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Polarized proton capture by deuterium and the $^2H(p,\gamma)^3He$ astrophysical S factor

G. J. Schmid,* R. M. Chasteler, C. M. Laymon, and H. R. Weller
Duke University, Durham, North Carolina 27708
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708

R. M. Prior
North Georgia College, Dahlonega, Georgia 30597

D. R. Tilley
North Carolina State University, Raleigh, North Carolina 27695
and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708
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The $^2H(\vec{p},\gamma)^3He$ reaction has been studied in the energy region $E_p=80$–0 keV ($E_{\mathrm{c.m.}}=53.3$–0 keV), where the quantities measured were $\sigma(\theta,E)$ and $A_y(\theta,E)$. Our result for the total $^2H(p,\gamma)^3He$ S factor at $E=0$ is $S(0)=0.121\pm0.012$ eV b (including systematic error), which is 52% lower than the presently accepted value. Some astrophysical aspects of this result are discussed. We have also extracted the $E1$ and $M1$ $S(E)$ components using our detailed angular distribution data. These data will provide sensitive tests for three-body calculations which include Coulomb and meson exchange current effects.

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The motivation to experimentally study the $^2H(\vec{p},\gamma)^3He$ reaction at low energies is twofold: first of all, to further test and refine the results of theoretical three-body calculations and second, to study the aspects of the $^2H(p,\gamma)^3He$ reaction which are of interest in astrophysics. The basic physics impetus for the current $^2H(\vec{p},\gamma)^3He$ work was provided by a recently published exact three-body calculation [1] for the $^2H(p,\gamma)^3He$ $M1$ astrophysical S factor at $E=0$ (which included Coulomb and meson exchange current effects), and by the prospect for future such calculations in the energy regime $E_p=80$–0 keV [2]. The value of the $^2H(p,\gamma)^3He$ S factor at these very low energies (specifically, for $E_p<10$ keV) is a quantity that has relevance to astrophysical processes such as the stellar proton-proton chain, and protostellar evolution.

Two previous studies of the $^2H(p,\gamma)^3He$ reaction have been made in the energy region of interest ($E_p<80$ keV) [3,4]. Our rationale for restudying this reaction comes from the fact that the existing data set below 50 keV (Griffiths *et al.* [3]) has large error bars and does not precisely determine either the absolute magnitude or slope (i.e., energy dependence) of the $^2H(p,\gamma)^3He$ S factor. The primary advantage that we have over the previous work is being able to use a large volume ($\sim130\%$ efficient) high purity germanium (HPGe) detector which gives exceptionally clean and well-resolved spectra. The high intrinsic resolution of this detector (4.2 keV at 5.5 MeV) allows us to directly view the energy dependence of the $^2H(p,\gamma)^3He$ reaction in our thick target spectra. Our second advantage is being able to use polarized proton beams of high intensity. This allows us to measure the vector analyzing power, $A_y(\theta)$, which has never been done before in this energy regime. The $A_y(\theta)$ observable has the benefit that it is devoid of the systematic errors which can be present in cross-section measurements. Since $A_y(\theta)$ arises solely from interference terms, it [when combined with the $\sigma(\theta)$ data] determines both the amplitudes and relative phase of the $E1$ and $M1$ multipole components, and thus provides a sensitive test of theoretical predictions of these quantities.

Our study of the $^2H(\vec{p},\gamma)^3He$ reaction took place at the Triangle Universities Nuclear Laboratory (TUNL), where an atomic beam polarized ion source [5] was available to produce beams of polarized protons at an energy of $E_p=80$ keV. In order to measure $A_y(\theta)$, the polarized source was allowed to fast spin flip (at 10 Hz) between two vector polarized spin states which had their axes of symmetry aligned perpendicular to the reaction plane. Our experimental method was to stop the 80 keV beam in a pure D_2O ice target, thereby creating a range of incident protons with energies E_p from 80 to 0 keV. This range of incident beam energies created outgoing γ rays, from $^2H(\vec{p},\gamma)^3He$, which had energies in the range $E_\gamma=5.49$–5.57 MeV. These γ rays were detected using an anticoincidence shielded coaxial HPGe detector surrounded by 10 cm of lead. Tests were done with various target biases (i.e., electron suppression) in order to ensure accurate beam current integration.

