BRIEF REPORTS

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Ground-state widths of ^{5}He and ^{5}Li determined in the ^{3}H$(d,\gamma)^5$He and the ^{3}He$(d,\gamma)^5$Li reactions

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We have measured the widths of the $\frac{3}{2}^-$ ground states of ^{5}He and ^{5}Li using the ^{3}H$(d,\gamma)^5$He and the ^{3}He$(d,\gamma)^5$Li reactions at $E_d = 8.6$ MeV. The γ-ray spectra were fitted with a convolution of the NaI line-shape response function, as measured with the ^{3}H$(p,\gamma)^4$He reaction, and a Breit-Wigner single-level expression. The widths extracted from the spectra were found to be $\Gamma_n = 1.36 \pm 0.19$ MeV for ^{5}He, and $\Gamma_p = 2.44 \pm 0.21$ MeV for ^{5}Li. These values, significantly different from previously quoted measurements, lead to reduced widths which are equal to within error, a result which is consistent with the charge-symmetry property of the nuclear force.

INTRODUCTION

The five-body systems consisting of ^{5}He and ^{5}Li are a frontier problem in few-body nuclear physics. With improvements in computer power and computational methods, the problem of performing exact calculations of five-body systems is now becoming tractable.[1] Part of the motivation to study these nuclei is their potential for supplying fusion energy via the $d + {}^3$H and $d + {}^3$He reactions, in which the cross sections are enhanced just above the threshold energy by a $J^\pi = \frac{3}{2}^+$ "fusion" resonance. It is therefore necessary to accumulate an accurate body of measured information for these systems against which to compare theoretical results. It is with this in mind that we have recently conducted an analysis of the ground-state widths of the ^{5}He and ^{5}Li nuclei using the ^{3}H$(d,\gamma)^5$He and the ^{3}He$(d,\gamma)^5$Li reactions.

In these reactions the deuteron is captured by the target to form a continuum state of ^{5}He or ^{5}Li, which, as indicated in previous angular distribution measurements,[2] decays to the ground state predominantly by $E1$ radiation. Both ground states are unbound to nucleon emission and therefore spontaneously decay to an alpha particle and a nucleon. Measuring the widths of these unbound ground states using capture reactions has the advantage of removing potential scattering terms encountered in scattering experiments. Also the large separations of the first excited states ($\sim$4–5 MeV) allow clean and unambiguous resolution of the ground-state transitions.

The ground states of ^{5}He and ^{5}Li have $J^\pi = \frac{3}{2}^-$ and are most easily pictured as a single nucleon in the $p_{3/2}$ shell-model orbital above a closed $s_{1/2}$ core. They are unbound by 0.89 and 1.97 MeV, respectively, in the n-α and p-α channels.[3] Previous charged-particle reactions established the widths of the ground states to be $\sim$1 MeV, corresponding to lifetimes of $\sim 10^{-22}$ sec. These experimental widths varied widely depending on the experimental setup and reactions used. For a review of experiments, see Refs. 3 and 4. The simplest measurement, nucleon scattering from ^{4}He at energies just above threshold, is complicated by potential scattering interference in the energy-dependent cross section. Warburton and McGruer[5] used the ^{4}He$(d,p)^5$He reaction and fitted a Gaussian to the high-energy side of the peak in their proton spectrum obtaining $\Gamma_{^5\mathrm{He}} = 0.55 \pm 0.03$ MeV. This fit the high-energy side well but failed to reproduce the long low-energy tail and therefore underestimated the width. Ohlsen and Young[4] used the same reaction and measured both the full width at half maximum (FWHM) of a Gaussian fit and the FWHM of the observed spectrum. The Gaussian fit gave a value of $\Gamma_{^5\mathrm{He}} = 0.57 \pm 0.02$ MeV in agreement with Warburton and McGruer. The observed spectrum had a FWHM of $\Gamma_{^5\mathrm{He}} = 0.85 \pm 0.05$ MeV. Cerny *et al.*[6] have studied both ^{5}He and ^{5}Li via the ^{7}Li$(p,{}^3$He$)^5$He and ^{7}Li$(p,t)^5$Li reactions, respectively. Widths of $\Gamma_{^5\mathrm{He}} = 0.80 \pm 0.04$ MeV and $\Gamma_{^5\mathrm{Li}} = 1.55 \pm 0.15$ MeV are quoted although it is not stated how these widths were obtained. Reference 3 quotes a best value

TABLE I. A summary of various measurements of the ^{5}He and ^{5}Li ground-state widths, as well as the reactions and methods of measurement used.

