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The ^{3}H(d,γ)^{5}He Reaction for $E_{\mathrm{c.m.}} \leq 300$ keV

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Abstract. The ^{3}H$(d,\gamma)^{5}$He reaction has been measured using a 500-keV pulsed deuteron beam incident on a stopping titanium tritide target at Ohio University's Edwards Accelerator Laboratory. The time-of-flight (TOF) technique has been used to distinguish the γ-rays from neutrons detected in the bismuth germinate (BGO) γ-ray detector. A stilbene scintillator and an NE-213 scintillator have been used to detect the neutrons from the ^{3}H$(d,n)^{4}$He reaction using both the pulse-shape discrimination and TOF techniques. A newly-designed target holder with a silicon surface barrier detector to simultaneously measure α-particles to normalize the neutron count was incorporated for subsequent measurements. The γ-rays have been measured at laboratory angles of 0°, 45°, 90°, and 135°. Information about the γ-ray energy distribution for the unbound ground state and first excited state of ^{5}He can be obtained experimentally by comparing the BGO data to Monte Carlo simulations. The ^{3}H(d,γ)/^{3}H(d,n) branching ratio has also been determined.

1 Introduction

The ^{3}H$(d,n)^{4}$He reaction has a very large cross section and provides the easiest approach to achieving fusion in the laboratory. However, about 1 in 10^{4} times in a deuterium-tritium environment, the ^{3}H$(d,\gamma)^{5}$He reaction can occur. This reaction has gained importance in the scientific community because of inertial confinement fusion (ICF) studies, particularly at the National Ignition Facility. One way to investigate the fusion burn in the deuterium-tritium fuel is by detecting γ-rays above about 10 MeV. The γ-rays are useful for diagnostic purposes because they come out of the implosion nearly unscattered, as opposed to the neutrons. The γ-rays also travel faster, and therefore arrive sooner, than the neutrons, allowing them to be detected without interference from the neutrons.

In addition to the ICF application, studying the reaction can lead to a better understanding of the properties of the unbound ^{5}He nucleus. Figure 1 shows the two low-lying ^{5}He states, which are unbound with respect to ^{4}He + n, leading to both states having significant width when compared to the $\frac{3}{2}^{+}$ resonance state. There are γ-ray transitions from the resonance state to the $\frac{3}{2}^{-}$ ground state and the $\frac{1}{2}^{-}$ first excited state, also known as γ_0 and γ_1, respectively. A consequence of the non-negligible widths of the final states, the γ-rays from these transitions are not monoenergetic, but rather have an energy distribution which lies primarily in the 10- to 17-MeV range.

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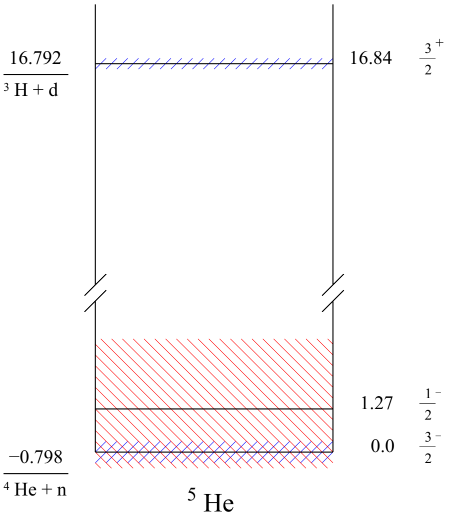

Figure 1. Selected levels in ^{5}He. In addition to the significant width in the lower-lying levels, they overlap, making it more difficult to experimentally determine their contributions to the overall lineshape.

Due to its importance, the ^{3}H$(d,\gamma)/^3$H(d,n) branching ratio has also been previously measured, however there is a discrepancy regarding the order of magnitude of the ratio. This discrepancy between experimental results for similar deuteron energies are likely due to undetected systematic errors, such as the manner in which the neutron background was addressed. Some reported data contains only measurements from the γ_0 branch, while others contain measurements from both the γ_0 and γ_1 branches. A summary of the branching ratio results from the last 50 years can be seen in Figure 2.