Figure 1(a) shows a typical $^2H(p,\gamma)^3He$ singles spectrum acquired with the HPGe detector (for $E_p=80$–0 keV). The full energy peak on the right-hand side is preceded by the first and second escape peaks, respectively. Raw spectra such as this were obtained for the $^2H(\vec{p},\gamma)^3He$ reaction at a total of 6 laboratory angles ($0°,30°,60°,90°,105°,120°$). A typical HPGe full energy peak count rate, for a laboratory angle of 90°, was about 400 counts/h. This count rate was monitored to gauge changes in the purity of the D_2O ice target (no problems were encountered). Figure 1(b) shows a blow up of the full energy peak (with the anticoincidence condition ap-

*Present address: Lawrence Berkeley Laboratory, Berkeley, CA 94720.

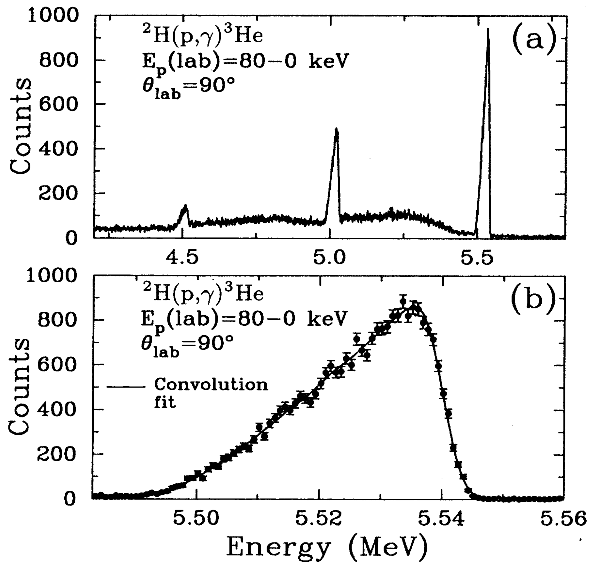

FIG. 1. A typical HPGe spectrum for $^2H(p,\gamma)^3He$ showing (a) the full response and (b) the full energy peak only. The solid line in (b) is our convolution fit to the raw spectrum.

plied), where the peak width is due to the spread in γ-ray energies present. The falling yield on the low energy side of the peak is due to the rapidly decreasing cross section (with decreasing beam energy) of the $^2H(p,\gamma)^3He$ reaction. The solid line in Fig. 1(b) is a convolution fit to the raw spectrum. This fit was performed by convoluting a parametrized $^2H(p,\gamma)^3He$ yield function with the known HPGe response function, and then varying parameters in order to obtain the best possible solution. In this manner, the spectrum is "deconvoluted," and the result is an exact expression for the $^2H(p,\gamma)^3He$ yield [and hence the $^2H(p,\gamma)^3He$ S factor] over the energy region E_p(lab)=80–0 keV ($E_{\text{c.m.}}=53.3$–0 keV). The good fit to the spectrum ($\chi^2/\nu=1.05$) demonstrates the validity of our deconvolution procedure, and hence the reliability of our $S(E)$ result.

The shape of the $^2H(p,\gamma)^3He$ yield function mentioned above was formed by the product of a parametrized $^2H(p,\gamma)^3He$ cross-section function, $\sigma(\theta,E)$, with a function representing the deuterium areal density of the D_2O target, $2\,dE/\text{STP}(E)$. The $\sigma(\theta,E)$ function had the form $\sigma(\theta)=[S(\theta,E_{\text{c.m.}})/E_{\text{c.m.}}]e^{-2\pi\eta}$, where η is the Sommerfield parameter [6] and $S(\theta,E_{\text{c.m.}})=S_0(\theta)+E_{\text{c.m.}}S_1(\theta)$ is the differential S factor [$S_0(\theta)$ and $S_1(\theta)$ are the free parameters to be determined]. The linear form for the S factor (representing the one model-dependent assumption of this analysis) is chosen on the basis of empirical evidence derived from previously published studies of other low energy, nonresonant, capture reactions [6]. The STP(E) function, representing the stopping of protons by D_2O ice, is known from two measurements which have been acquired in the energy region 20 keV $<E_p<100$ keV [7,8]. The STP(E) curve used in the current analysis was derived by fitting these data points to a standard empirical form [9], and then extrapolating this shape smoothly to zero energy. The absolute scale of the parametrized yield function required the additional knowledge of the total integrated charge, and the efficiency times solid angle ($\varepsilon\, d\Omega$) for the HPGe full energy peak. A value for $\varepsilon\, d\Omega$ was determined by using an absolutely calibrated mixed radionuclide source [10] (traceable to NIST) which emitted γ-ray lines up to $E_\gamma=1.84$ MeV. Once $\varepsilon\, d\Omega$ was determined at this top energy, the efficiency vs energy curve obtained from a ^{66}Ga source [11] (which emits γ-ray lines from 0.8–4.8 MeV) was used to extrapolate the results up to 5.5 MeV, where the $\varepsilon\, d\Omega$ value was needed.

