Reaction $^2H(^3He,\gamma)^5Li$ at center-of-mass energies between 25 and 60 keV

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The gamma ray to proton branching ratio, Γ_γ/Γ_p, of the $^2H+{}^3He$ reaction has been measured between center-of-mass energies of 25 and 60 keV. The ratio of the ground-state gamma reaction $^2H(^3He,\gamma_0)^5Li$ to the dominant reaction $^2H(^3He,p)^4He$ is observed to be roughly constant over this energy range with a best value of $(4.5\pm1.2)\times10^{-5}$. This ratio for the gamma-ray reaction to the ^5Li first excited state is measured to have a value of $(8\pm3)\times10^{-5}$. The excitation energy of the first excited state is estimated to be 3.0 ± 1.0 MeV.

I. INTRODUCTION

The reaction $^3He(d,\gamma)^5Li$ previously had been studied down to deuteron bombarding energies of about 200 keV.[1-5] These studies indicated that, at the well-known resonance in the $d+{}^3He$ reaction[6] at a deuteron bombarding energy of 450 keV, the gamma-ray branching ratio roughly agrees with that recently measured at the Colorado School of Mines for the d+t reaction.[7] This is as expected on the basis of charge symmetry. In addition, the reaction $^3He(d,\gamma)^5Li$ has recently been proposed as a possible diagnostic of very high temperature plasmas containing a mixture of deuterium and ^3He.[8] For Maxwellian plasmas, most of the nuclear reactions occur at energies near the Gamow peak energy.[9] This energy thus determines the energy at which a given reaction cross section must be known if the yield of the reaction at a given temperature is to be predicted. The value E_0 of the Gamow peak energy is given by[9]

$$E_0=\{\pi\alpha Z_1Z_2kT(\mu c^2/2)^{1/2}\}^{2/3}\ .$$

In this expression α is the fine structure constant, the Z's are the charges of the reactants, μ is their reduced mass, and T is the plasma temperature. For a deuterium ^3He plasma therefore, $E_0=1.057(kT)^{2/3}$, where kT and E_0 are in MeV.

Plasma temperatures currently being achieved in the controlled thermonuclear research (CTR) effort range up to about 7 keV.[10] This temperature corresponds to a Gamow peak c.m. energy of 39 keV. The lowest deuteron bombarding energy at which the $^3He(d,\gamma)^5Li$ reaction has been measured is 200 keV. This corresponds to a center-of-mass energy of 120 keV and as such is significantly greater than the Gamow peak energies characterizing the current CTR effort.

II. EXPERIMENT

We have measured the $^3He(d,\gamma)^5Li$ reaction for center-of-mass energies between 25 and 60 keV. These center-of-mass energies correspond to the Gamow peak energies of deuterium ^3He plasmas with temperatures ranging from 3.6 to 13.5 keV. The measurements were made by bombarding a thick, deuterated polyethylene target with singly ionized ^3He ions from the Cockcroft-Walton charged particle accelerator in the Physics Department at the Colorado School of Mines. The reaction produces 16.6-MeV gamma rays corresponding to the transition to the ^5Li ground state. These gamma rays were measured with a 10.2 by 10.2 cm cylindrical NaI(Tl) scintillator which was fabricated by the Harshaw Chemical Com-