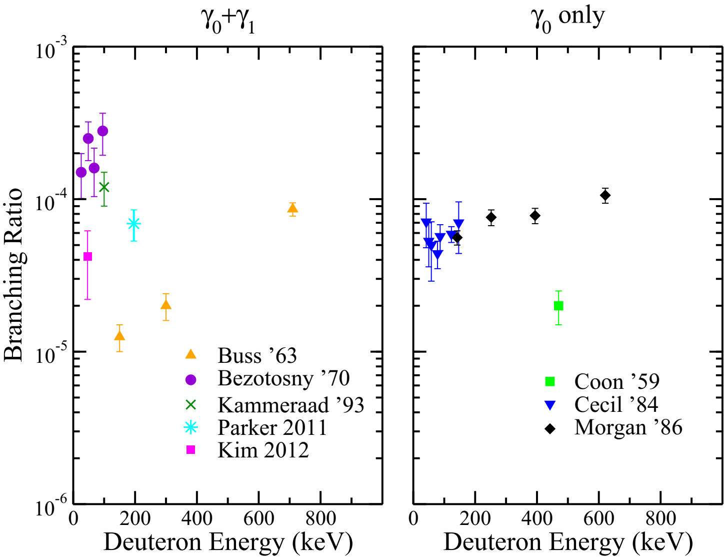

Figure 2. Summary of the branching ratios of ^{3}H$(d,\gamma)/^3$H(d,n). See references [1] and [2] for references to the other previous measurements.

2 Experimental Technique

The experiments were performed using the 4.5-MV Tandem Pelletron Accelerator at the John E. Edwards Accelerator Laboratory on the Ohio University campus. The beam swinger and concreteshielded TOF tunnel [3] were crucial for the experimental set-up. Another important aspect of the experiments was the pulsed and bunched deuteron beam tuned to deliver beam packets with 200 ns between pulses to utilize the TOF technique. Sending the beam to the target in packets provides a means for a time correlation between when the packet hits the target and when the γ-rays or neutrons reach the detector. As γ-rays can also be produced from natural radioactivity or from the capture of thermal neutrons, these events would be seen as "out of time" on the TOF spectrum, indicating that they are not from the desired reaction. The neutrons will appear in the spectrum at different times, based on their energy. As higher-energy neutrons will reach the detector sooner than lower-energy neutrons, due to the difference in their velocities, the different events can be distinguished.

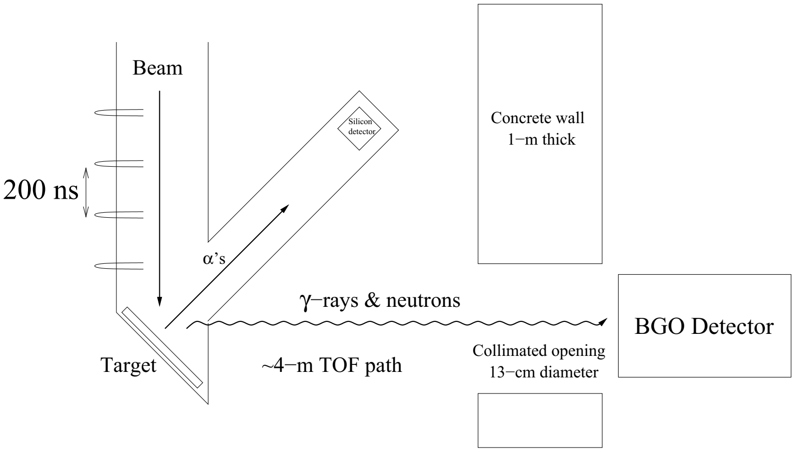

Figure 3. On-axis γ-rays and neutrons will go along the path toward the collimated tunnel entrance, and ultimately to the BGO γ-ray detector. Figure not drawn to scale.