In addition to the parametrized $^2H(p,\gamma)^3He$ yield function, a form for the HPGe response function was needed in order to carry out the deconvolution procedure. The HPGe response function used was a convolution of two separate components: an intrinsic monoenergetic response function; and a kinematic response function [which accounts for the fact that the γ-ray energy in $^2H(p,\gamma)^3He$ is a function of angle]. The intrinsic response function was obtained from measurements of radioactive monoenergetic sources, while the kinematic component was calculated using Monte Carlo techniques. Once the total HPGe response function was obtained, it was then convoluted with the parametrized $^2H(p,\gamma)^3He$ yield function and fit to the raw spectra [Fig. 1(b)] by minimizing the chi-squared (using the MINUIT [12] code). Background components were added in during the fit. The energy calibration of the spectra in keV/channel was determined from background lines (e.g., ^{40}K, radiothorium), although the absolute energy scale (determined to within ± 0.8 keV), was treated as a free parameter in the fit. It should be emphasized that since the fit to a given spectrum is done simultaneously to all the data, the extrapolation to zero energy will be based primarily on the more accurate high energy data. For this reason, effects present only at very low energies, such as Coulomb screening effects [13] and unknown low energy STP(E) values, should not affect our results.

The final result of the deconvolution analysis is a set of $S(\theta,E)$ data. In order to get an expression for the total S factor $S(E_{\text{c.m.}})=S_0+S_1E_{\text{c.m.}}$ we can fit the $S(\theta,E)$ data to Legendre polynomials, and then integrate the resulting functions over all angles. The results for S_0 and S_1 are $S_0=0.121\pm0.005$ eV b and $S_1=0.0052\pm0.0004$ eV b/keV, where the errors do not include a 9% overall systematic uncertainty. The components of this overall systematic error are as follows: 6% for STP(E_p); 6% for $\varepsilon\, d\Omega$; and 1% for beam current integration. The deconvolution result for $S(E_{\text{c.m.}})$ is plotted in Fig. 2 as the solid line. The solid data points in Fig. 2 are the results of a "binning analysis" on the current raw spectra. In the binning analysis, the full energy peak of the acquired spectrum at each angle was divided into 7 bins, starting at $E_p=10$ keV and going in steps of 10 keV up to $E_p=80$ kev. The background subtracted yields acquired in this manner were also corrected for the effects of "tailing" in the HPGe response function. The binning results for the total cross section (derived from a Legendre fit to the binned angular distribution data using the A_0, A_1, and A_2 coefficients) are plotted at the center-of-bin beam energy ($\bar{E}_p$), and include the 9% systematic error in their error bars. Based on the uncertainty in the energy calibration, an overall uncertainty of ± 1 keV is assigned to the $\bar{E}_p$ values.