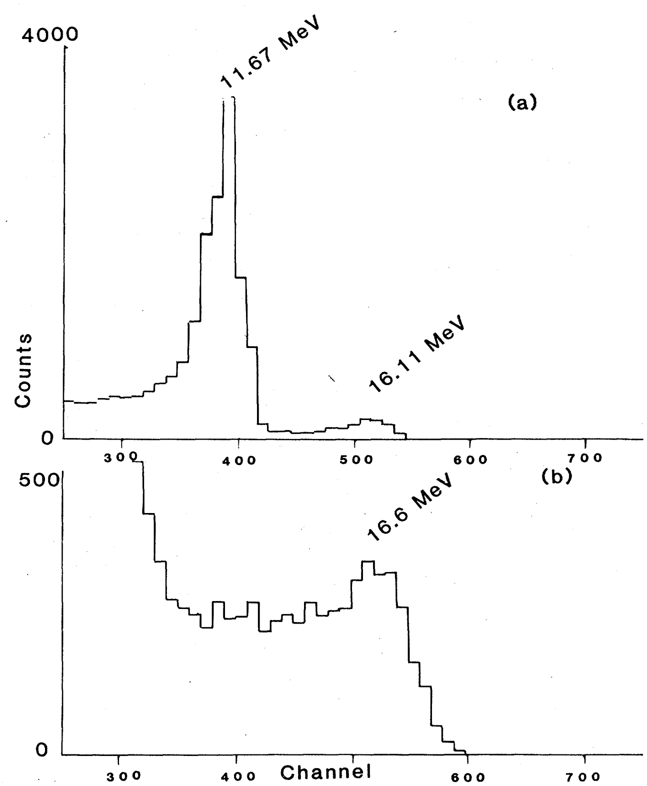

FIG. 1. Comparison of gamma-ray spectra from (a) the calibrating reaction $^{11}B(p,\gamma)^{12}C$ and (b) the reaction $^2H(^3He,\gamma)^5Li$. The proton bombarding energy in (a) is 163 keV. The ^3He bombarding energy in (b) is 140 keV.

pany. The detector was surrounded by a 30.5 cm diameter by 20.3 cm long NaI(Tl) annular scintillator which served to suppress cosmic rays and the Compton tails in the gamma detector. This particular detector system and the measurement of its absolute detection efficiency for gamma ray energies up to 16 MeV are described in Ref. 11.

The resonant reaction $^{11}B(p,\gamma)^{12}C$ was used to establish the energy calibration of the gamma-ray spectrometer system. This reaction was also used to determine the expected experimental energy resolution of the system. A gamma-ray energy spectrum of this reaction is shown in Fig. 1(a). The gamma-ray spectrum measured during the ^3He bombardment of the deuterium target is shown in Fig. 1(b). Concurrently with the gamma-ray measurements, we measured the protons and alpha particles from the dominant branch of the $d+{}^3He$ reaction, $^2H(^3He,p)^4He$. These measurements were made with a silicon surface barrier detector mounted *in vacuuo* at an angle of 135° relative to the forward beam direction and protected from the elastically scattered ^3He ions by a 2 mg/cm^2 foil of aluminum.

A typical spectrum is shown in Fig. 2. By concurrently measuring the charged particles and gamma rays, we were able to make a direct measurement of the branching ratio $^3He(d,\gamma)^5Li/^3He(d,p)^4He$ independent of the composition of the target and independent of the stopping power of the ions in the target. This assumes that the branching ratio is roughly independent of energy, an assumption which can be checked by measuring the ratio of the yields at several energies. This technique is described in the report of our measurement of the gamma-ray to charged-particle branching ratio of the d + t reaction.[7]

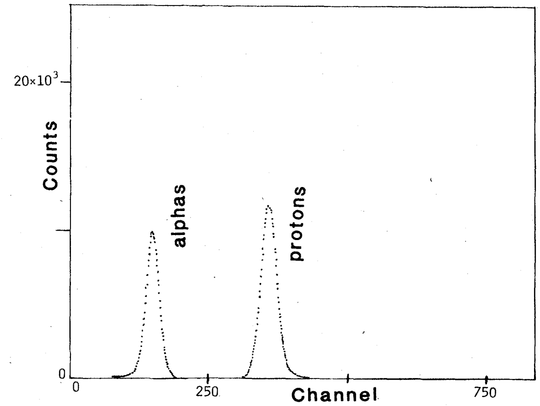

FIG. 2. Charged particle energy spectrum showing the 14.8 MeV protons and 3.8 MeV alpha particles from the reaction $^3He(d,p)^4He$. The ^3He bombarding energy is 140 keV.