The shielding and collimation provided by the tunnel, as seen in Figure 3, are key in the set-up. The collimated opening is useful because it provides shielding against nearly all of the γ-rays produced away from the target and scattered neutrons from being seen by the BGO. The distance of approximately 4 m is very beneficial to the TOF aspect of the experiment. By placing the BGO at that distance, the arrival time of the 14-MeV neutrons is about 75 ns after the γ-rays, giving a very good peak separation in the spectrum.

The main detector for the experiments was a 10.16-cm-diameter, 10.16-cm-thick BGO for the purpose of detecting the γ-rays. A BGO was chosen for the experiments because of the increased efficiency for γ-rays over other detector materials such as NaI. The high density and large atomic number of the bismuth helps the BGO have a large probability per unit volume for pair production, which is highly desirable for γ-rays with energies above 10 MeV.

In order to investigate the neutrons produced in the reaction, multiple detectors were implemented. A stilbene detector, which has excellent pulse shape discrimination, was utilized to look at the main flux of 14-MeV neutrons in the swinger area. An NE-213, located inside the tunnel area, was included to confirm the information in the stilbene spectrum and to provide an absolute neutron measurement, which can be done with a separate calibration reaction. As α-particles will be produced in a 1:1 ratio with the 14-MeV neutrons, a method to detect them was included in later measurements by placing a silicon surface-barrier detector inside the stainless steel target holder, vacuum sealed to the tritium disk holder. Beyond the simple cross-check of detecting α-particles in addition to neutrons, the method provides an absolute normalization of the neutron detector efficiency.

The tritium target for the measurements was of the solid metal tritide type, with a tritium to titanium ratio guaranteed to be $\geq$ 1.5, while the maximum achieved is known to be about 2.0. The solid target was chosen over the gas cell due to the increased safety precautions and recycling needs the gas cell would call for. There is also additional energy loss that takes place in the foil that seals a gas target that is not present with the solid one. Additional targets for detector calibration purposes were also used. A boron carbide target was utilized for the $^{11}B(d,n\gamma_{15.1})^{12}C$ reaction to provide a monoenergetic γ-ray to give an energy calibration for the BGO above standard offline sources, as well as provide input for the response function. To characterize and calibrate the silicon detector, protons were scattered off of a polished copper target at multiple energies.

3 Analysis and Outlook

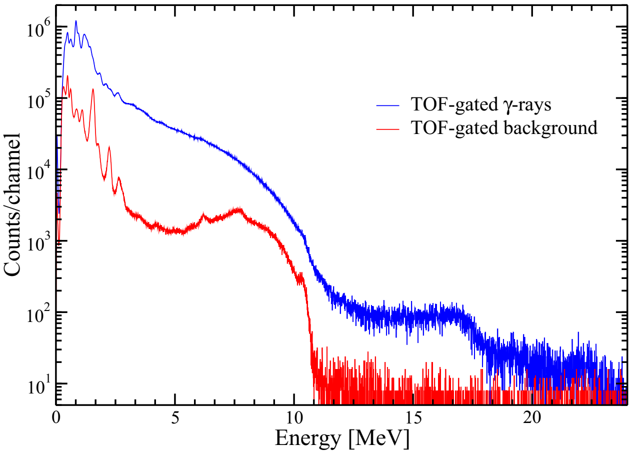

Figure 4. BGO spectrum for approximately 48 hours of beamtime at a laboratory angle of 90°. The γ-rays are gated by the TOF spectrum with an equal number of channels per gate for the same data set.

Analysis is currently underway for data at each laboratory angle. A sample of the γ-ray spectrum from the BGO detector can be seen in Figure 4. The γ-rays of interest for the $^3H(d,\gamma)^5He$ reaction are in the broad peak around 17 MeV; the higher-energy peak is presumably from fast neutron capture on the stainless steel target holder. GEANT4 will be used to determine the efficiency of the BGO for the target-to-detector distance of the set-up for the γ-ray energy range of interest. The relative γ_0 and γ_1 branches will be determined by adjusting the input parameters of the R-matrix calculation-based γ-ray distribution. The 14-MeV neutron yield will be determined using the α-particle yield in the silicon detector for the cross-normalization.

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