Also shown in Fig. 2 are the results of the previous $^2H(p,\gamma)^3He$ experiment of Griffiths *et al.* [3], indicated by

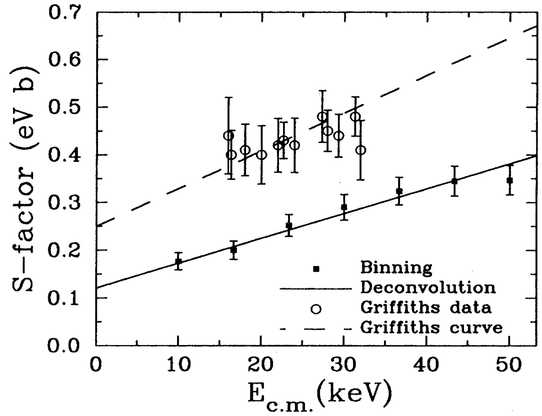

FIG. 2. Current results for the ^{2}H$(p,\gamma)^3$He S factor (the solid points and solid line) are plotted vs c.m. energy. The previous results of Ref. [3] (the open points) are also shown, where the dashed curve is a DC calculation normalized to their data. Systematic error is included in all points on this graph.

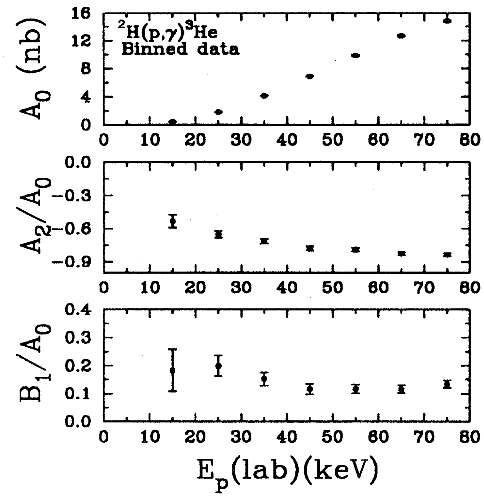

FIG. 3. The currently acquired ^{2}H$(\vec{p},\gamma)^3$He data as parametrized in terms of finite geometry corrected Legendre coefficients, where $\sigma(\theta)=A_0+A_2P_2(\cos\theta)$ and $\sigma(\theta)A_y(\theta)=B_1P_1^1(\cos\theta)$ at each energy [the A_1 and B_2 coefficients are identically zero in this case due to the constraints which were imposed (see text)]. Only statistical error is shown in the error bars.

the open circles (systematic uncertainties are included in the error bars). The present results are 41–52% lower than the Griffiths *et al.* results over the measured energy region. Comparison of our data with the results of Ref. [4] is not attempted due to the large bin widths used there (resulting in large uncertainties in the center-of-bin beam energies). The data points of Griffiths *et al.* were obtained by deconvoluting thick target yields using a theoretical $\sigma(E)$ energy dependence. The dashed line represents a direct capture (DC) calculation done by Griffiths *et al.* normalized to their data by an overall multiplicative constant. Using this curve, they extract an S_0 value [3] of 0.25 ± 0.04 eV b (including systematic uncertainty) and an S_1 value of 0.0079 (no quoted error). If we cast the S factor into the form $S(E_{\mathrm{c.m.}})=S_0[1+(S_1/S_0)E_{\mathrm{c.m.}}]$, the theoretical Griffiths *et al.* curve gives $S_1/S_0=0.0316$ (no error bars are shown, since this ratio is completely theoretical in nature). The currently extracted result for S_1/S_0 is 0.0430 ± 0.0034 keV (showing statistical error only), which is 36% higher than the Griffiths *et al.* result, thus demonstrating a different energy dependence for the total S factor.

With regard to the difference in absolute magnitude between the current results and those of Griffiths *et al.*, it is important to point out the fact that Griffiths *et al.* used STP (E_p) data acquired for H_2O vapor even though their target was actually D_2O ice. Based on the proposed "physical state effects" [14–17] it should be expected that the STP(E_p) values for H_2O vapor will be 10–15 % higher than the results for D_2O ice. This has been verified by experiment [18,19]. Since the measured S factor scales directly with STP(E), this indicates that the S-factor values of Griffiths *et al.*, shown in Fig. 2, are high by about 10–15 % due to this effect alone.