III. ANALYSIS AND RESULTS

Because of the large natural widths of the ^5Li ground and excited states ($\Gamma_0=1.5$ MeV, $\Gamma_1=3-7$ MeV,[6] the gamma rays corresponding to transitions to the ^5Li ground and excited states are not resolved in Fig. 1(b). Two methods were employed in order to extract the ground state gamma-ray yields. The simplest method consisted in counting the number of events recorded be-

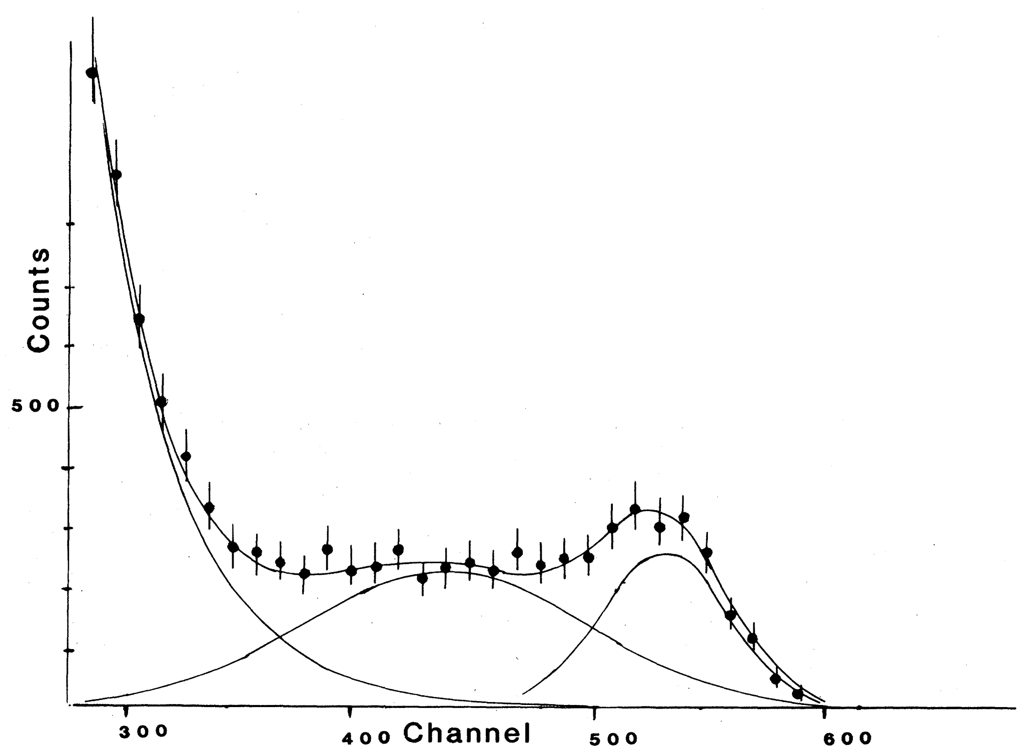

FIG. 3. Gamma ray energy spectrum for the reaction $^2H(^3He,\gamma)^5Li$ together with the least-square fit assuming ^5Li ground and first excited state gamma-ray transitions and a low energy exponentially decreasing background. These are the same data which were plotted in Fig. 1(b) for 140 keV. The error bars are purely counting errors.

tween channels 480 and 600 in Fig. 1(b). The second method consisted in making a least-squares fit to the observed energy spectrum, assuming an exponentially decreasing background, a broad first excited state, and a ground-state transition. The centroid of the ground state transition was fixed at a value determined by the energy calibration [Fig. 1(a)]. Both Gaussian and Lorentzian line shapes were assumed for the ground and first excited states. No effort was made to incorporate the small low energy tails of the gamma rays [note the peak shape of the 11.67 MeV gamma ray in Fig. 1(a)]. The widths of both ^{5}Li states, the excitation energy of the first excited state, and the two parameters characterizing the exponential background were treated as free parameters.

A typical best fit comparing the two gamma rays, the exponential background, their sum, and the actual data points is given in Fig. 3. The best fit width of the ground state transition is consistent with the resolution of a narrow line [the 11.67 MeV gamma ray in Fig. 1(a)] folded into the natural linewidth of the ^{5}Li ground state. The best fit to the entire spectrum was not very sensitive to the energy of the excited state. We found, however, that a reasonable fit to the spectrum could not be obtained if the excitation energy of the excited state was constrained to be 5–10 MeV, the accepted value as given in Ref. 6. We were able to obtain reasonable fits for lower energies of the first excited state between about 2.5 and 3.5 MeV. We should note that this range of excitation energies is consistent with one earlier measurement of the ^{5}Li first excited state by Kraus, Linck, and Wery,[12] who found $E_{\rm exc}=2.5\pm0.4$ MeV.

