ASTROPHYSICAL S FACTOR OF $^3H(\alpha,\gamma)^7Li$ ☆

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The reaction $^3H(\alpha,\gamma)^7Li$ has been investigated for $E_{CM}=79$–464 keV with the use of Ge(Li) detectors. The astrophysical $S(E)$ factor is found to be energy-dependent, rising smoothly to $S(0)=0.14\pm0.02$ keV b at zero energy. This is a factor of two higher than the value incorporated in the compilations. The energy dependence of the data is consistent with recent microscopic and direct capture model calculations. The higher ^7Li production rate is of interest to primordial nucleosynthesis.

The nuclides ^2H, ^3He, ^4He and ^7Li are made primarily by big-bang nucleosynthesis in a network of nuclear reactions [1–3]. Calculated abundances based on cross sections for these reactions are compared with observed abundances. This comparison is used to deduce information on the baryon density of the Universe and has implications in other fields including cosmology and particle physics [1–3]. For these reasons improved input data are needed, such as the rate [3] for the reaction $^3H(\alpha,\gamma)^7Li$. The cross section $\sigma(E)$ of this reaction ($Q=2468.0\pm0.8$ keV [4]) has been studied [5,6] down to $E_{CM}=150$ keV. The data [5] were consistent with an energy-independent astrophysical $S(E)$ factor,

$$S(E)=\sigma(E)E\exp(2\pi\eta)\ ,$$

where $2\pi\eta=82.07/E^{1/2}$ (E is the CM energy in keV), with $S(0)=0.064$ keV b. The reaction was shown to be dominated [5] by the direct capture (DC) process [7] into the ground state (DC→0) and the 478 keV state (DC→478), with a branching ratio around 0.4. The above result has been recommended in the compilations [8]. Recent microscopic as well as DC model calculations [9–12] predict an $S(E)$ factor that increases slowly with decreasing energy, which is also consistent with the data [5], leading to $S(0)\simeq0.10$ keV b. In order to test the predictions of these recent calculations, further detailed measurements of this reaction appeared desirable, especially at low energies (primordial nucleosynthesis occurs at an effective energy of $\simeq10$ keV).

The experiments were carried out at the 1 MV JN Van de Graaff accelerator at the University of Toronto with α particle currents of 2–13 μA. The experimental set-up was similar to that described previously [13]. Briefly, the beam passed through a 1.0 cm Ta collimator and was defocused on the target to a beam spot of 1.4 cm diameter, to reduce trit-

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ium loss. The Ti^3H target [#1] (about 20 μg/cm^2 thick, on a Cu backing) was directly watercooled. A liquid-nitrogen (LN_2) cooled in-line Cu tube extended close to the target. A voltage (−300 V) was applied to the Cu tube to minimize the effects of secondary electron emission. With this tube and additional LN_2 traps in the vacuum system, no carbon-buildup on the target was observed. The γ-rays were observed with well-shielded 80 and 104 cm^3 Ge(Li) detectors of about 1.9 keV energy resolution (for $E_\gamma = 1.33$ MeV). The efficiency curves of the detectors were determined for $E_\gamma = 0.3$–6.8 MeV using calibrated sources as well as γ-rays from the 278 keV resonance in $^{14}N(p,\gamma)^{15}O$. The energy calibration of the detectors was obtained using the well-known energies of several background γ-ray lines (fig. 1).

For the measurement of excitation functions, the 104 cm^3 Ge(Li) detector was placed at $\theta_\gamma = 0°$ and at a distance to the target $d \simeq 1.0$ cm. Target stability was monitored by periodic γ-yield determinations at $E_{CM} = 247$ keV; the yield remained constant within ±5%. The effective beam energies E_{CM} within the target were determined to a precision of ±0.5 keV from the centroid $E_\gamma(0°)$ of the DC→0 peak (fig. 1):

$$E_{CM} = E_\gamma(0°) - \Delta E_{DS}(0°) + \Delta E_R - Q\,,$$

where $\Delta E_{DS}(0°)$ is the Doppler shift and ΔE_R the nuclear recoil. The above error in E_{CM} leads to an uncertainty of ±2.5% in the cross section at the lowest energy of 79 keV. In all runs the energies of the DC→478 keV peak were consistent with the above E_{CM} determinations within experimental errors. Furthermore, the E_{CM} energies were chosen such that both the DC→0 and DC→478 keV peaks were not obscured from background lines.

Anisotropies, $I_\gamma(0°)/I_\gamma(90°)$, were obtained at $E_{CM} = 114$, 253 and 396 keV with the two detectors placed at $d \simeq 5$ cm. The data show isotropy within experimental errors and are consistent with previous work [5] and with DC model predictions [7].

