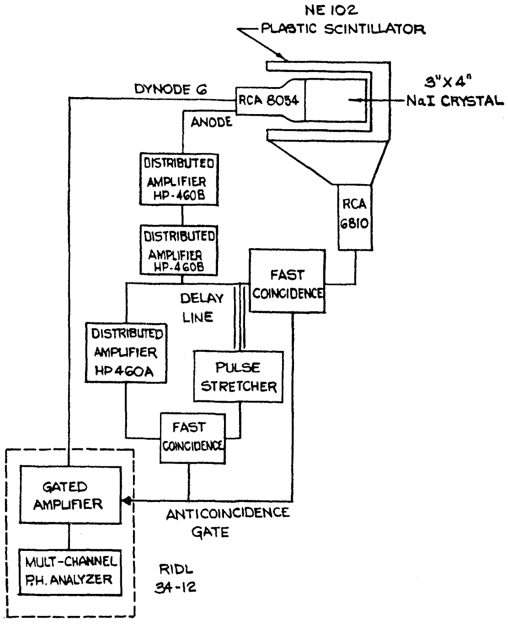

FIG. 2. Electronics block diagram.

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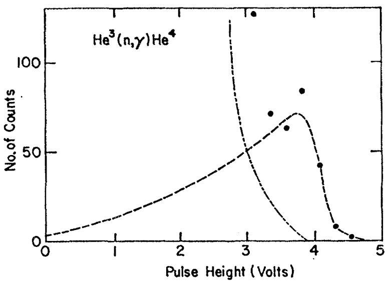

FIG. 3. — — — — Pulse-height distribution from He^3-$(n,\gamma)He^4$ γ rays at 90°. — — — — Background.

ice target were observed with the same detector arrangement. To test that the observed pulses really were produced by gamma rays in the target, a small 1-cm-thick lead absorber was placed between the target and the crystal. This reduced the number of counts above 18 MeV by a factor of 2.1. The background, resulting mostly from neutron capture in the NaI crystal, was reduced only by approximately 15%.

$He^3(n,\gamma)He^4$ REACTION

Results

The differential cross section at 90° to the direction of the incident neutrons is measured to be 5_{-1}^{+2} μb/sr. Besides the statistical errors, systematic errors may be introduced by a smaller than calculated neutron yield, geometrical misalignment of the He^3 cylinder and uncertainty in the energy calibration of the pulse-height distribution in the NaI crystal. (See Figs. 3 and 4.) Runs at 45° give a cross section ratio

$$\sigma(90°)/\sigma(40°)\approx 2.$$

This agrees with the expected P-wave capture of the neutron and electric dipole radiation. Assuming an angular distribution of

$$I\sim\sin^2\Theta,$$

the total cross section is determined to be 42 μb.

Discussion

At our incident particle energy the cross section of the reaction $T(p,\gamma)He^4$ is expected to be of the same order of magnitude as that of $He^3(n,\gamma)He^4$. The experiment of Perry and Bame gives, for a proton energy of 4 MeV, a differential cross section of 10 μb/sr for $T(p,\gamma)He^4$. This result has been confirmed by two more recent experiments.[10,11] Because of the possible experimental uncertainty mentioned above, these values seem not to be significantly different. Measurements of the photodisintegration cross section of He^4 have been made for the (γ,p) and the (γ,n) reactions with bremsstrahlung beams. Gorbunov and Spiridonov[12] measured both cross sections at the same time with a cloud chamber. Therefore, their cross-section ratio should be much more reliable than one which results from two experiments which are performed under entirely different conditions. Their result for the (γ,p) reaction agrees well with Ref. 5. Unfortunately, they were not able to measure the (γ,n) cross section for gamma energies which correspond to neutron energies lower than 8.5 MeV in the inverse reaction. This makes a direct comparison with our result impossible. If we look at the higher energy results, i.e., between 27- and 40-MeV gamma energy, the ratio of the cross sections of the two reactions $(\sigma_{\gamma,p})/\sigma_{(\gamma,n)}$ varies from 0.9 to 1.6. But the authors point out that the deviation of this ratio from 1 could possibly be due to a systematic error of the experiment.

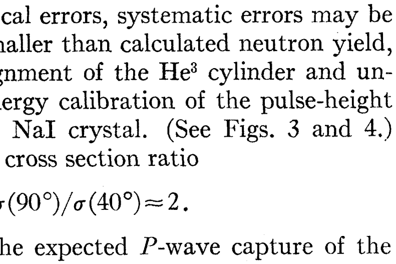

FIG. 4. Pulse-height distribution from $He^3(n,\gamma)He^4$ γ rays at 90°. The background has been subtracted.

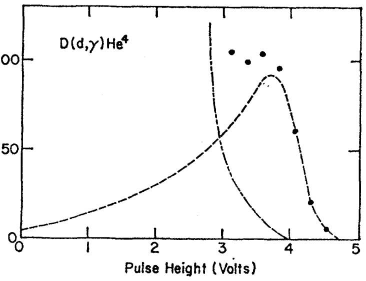

FIG. 5. — — — — Pulse-height distribution from $D(d,\gamma)$-He^4 γ rays at 1.35-MeV deuteron energy at 45°. — — — — Background.