$\Gamma_{^5\mathrm{He}}$ (MeV)	$\Gamma_{^5\mathrm{Li}}$ (MeV)	Reaction	Method of measurement	Ref.
1.36 ±0.19	2.44±0.21	^{3}H(d,γ)^{5}He, ^{3}He(d,γ)^{5}Li	Single-particle width in BW shape	Present work
0.61 ±0.03	1.24±0.03	^{3}H(d,γ)^{5}He, ^{3}He(d,γ)^{5}Li	FWHM of resonance curve	Present work
0.6 ±0.02	~1.5		Average value of several studies	3
0.57 ±0.02		^{4}He(d,p)^{5}He	Gaussian fit to proton spectrum	4
0.85 ±0.05		^{4}He(d,p)^{5}He	FWHM of proton spectrum	4
0.55 ±0.03		^{4}He(d,p)^{5}He	Gaussian fit to proton spectrum	5
0.80 ±0.04	1.55±0.15	^{7}Li(p,^{3}He)^{5}He, ^{7}Li(p,t)^{5}Li	Not stated	6
0.525±0.030		^{3}He(t,p)^{5}He	FWHM of proton spectrum	7
	2.6 ±0.4	^{3}He(d,γ)^{5}Li	FWHM of resonance curve	8

for the width of ^{5}He from the work above and others to be $\Gamma_{^5\mathrm{He}}=0.6\pm0.02$ MeV. For ^{5}Li only a value of $\Gamma_{^5\mathrm{Li}}\sim1.5$ MeV is quoted. Table I summarizes these and other[7,8] various experimental widths and the methods of measurement used.

EXPERIMENT

In the present work we have measured γ rays from the ^{3}H(d,γ)^{5}He and ^{3}He(d,γ)^{5}Li reactions at $\theta_{\mathrm{lab}}=90°$ using an 8.6 MeV deuteron beam which was obtained from the FN tandem Van de Graaff accelerator at the Triangle Universities Nuclear Laboratory (TUNL). Capture γ rays were detected in two anticoincidence-shielded 25.4 cm×25.4 cm NaI(Tl) spectrometers[9] whose back faces were located 149 cm from the target. Each spectrometer was surrounded by 10 cm of Pb shielding as well as 20 cm of lithium-carbonated paraffin to moderate neutrons. Cadmium or boron sheets in front of the spectrometers also absorbed thermal neutrons. A tapered collimator in the front Pb shield defined a solid angle of 23 msr which completely illuminated the back face of the spectrometer.

A self-supporting tritiated titanium foil with a tritium thickness of 2.2 mg/cm^2 and a comparable titanium thickness was used to measure γ rays from ^{5}He, and a pure titanium foil was used to subtract out the background γ rays due to the titanium. To measure γ rays from ^{5}Li, a gaseous ^{3}He target was operated at a pressure of 49.6 kPa with a 1.27-μm nickel beam-entrance foil and a 2.54-μm Havar beam-exit foil. Lead and tungsten shadow bars were used to prevent the NaI spectrometers from viewing these foils and allowed the spectrometers to see a region of gas which was 3.6 cm long when the spectrometer was at 90°, corresponding to a target thickness of 0.22 mg/cm^2. A spectrum with no gas in the target was taken in this configuration to determine the γ-ray background from the foils. No background in the energy range of interest was detected. Figure 1 shows a typical ^{5}He background-subtracted γ-ray spectrum and a typical ^{5}Li γ-ray spectrum.

