Measurement of the Ground-State Gamma-Ray Branching Ratio of the *dt* Reaction at Low Energies

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The branching ratio $\Gamma_{\gamma 0}/\Gamma_\alpha$ for the $d+t$ reaction has been measured between deuteron energies of 45 and 146 keV. Pair-coincidence spectrometry and pulse-shape discrimination were employed to reduce the neutron effects in the NaI(Tl) gamma-ray detector. The branching ratio is found to be constant over the energy range of the measurements with a best value $\Gamma_{\gamma 0}/\Gamma_\alpha = (5.4 \pm 1.3) \times 10^{-5}$. This value is significantly greater than cluster-model calculations of the branching ratio.

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Over the past thirty years, there have been several studies of the reaction $T(d,\gamma)^5He$.[1–6] At low energies, in the region of the resonance for d-t center-of-mass energy of 67 keV,[7] there is considerable disagreement as to the ground-state gamma-ray branching ratio, $\Gamma_{\gamma 0}/\Gamma_\alpha$, of the reaction $T(d,\gamma)^5He$ to the dominant reaction $T(d,n)^4He$. Values of this branching ratio vary between 2×10^{-5} and 3×10^{-4}.[2,3] Because of the potential application of this gamma ray to the diagnostics of high-temperature DT plasmas,[8] it is essential that the disagreement between the reported values of the branching ratio $\Gamma_{\gamma 0}/\Gamma_\alpha$ be resolved.

We have measured the ground-state gamma-ray branching ratio in the region of the low-energy resonance. Our measurements were made during the bombardment of a thick tritiated titanium target by deuteron beams of energy between 45 and 146 keV from the Colorado School of Mines Cockcroft-Walton charged-particle accelerator.

The gamma-ray branching ratio was determined from simultaneous measurements of the yield of the 16.79-MeV gamma ray corresponding to the transition to the ^5He ground state and of the yield of the 3-MeV alpha particle corresponding to the neutron decay to the ^4He ground state. The gamma-ray detector consisted of a 7.6-cm×7.6-cm cylindrical "plug" NaI(Tl) scintillator surrounded by a NaI(Tl) split annulus. The alpha-particle detector consisted of a 1-mm-thick surface-barrier silicon detector which was fixed at an angle of 135° relative to the forward beam direction and was protected from the back-angle elastically scattered deuterons by a 2-mg/cm^2 aluminum foil. The tritiated titanium target was mounted on the back wall of a semicircular scattering chamber at a distance of 3 cm from the front face of the NaI(Tl) crystal.

The yield of detected reaction products Y^{det} per incident deuteron of energy E_0 is given by

$$Y^{\text{det}} = \epsilon(E) \int_{E_0}^{0} \frac{\sigma(E)}{dE(E)/dn} f(E)\, dE, \qquad (1)$$

where $\epsilon(E)$ is the detector efficiency, including solid angles, $\sigma(E)$ is the cross section for the particular reaction [in this case $T(d,\gamma)^5He$ or $T(d,n)^4He$], $dE(E)/dn$ is the stopping power, and $f(E)$ is the fractional density of tritium atoms in the target at a depth corresponding to an energy E. In Eq. (1) the efficiency $\epsilon(E)$ is removed from the integrand since the variation of energy within the target (no greater than 150 keV) is less than 1% of the energy of the gamma ray (about 17 MeV).

The cross section for the reaction $T(d,\gamma)^5He$ will be related to that of the reaction $T(d,n)^4He$ by the branching ratio

$$\sigma_{T(d,\gamma)^5He} = (\Gamma_\gamma/\Gamma_\alpha)\sigma_{T(d,n)^4He}. \qquad (2)$$

If the branching ratio $(\Gamma_{\gamma 0}/\Gamma_\alpha)$ is independent of energy, then it may be factored out of the integral expression for Y_α^{det} and therefore

$$\frac{Y_{\gamma 0}^{\text{det}}}{Y_\alpha^{\text{det}}} = \frac{\Gamma_{\gamma 0}}{\Gamma_\alpha} \frac{\epsilon_\gamma(E_\gamma)}{\epsilon_\alpha(E_\alpha)}. \qquad (3)$$

The ratio of the yields of the ground-state gammas and alphas may thus be used to measure the ground-state branching ratio $\Gamma_{\gamma 0}/\Gamma_\alpha$, independent of the details of the reaction cross section, the stopping powers, and the concentration of tritium atoms in the target, under the assumption that the branching ratio is independent of energy. This assumption may be tested by measuring the thick-target yield ratios at incident energies above and below the peak in the resonance. This assumption is likewise supported by the recent measurement[9] of $T(d,n)^4He$ between deuteron energies of 8 and 80 keV in which the measured cross section could be well fitted by a single level resonance shape.