The only measurement of the (γ,n) cross section at lower energies covers the range from threshold up to 26 MeV.[13] The cross section at 23.5 MeV depends on the shape of the curve which is fitted to the experimental points and corresponds to a value between 70 and 100 μb for the $He^3(n,\gamma)He^4$ reaction at $E_n=4$ MeV.

$D(d,\gamma)He^4$ REACTION

Results

Spectra of the $D(d,\gamma)$ rays were taken at three different energies, 0.8, 1.35, and 2.25 MeV and three different angles, 0°, 45°, and 90°. (See Fig. 5.) At higher energies the high background made it impossible to see any gamma rays from this reaction. Because of the identity of the two particles, the angular distribution must be symmetric around 90°. The differential cross section at 45° at 1.35 MeV was measured to be $(2_{-1}^{+2})\times 10^{-33}$ cm²/sr. At 0° the radiation was weaker

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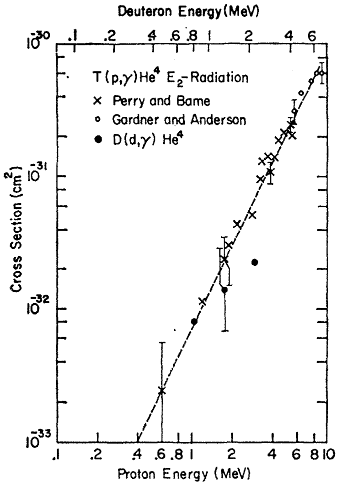

FIG. 6. Cross sections of the $D(d,\gamma)He^4$ reaction and the quadrupole component of the $T(p,\gamma)He^4$ reaction.

(approximately $\frac{1}{2}$). Since no radiation could be observed at 90°, an upper limit is inferred for the differential cross section of 0.5×10^{-33} cm²/sr. The large background and poor statistics made it impossible to get a quantitatively more accurate result.

Discussion

This reaction and its inverse have never been observed before. It has been discussed by Flowers and Mandl.[4] Electric dipole radiation is forbidden by the isobaric spin selection rules. Several authors give upper limits for the cross sections. Fowler *et al.*[14] covered the same energy range as our experiment, but their detector was not sensitive enough to observe the reaction. Their upper limit was $\sigma\lesssim10^{-31}$ cm². Gorbunov and Spiridonov, using a 170-MeV bremsstrahlung beam for the inverse reaction, covered a much larger energy range in which the cross section is expected to be larger than at our energy. Their upper limit corresponds to a bremsstrahlung-weighted cross section which is 50 times smaller than the one of the reaction $He^4(\gamma,p)T$. Therefore, their limit for the $D(d,\gamma)He^4$ reaction is around 10^{-30} cm². Poirier and Pripstein[15] studied the reaction at a much higher energy. They used a 460-MeV deuteron beam and found the differential cross section at 65° to the deuteron beam in the center-of-mass system to be $\sigma\lesssim0.23\times10^{-33}$ cm²/sr. A recent theoretical estimate of this cross section has been made by Delves.[16] He describes the ground state of the alpha particle as a superposition of the three cluster states (T,p), (He^3,n) and (D,D). The scattering matrix, describing the various states of the four nucleons, gives an estimate of the fraction of the time that He^4 appears as two deuterons. This estimate is used to calculate the cross section of the reaction $D(d,\gamma)He^4$. His result for a deuteron energy of 1 MeV, assuming electric quadrupole radiation, is about a factor of 10^3 smaller than our measured cross section of 1×10^{-32} cm². The failure of this theory is at least partly due to the fact that the cluster model should not be applied for the description of the alpha particle, because the three clusters T, He^3, and D are too weakly bound compared to the energy which is required to break the alpha particle up into either one of the three cluster states.

The observed angular distribution indicates, however, a predominantly quadrupole transition, such as

$$^1D_2\rightarrow{}^1S_0.$$

More accurate data on the angular distribution and the excitation function of this reaction would allow further conclusions to be drawn regarding the mechanism of this reaction.

The $^1D_2\rightarrow{}^1S_0$ transition has been considered responsible for a $\sin^2\Theta\cos\Theta$ interference term in the angular distribution of the proton capture gamma rays in tritium[5,10,11];

$$\begin{aligned}I(\Theta)&\sim(\sin\Theta+a\sin\Theta\cos\Theta)^2\\&\sim\sin^2\Theta+2R(a)\sin^2\Theta\cos\Theta+a^2\sin^2\Theta\cos^2\Theta.\end{aligned}$$

The cross-section ratio of the quadrupole transition and the dipole transition is

$$\sigma_{E_2}/\sigma_{E_1}=a^2/5.$$

In Fig. 6 the measured cross sections of the $D(d,\gamma)He^4$ reaction and the quadrupole component of the $T(p,\gamma)He^4$ reaction are plotted against the energies of the incoming particles corresponding to the same wavelength in the center-of-mass system. a is assumed to be real. Therefore, the cross section of the $T(p,\gamma)He^4$ reaction is underestimated by a factor $R(a)^2/a$. The cross sections are of the same order of magnitude. The two reactions differ, of course, in their initial states. In particular, they differ in their excitation energy and in the statistical weight of the singlet state, which is $\frac{1}{4}$ for the (T,p) system and $\frac{1}{6}$ for the (D,D) system.

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