The NaI detector line-shape response function was measured using the ^{3}H(p,γ)^{4}He reaction at $E_p=2.5$ MeV, yielding γ rays with $E_\gamma=21.6$ MeV. The response of the detector to these incident γ rays yields a spectrum with finite resolution (~3%) and a long low-energy tail (shown in Fig. 2), thus requiring the response function to be parametrized in terms of two quantities, the incident γ-ray energy E_γ and the response energy E. This response function, NaI(E,E_γ), has been measured at

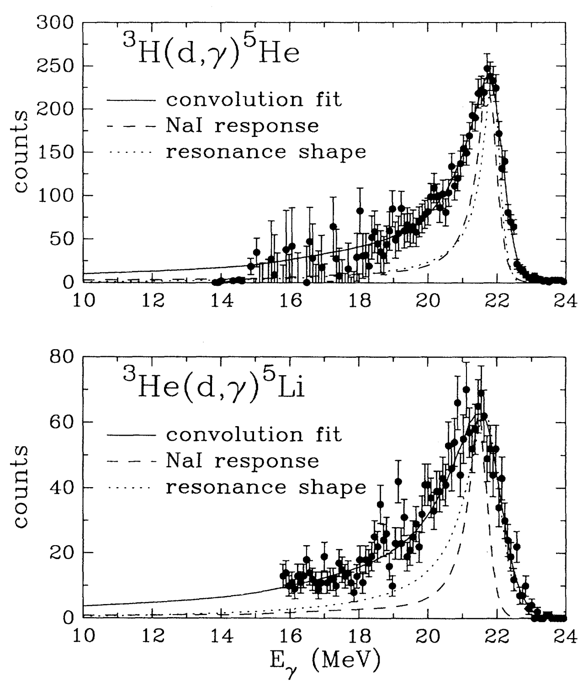

FIG. 1. Upper panel: A typical γ-ray spectrum for ^{3}H(d,γ)^{5}He at $E_d=8.6$ MeV and $\theta_{\mathrm{lab}}=90°$ which was obtained by subtracting a pure titanium foil spectrum from a tritiated titanium foil spectrum. The error bars represent the statistical uncertainties for both of these measurements. The convolution of the NaI response function and the resonance shape was fitted in the range 20.0 MeV $\le E_\gamma \le$ 24.0 MeV. Lower panel: A typical γ-ray spectrum for ^{3}He(d,γ)^{5}Li at $E_d=8.6$ MeV and $\theta_{\mathrm{lab}}=90°$. No background subtraction was needed. The error bars represent the statistical uncertainties in the measurement. The convolution of the NaI response function and the resonance shape was fitted in the range 19.0 MeV $\le E_\gamma \le$ 24.0 MeV.

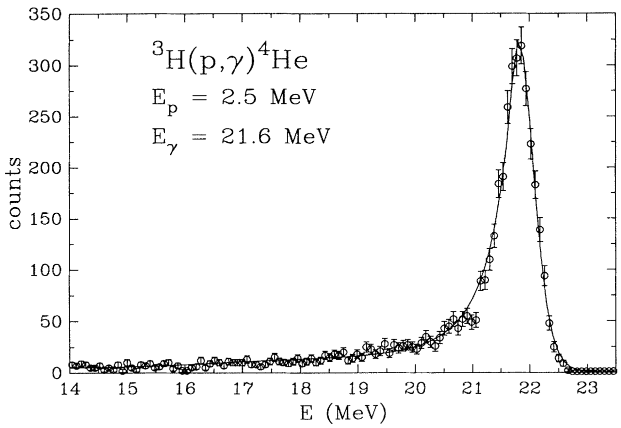

FIG. 2. Spectrum of the NaI detector response function as measured in the $^3H(p,\gamma)^4He$ reaction at $E_p = 2.5$ MeV. The error bars represent the statistical uncertainties in the measurement. The solid curve represents the best fit to the data.

several incident γ-ray energies and the percent resolution, $\Delta E / E_\gamma$, was taken to be constant in the region of interest for the current experiment.[9]