The ground state gamma ray yields taken from the best fits are consistent with the counting estimates noted above. The errors in the measured yields were taken to be simple counting errors in the count estimates. The center-of-mass angular distributions of both the gamma rays and the charged particles were assumed isotropic.[13] Small corrections to the yields were made in calculating the branching ratios to account for the corresponding anisotropies in the laboratory. The branching ratios as determined by these gamma-ray and charged-particle yields are shown as a function of incident ^{3}He energy in Fig. 4 and are compared with branching ratios determined from recent previous studies of the ^{3}He$(d,\gamma)^5$Li reaction. The kinematic endpoint for the reaction ^{2}H$(^3$He$,\gamma)$p^{4}He is 18.4 MeV, which corresponds to channel 580 in Figs. 1(b) and 3.

Our measured values of the branching ratio of the ground state gamma ray γ_0, between center-of-mass energies of 25 and 60 keV, appear to be roughly constant, with an error weighted average of $\Gamma_{\gamma_0}/\Gamma_p=(4.5\pm1.2)\times10^{-5}$. This constancy is expected if the reactions are dominated by a single resonance and have high-energy products. The lowest energy point, though suffering from relatively large error bars, does suggest a slight energy dependence to the branching ratio. A simple extrapolation to lower energies would indicate a branching ratio at $E=0$ of about $(8\pm2)\times10^{-5}$. The error on the average constant value of the branching ratio includes a 20% uncertainty in the gamma-ray detector efficiency.[11] From the least squares fitting procedure discussed above, we were also able to make a rough estimate of the gamma-ray branching ratio to the ^{5}Li first excited state at a center-of-mass energy of 60 keV of $\Gamma_{\gamma_1}/\Gamma_p=(8\pm3)\times10^{-5}$; with the error due primarily to the uncertainties in the fitting procedures and assumptions.

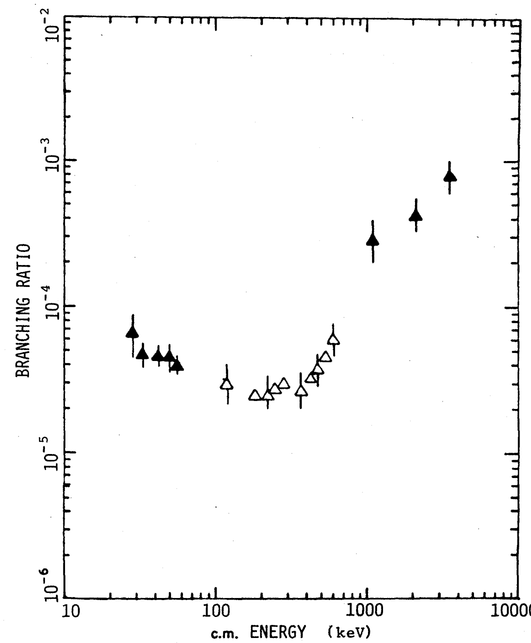

FIG. 4. Measured ground state gamma-ray branching ratios for the reactions ^{3}He$(d,\gamma_0)^5$Li$/^3$He$(d,p)^4$He. Present measurements are the solid symbols at center-of-mass energies below 100 keV. The open symbols are from Ref. 4. The solid symbols at center-of-mass energies above 1 MeV are from Ref. 5.

IV. APPLICATIONS

As noted above, the ^{3}He$(d,\gamma)^5$Li reaction has been proposed as a diagnostic of high temperature d-^{3}He plasmas.[8] The results of the present work constitute a calibration of this diagnostic for Maxwellian plasmas with temperatures between 3.6 and 13.5 keV. By extrapolating the present results to lower energies, or by interpolating to the measurements at higher energies, the applicable temperature range may be extended. The most straightforward application of this reaction as a high temperature plasma diagnostic will be as a thermometer of Maxwellian plasmas. By virtue of the approximately constant value of the branching ratio over the range of energies studied, the reactivity for production of the gamma ray will be linearly related to the known reactivity of the ^{3}He$(d,p)^4$He reaction.[14] A measured value of the gamma ray yield, knowing the plasma densities and the detector efficiencies, will allow a determination of the plasma temperature. This diagnostic may prove particularly useful in the context of magnetic confinement CTR devices where the primary reaction products, the proton and the ^{4}He, will tend to be confined by the magnetic fields.

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