We can extract the $E1$ and $M1$ components of the ^{2}H$(p,\gamma)^3$He S factor by performing a transition matrix element (TME) fit to our binned angular distribution data sets at each energy (including the analyzing power). We make use of the deconvolution results for $S_0(\theta)$ to obtain a data set at zero energy. In order to obtain unique solutions in the TME analysis, it is necessary to impose some constraints on the free parameters. We make the assumption that the two $E1$ transition matrix elements have equal amplitudes and phases which reduces the problem to three free parameters: an $E1$ amplitude; an $M1$ amplitude; and a relative phase. This assumption is equivalent to requiring a $\sin^2\theta$ $E1$ distribution and an isotropic $M1$ distribution (equivalent to the assumption of Griffiths *et al.* [3], except that now we also determine the $E1$-$M1$ relative phase). Based on the results of our binning analysis we have shown that this assumption is accurate at all energies measured. While all of our results for the $E1$ and $M1$ S factors (as a function of energy) will be discussed in detail in a future paper, we present here the current results at $E=0$. Our extracted values are $M1S(0)=0.079\pm0.008$ eV b and an $E1S(0)=0.053\pm0.005$ eV b. It should be noted that the total $S(0)$ value quoted earlier, which was derived without the constraints discussed above, is 8% lower than the sum of the $E1$ and $M1$ $S(0)$ values. The experimental value for $M1S(0)$ can be compared to a recently published three-body Faddeev calculation for this quantity [1], which includes both Coulomb and meson exchange current effects. Our result for $M1S(0)$ is 27% lower than the calculated result [1] of 0.108 ± 0.004 eV b. The experimentally extracted value of Griffiths *et al.* was 0.12 ± 0.03 eV b [3]. Figure 3 displays the results of a parametrization of our binned angular distribution data in terms of the coefficients of Legendre and first associated Legendre polynomials. The Legendre coefficients shown in Fig. 3 were obtained using the constraints described above which sets A_1 and B_2 to zero (see caption for Fig. 3). These coefficients can be used to test the validity of future theoretical work on the ^{2}H$(\vec{p},\gamma)^3$He reaction in this energy regime.

Since the absolute magnitude for our measured ^{2}H$(p,\gamma)^3$He S factor is lower than the currently accepted value, it is interesting to consider the possible astrophysical consequences. Although ^{2}H$(p,\gamma)^3$He is known to take part in the solar proton-proton chain, the sensitivity of this process to the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ reaction rate is expected to be negligible for the following reason: $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ follows the weakly interacting $p+p \rightarrow D+e^{+}+\nu$ in the proton-proton sequence [6], and thus has its reaction rate effectively bottlenecked by some 18 orders of magnitude. This leads to the conclusion that a 52% change in the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ S factor will have no effect on energy production in the proton-proton chain, and thus, for example, will have no bearing on the solar neutrino problem [6].

Despite its relative unimportance in main-sequence stellar burning, the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ reaction plays a very significant role in the process of pre-main-sequence stellar evolution. Once a developing protostar is hot enough ($\sim 10^{6}$ K), $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ becomes the first nuclear reaction to ignite, and it proceeds by burning the primordial deuterium which is present. A recent calculation [20] has shown that this burning leads to a "thermostat" effect, whereby the temperature of the protostellar core is held to a constant temperature and the mass-radius relation of the core is tightly constrained. The manifestation of this "thermostat" effect is a theoretical stellar birthline (on an H-R diagram) which can be directly compared to experimental observations of T Tauri stars. The sensitivity of this calculation to the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ S factor is a topic which, in the light of the current results, appears to warrant further study. Earlier calculations on protostellar evolution [21–23] have also addressed the issue of deuterium depletion in heavy stars. These calculations have indicated that primordial deuterium could possibly survive the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ burning process in heavy protostars, and thus be present in the outer envelopes of heavy main-sequence stars. Recent theory argues against this scenario [24]. However, the current experimental results, which indicate a lower $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ S factor (and thus, ostensibly, a lower deuterium depletion rate), could potentially alter these arguments.

In conclusion, our results for the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ S factor (in the energy regime $E_{p}<80$ keV) demonstrate a different absolute magnitude, and a different energy dependence, than currently believed. Furthermore, our accurately measured angular distribution data, presented here as Legendre polynomial coefficients, must be accounted for in future theoretical treatments of the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ reaction. Astronomical calculations which involve the $^{2}\mathrm{H}(p,\gamma)^{3}\mathrm{He}$ reaction rate in the energy regime $E_{\mathrm{c.m.}}<53.3$ keV need to be reexamined in light of our new results.

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