Since the neutron production rate exceeds the expected gamma production rate by four or five orders of magnitude, and since the spectrum of neutron-induced reactions in NaI(Tl) extends to nearly 20 MeV,[10] it was necessary to discriminate against such reactions. Previous measurements at higher energies employed neutron time of flight to accomplish this discrimination.[4,5] We relied on two techniques:

(1) *Pair-coincidence spectrometry.*— We required each half of the split annulus to detect simultaneously a 511-keV gamma ray. This requirement is a well-known technique for high-energy gamma-ray spectrometry where pair production is the dominant mode of gamma-ray conversion.[11] This technique selects the second escape peak in the plug detector, producing a relatively narrow line shape at the expense of overall detection efficiency. This technique also eliminates cosmic-ray background.

(2) *Pulse-shape discrimination.*— Pulse-shape discrimination (PSD) has been used to study (n,p) and (n,α) reactions in NaI(Tl) scintillator,[12] and has been used with organic scintillators to study gamma fluxes in intense neutron background.[13] There are, however, no reported uses of PSD in NaI(Tl) to study high-energy gamma rays in the presence of intense neutron backgrounds. The PSD was carried out with a time-to-amplitude converter (TAC) being started by the onset and stopped by the crossover of the doubly differentiated signals from the plug detector. A typical TAC spectrum is shown in Fig. 1 where the γ's are seen to be well separated from the alpha particles resulting from the (n,α) reactions in the scintillator.

A given event in the gamma detector was recorded if it satisfied both the pair coincidence and PSD requirement.

Two low-energy charged-particle reactions producing high-energy gamma rays were used to calibrate the measurements of the reaction $T(d,\gamma)^5He$. The reactions $^{11}B(p,\gamma)^{12}C$ and $^{11}B(p,\alpha)^8Be$ have a well-known resonance (through the ^{12}C 16.11-MeV 2^+ $T=1$ level) at a proton bombarding energy of 163 keV.[14] This resonant reaction produces gamma

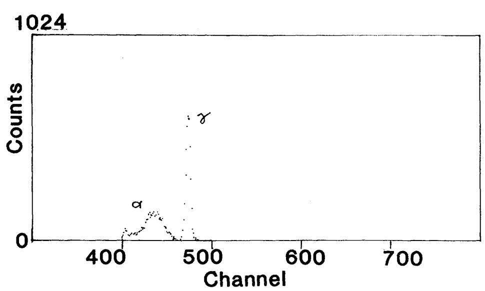

FIG. 1. Pulse-shape–discrimination TAC spectrum showing neutron-induced α's separated from γ's. There is 0.40 nsec/channel in this spectrum. The discriminators on the "start" and "stop" signals to the TAC were set at about 8-MeV gamma-ray energy.

rays of 4.44, 11.67, and 16.11 MeV and was measured with identical geometrical and electronic conditions as the measurements of the reaction $T(d,\gamma)^5He$. The reaction $T(p,\gamma)^4He$ produces a 19.8-MeV gamma ray for low-energy protons. These two reactions were used as follows: (a) Both reactions were used to calibrate the energy of the gamma detector. (b) The ^{11}B reactions were used to determine the absolute gamma-ray detection efficiency of the system by concurrently measuring the ground-state α decay to ^8Be. [Equation (3) was used in this calibration where the branching ratio is *known* and the ratio of the efficiencies is *unknown.*] The width $\Gamma_{\gamma 1}$ of the 11.67-MeV gamma ray was used in the efficiency calibration since the width, $\Gamma_{\gamma 0}$, of the 16.11-MeV gamma ray has not been accurately determined.[7] (c) Both reactions were used to define the peak shape of the 16.7-MeV gamma ray. A small correction was made for the natural linewidth of the ^5He ground state.[7] (d) Both reactions were used to associate the upper peak in the TAC spectrum (Fig. 1) with gamma rays.

The gamma-ray spectrum measured during the proton bombardment of a thick metallic boron target at a proton energy of 163 keV is shown in Fig. 2(a). The second escape peak from the 11.670-MeV gamma ray (corresponding to the transition of the 16.110-MeV level to the 4.439 2^+ $T=0$ level) is evident as is the second escape peak from the 16.110 weak ground-state transition. The efficiencies determined with use of this reaction were corrected for small anisotropies in the laboratory distribution of the alphas and gammas associated with the reactions $^{11}B(p,\gamma)^{12}C$,[15] $^{11}B(p,\alpha)^8Be$,[16] $T(d,\gamma)^5He$, and $T(d,n)^4He$.[9] A small correction was likewise made in extrapolating the gamma-ray efficiency from an energy of 11.670 to 16.7 MeV.[17] The gamma-ray spectrum measured during the bombardment of the tritiated titanium target by 120-keV protons is shown in Fig. 2(b). The 19.88-MeV gamma ray from the reaction $T(p,\gamma)^4He$ is indicated. The gamma-ray spectrum measured during the deuteron bombardment of the tritiated titanium target at a deuteron bombarding energy of 90 keV is shown in Fig. 2(c). The 16.7-MeV gamma ray is evident, centered at about channel 550. The yield of this gamma ray was extracted from the total number of counts between channels 520 and 600 under the assumption of a flat background determined from the average number of counts between channels 600 and 700. Because of the background events below an energy of about 14 MeV, no attempt was made to measure the yield of gamma rays to the very broad ^5He excited state.[7]