ANALYSIS

According to the theory of resonance reactions, the energy-dependent shape of an isolated resonance for an electric dipole ($E1$) transition and an N-α breakup channel (where $N = p$ or n) can be described in terms of a Breit-Wigner form:

$$\mathrm{BW}(E_\gamma) = \frac{1}{k^2} \frac{E_\gamma^3 \Gamma_N}{[E_\gamma - E_{\mathrm{res}} + \Delta(E_N)]^2 + \left[\frac{\Gamma_N}{2}\right]^2} , \quad (1)$$

where Γ_N is the width of the N-α channel, E_N is the nucleon emission energy, and E_γ^3 is the energy-dependent piece of the γ-ray width Γ_γ. We have assumed $\Gamma_\gamma \ll \Gamma_N$ so that the total width $\Gamma = \Gamma_N + \Gamma_\gamma \approx \Gamma_N$. The energy dependence of the nucleon widths Γ_N is determined by the relation $\Gamma_N = 2P_l(E_N)\gamma^2$, where γ^2 is the reduced width and $P_l(E_N)$ is the penetrability of the nucleon, which for this case has an orbital angular momentum $l = 1$. $P_1(E_N)$ was calculated directly from the confluent hypergeometric functions, F_1 and G_1, for several choices

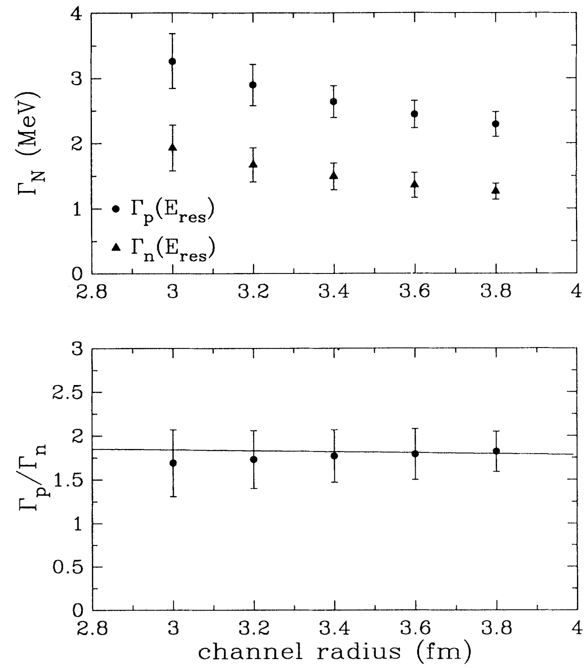

FIG. 3. Upper panel: The neutron resonance width Γ_n at the resonance energy $E_n = 0.89$ MeV as measured in the $^3H(d,\gamma)^5He$ reaction and the proton resonance width Γ_p at the resonance energy $E_p = 1.97$ MeV as measured in the $^3He(d,\gamma)^5Li$ reaction plotted as a function of the channel radius. Lower panel: The ratio of the above widths demonstrating the insensitivity of this ratio to the channel radius. The solid curve is the ratio of penetrabilities $P_1^p(E_{\mathrm{res}})/P_1^n(E_{\mathrm{res}})$ as discussed in the text.

of channel radius. Similarly, the energy dependence of the level shift, $\Delta(E_N)$, is determined from the shift function $S_1(E_N)$ in the relation $\Delta(E_N) = -[S_1(E_N) - B]\gamma^2$ where B, the boundary condition, was chosen such that $\Delta(E_{\mathrm{res}}) = 0.0$. Both the penetrability and the shift function are defined according to the Lane and Thomas definitions.[10] The γ-ray energy is simply related to the nucleon emission energy by kinematic considerations for both the $^3H(d,\gamma)^5He \rightarrow {}^4He + n$ and the $^3He(d,\gamma)^5Li \rightarrow {}^4He + p$ reactions. For the ^5He reaction, E_{res} corresponds to a neutron energy of $E_n = 0.89$ MeV and a γ-ray energy of $E_\gamma = 21.8$ MeV. For the ^5Li reac-

TABLE II. The results of the present experiment. All energies, widths, and reduced widths are quoted in units of MeV in the center-of-mass system. The penetrability and shift functions are dimensionless and were calculated using the confluent hypergeometric functions. The γ-ray energy at the resonance E_γ and the nucleon energy at the resonance E_N are from Ref. 3. Γ_N, γ^2, and FWHM were measured in this experiment as described in the text. The errors for our FWHM measurements were obtained by constructing a Breit-Wigner resonance for $\Gamma_N + \Delta\Gamma_N$ and $\Gamma_N - \Delta\Gamma_N$, and taking half the difference of their FWHM values.