The yields at each E_{CM} needed correction only for detector efficiencies and accumulated charge, since the angular distribution corrections were negligible. The summed yields (DC→478 plus DC→0) have been used to obtain the total $S(E)$ factor, which is shown along with the branching ratios

[#1] Supplier: Amersham, Canada.

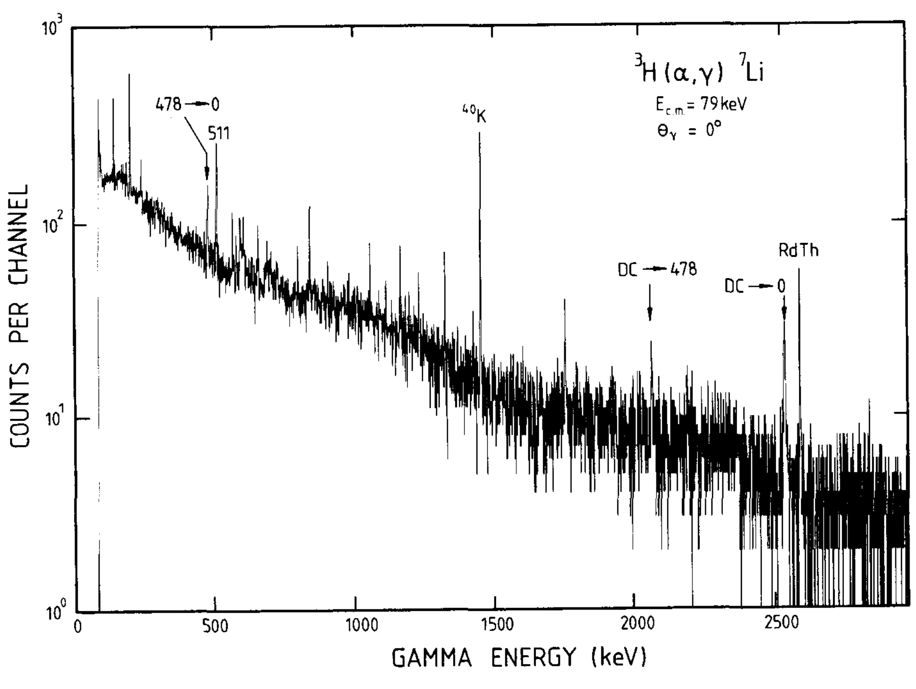

Fig. 1. Sample γ-ray spectrum is shown as obtained with the 104 cm^3 Ge(Li) detector at the lowest energy. The centroid and width of the DC→0 full energy peak was used to determine the effective beam energy within the target and the target thickness, respectively.

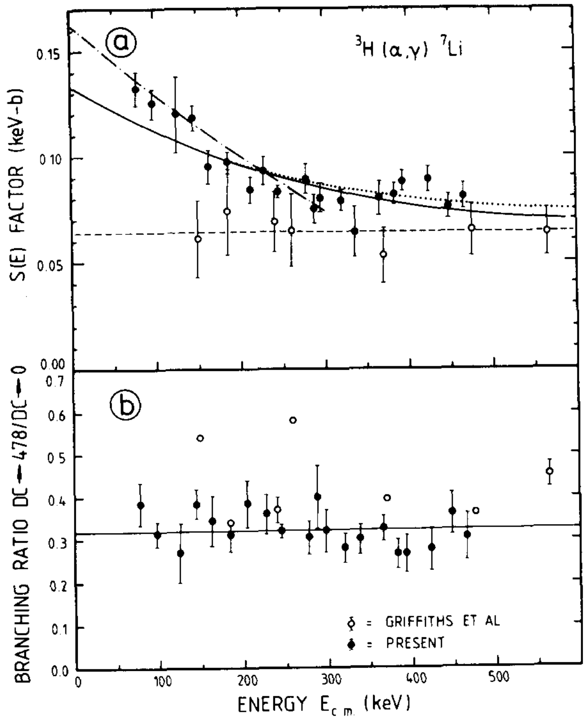

Fig. 2. Shown are the data of previous [5] and present work for (a) the total $S(E)$ factor and (b) the branching ratio DC→478/DC→0. An additional error to the total $S(E)$ factor of ±15% from the uncertainty in the absolute cross section has to be added to the present data. In previous work [5], errors have been quoted only for a few data points. The dashed line through the previous data points assumes [5] a constant $S(E)$ factor. The solid curves are the results of our DC model calculations normalized to the present data. Similarly, the dotted and dash-dotted curves are the results of microscopic [9–11] and DC [12] model calculations, respectively, where the latter is valid at $E_{CM} \leqslant 300$ keV.

(DC→478/DC→0), in fig. 2. The DC→478 data represent the weighted average of the results obtained for the DC→478→0 cascade.