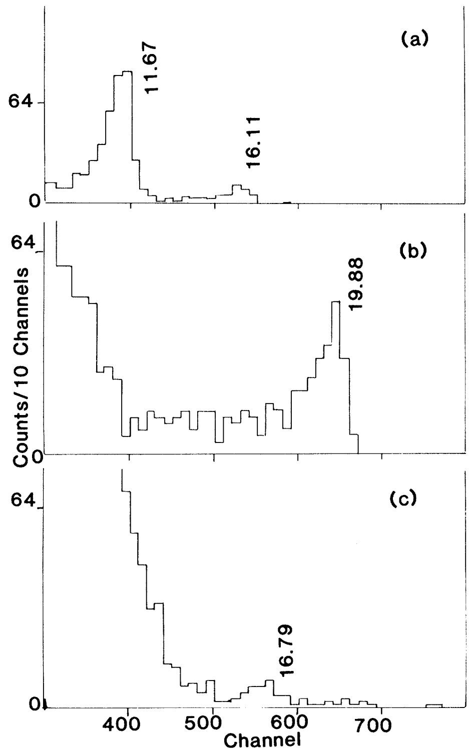

FIG. 2. Gamma-ray energy spectra. In these spectra, the peak labels refer to the full energy of the gamma ray rather than the energy of the second escape peak. (a) The reaction $^{11}B(p,\gamma)^{12}C$ at $E_p = 163$ keV; (b) the reaction $T(p,\gamma)^4He$ at $E_p = 120$ keV; (c) the reaction $T(d,\gamma)^5He$ at $E_d = 90$ keV.

The assumption that the peak at channel 550 was a gamma ray originating from the target was checked by measurement of the yield with 1.9 cm of lead inserted between the target and the detector. As expected, the yield was reduced by about 70%.

With use of the yields of the 16.7-MeV gamma ray and the yields of the concurrently measured alphas, the ground-state gamma-ray branching ratio $\Gamma_{\gamma 0}/\Gamma_\alpha$ was determined from Eq. (3) between energies of 45 and 146 keV. These measured branching ratios are shown in Fig. 3 where they are compared to previous measurements of the branching ratio at low energies. The error bars in our measured values which are indicated in Fig. 3 are purely relative counting errors. There will be an additional systematic uncertainty of about 20% primarily due to the reported error in the branching ratio $\Gamma_{\gamma 1}/\Gamma_\alpha$ of the $^{11}B+p$ reaction which was used to determine the efficiency in the present measurement.

To within the relative errors of each of our data points, our values of the thick-target branching ratios shown in Fig. 3 to appear to be constant with energy as expected. We thus conclude that the branching ratio $\Gamma_{\gamma 0}/\Gamma_\alpha$ is constant over the deuteron energy range of about 40 to 150 keV and that the best value (the error-weighted average) from our seven measurements is

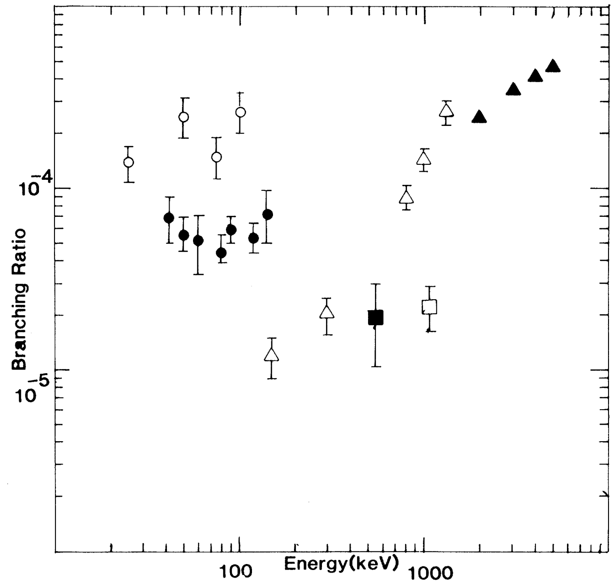

FIG. 3. Measured values of the branching ratio $\Gamma_{\gamma 0}/\Gamma_\alpha$ for the *dt* reaction. Present work, solid circles; Ref. 2, open triangles; Ref. 3, open circles; Ref. 4, solid square; Ref. 5, solid triangles; Ref. 6, open square.

$$\Gamma_{\gamma 0}/\Gamma_\alpha = (5.4 \pm 1.3)\times 10^{-5}.$$

The uncertainty in this best value includes the systematic uncertainty noted above. The measured branching ratio is significantly greater than cluster-model calculations of the branching ratio which predict $\Gamma_{\gamma 0}/\Gamma_\alpha = 1.7\times 10^{-5}$.[18] However, it should be emphasized that the predictions in Ref. 18 can be dramatically changed by small variations in cluster-model parameters and the calculations in Ref. 18 might in fact be reconciled with the present measurements by such minor variations. It would be interesting to pursue the application of resonating-group methods, such as have recently proved successful in calculations of the reaction $^3He(^4He,\gamma)^7Be$,[19] to the reaction $T(d,\gamma)^5He$. Finally, our measured value of the ground-state gamma-ray branching ratio tends to restore the violation of mirror symmetry which was indicated in Ref. 2.

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