	E_γ (MeV)	$E_N = E_{\mathrm{res}}$ (MeV)	$P_1(E_{\mathrm{res}})$	$S_1(E_{\mathrm{res}})$	$\Gamma_N(E_{\mathrm{res}})$ (MeV)	γ^2 (MeV)	FWHM (MeV)	χ_ν^2
^{5}He	21.8	0.89	0.205	−0.694	1.36±0.19	3.32±0.46	0.61±0.03	1.01
^{5}Li	21.5	1.97	0.366	−0.635	2.44±0.21	3.33±0.29	1.24±0.03	0.83

tion, E_{res} corresponds to a proton energy of $E_p=1.97$ MeV and a γ-ray energy of $E_\gamma=21.5$ MeV. These values were taken from Ref. 3 and were not measured in this experiment.

The γ-ray spectra from our NaI spectrometer were fitted using the minimization code MINUIT with a convolution of the measured energy-dependent response function of the NaI spectrometer and the Breit-Wigner resonance shape described above. The functional form used is

$$F(E) \propto \int \mathrm{NaI}(E,E_\gamma)\mathrm{BW}(E_\gamma)dE_\gamma \ , \qquad (2)$$

where $\Gamma_N(E_N=E_{\mathrm{res}})$ and the overall height of $F(E)$ were varied, and the entire convoluted form was shifted up or down in energy to allow for spectrum calibration errors. The lack of a precise spectrum calibration prevented us from extracting values for E_{res}. From the extracted widths, we reconstructed the resonance shape using Eq. (1). Figure 1 shows the best fits to the ^{5}He and ^{5}Li spectra (solid curve), as well as the NaI response function and the BW shape used in the convolution.

RESULTS

Table II summarizes the results of the best fit to the data. Using a channel radius of $r=1.4(4^{1/3}+1^{1/3})=3.6$ fm, the FWHM of the resonance curves that we have extracted are comparable to the values of previous measurements as quoted in Table I, but they differ from the average values quoted by Ref. 3. The dependence of the widths, Γ_p and Γ_n, on the channel radius is plotted in Fig. 3. It was found that while the individual widths vary with radius, the ratio of the widths Γ_p/Γ_n is insensitive to the radius (see Fig. 3). We can make a simple prediction of this ratio by setting $\gamma_p^2=\gamma_n^2$, as expected from the charge symmetry of the nuclear force. With this assumption, the ratio of widths is given by

$$\Gamma_p(E_{\mathrm{res}})/\Gamma_n(E_{\mathrm{res}})=2P_1^p(E_{\mathrm{res}})\gamma_p^2/2P_1^n(E_{\mathrm{res}})\gamma_n^2 \approx P_1^p(E_{\mathrm{res}})/P_1^n(E_{\mathrm{res}})=1.79 \ .$$

This prediction is in agreement with the measured ratio $\Gamma_p/\Gamma_n=1.79\pm0.29$.

CONCLUSION

Within the framework of resonance reaction theory, we have measured the ground-state widths of ^{5}He and ^{5}Li to be $\Gamma_n=1.36\pm0.19$ MeV and $\Gamma_p=2.44\pm0.21$ MeV, assuming pure $E1$ radiation. These values vary significantly from previously published widths due to the energy dependence of the penetrability and shift functions. The FWHM of the Breit-Wigner functions corresponding to these widths, however, do fall within the range of previous measurements. From our results, the relative magnitudes of $\Gamma_n(E_{\mathrm{res}})$ and $\Gamma_p(E_{\mathrm{res}})$ can be explained simply in terms of the relative penetrability of the neutron and proton through their respective Coulomb and angular momentum barriers. Furthermore, the ratio of these widths is consistent with the property of charge symmetry in the nuclear force.

Note added in proof: The authors of Ref. 8 used a method and means of analysis which were in principle identical to the present work and obtained a value for $\Gamma_{^5\mathrm{Li}}$ which agrees within error with the present result. Unfortunately, there is ambiguity in the definition of the width which they have extracted.

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