The number of tritium atoms/cm^2, N_T, was determined via reference to the well-known [14] cross section of $\sigma_T = 30 \pm 2$ μb at $E_p = 1$ MeV for the ^{3}H(p,γ)^{4}He reaction. The 20 MeV γ-ray yield, N_γ, from this reaction was observed with a 7.6 cm diameter ×7.6 cm long NaI(Tl) crystal at $\theta_\gamma = 125°$ ($d = 10$ cm) having a total γ-ray efficiency $\varepsilon_\gamma = 0.015$ [15]. After extrapolation of the observed spectrum shape from $E_\gamma = 6$ to 0 MeV, and correction for absorption A_γ in the target chamber ($A_\gamma = 0.92$), the value of $N_T = (3.0 \pm 0.4) \times 10^{17}$ atoms/cm^2 was obtained. The quoted error was arrived at by the quadratic addition of uncertainties in σ_T (±7%), ε_γ (±5%), A_γ (±3%), N_γ (±7%) and charge integration (±5%). The N_T value is consistent with the quoted activity of the target (16 mCi per cm^2) and the observed target thickness ($\Delta_{CM} = 12.2$ keV at $E_{CM} = 247$ keV) using stopping power tables [16] and assuming a target stoichiometry of Ti^{3}H$_{1.2}$ [17]. With this N_T value, the absolute cross section for ^{3}H(α,γ)^{7}Li at $E_{CM} = 247$ keV was found to be $\sigma = 1.81 \pm 0.26$ μb ($S = 0.083 \pm 0.012$ keV b). The error includes the uncertainties in N_T (±13%), Ge(Li) detector efficiency (±5%), charge measurement (±5%) and statistics (±2%). Griffiths et al. [5] report $\sigma = 1.43 \pm 0.30$ μb at $E_{CM} = 240$ keV (fig. 2a).

The calculations of the DC cross sections follow closely those described previously [7] and use a Woods–Saxon potential with radius $R = 3.3$ fm and surface width $a = 0.7$ fm. The ground state and 478 keV state were assumed to be 2p alpha cluster states. For the calculation of the radial wave function of the initial state, hard-sphere and Coulomb phase shifts were used. The calculations predict a nearly energy-independent branching ratio (solid curve in fig. 2b), in agreement with the data, but an absolute value of 0.42 in contrast to the observed value of 0.32 ± 0.01. The predicted energy dependence of the total $S(E)$ factor (solid curve in fig. 2a) is also in good agreement with the data, except for the absolute scale [S_{th}(247 keV) = 0.11 keV b]. The present results lead to alpha spectroscopic factors of $C^2S = 0.81 \pm 0.12$ and 0.61 ± 0.09 for the ground state and 478 keV state, respectively. The corresponding values from the data of Griffiths et al. [5] are $C^2S \simeq 0.57$ and 0.58.

In summary, the present data and DC model calculations verify the recent model predictions [9–12] of a slowly increasing $S(E)$ factor with decreasing energy [#2]. The $S(E)$ factor at zero energy, extrapolated via the DC model (solid curve in fig. 2a), is $S(0) = 0.134 \pm 0.020$ keV b, where the quoted error includes only experimental uncertainties. The results of microscopic model calculations [9–11] (dotted

[#2] It should be pointed out that the $S(E)$ factor for the mirror reaction ^{3}He(α,γ)^{7}Be has been known for a long time to increase at low energies (see ref. [10] and references therein).

curve in fig. 2a; normalized to the present data with a factor of 1.26) lead to the same $S(0)$ value. Like the DC model calculations, the microscopic model calculations [9–11] also predict a nearly energy-independent branching ratio of 0.42–0.45, in contrast to the observed value quoted above. Since the microscopic model calculations did not reproduce accurately the observed branching ratio, it appeared not appropriate to use their absolute $S(E)$ values but rather to normalize the calculated $S(E)$ curves to the data. It should be noted that the recent microscopic model calculations of Kajino [10] allow $S(0)$ to be in the range 0.08–0.19 keV b. The earlier calculations of Williams and Koonin [12] at $E_{CM} \leqslant 300$ keV (dash-dotted curve in fig. 2a; also normalized to the present data) yield $S(0) = 0.162 \pm 0.024$ keV b. The average value of these three calculations is $S(0) = 0.148$ keV b. If the previous data are included in a weighted normalization, the average $S(0)$ value reduces to 0.14 ± 0.02 keV b. This recommended $S(0)$ value is about a factor of two higher than the value of 0.064 keV b incorporated in the compilations [8].

For low values of the baryon density of the Universe, ^{7}Li is primarily produced and destroyed via the reactions [1–3] ^{3}H$(\alpha,\gamma)^7$Li and ^{7}Li(p,α)^{4}He, respectively. Recent experimental work on the reaction ^{7}Li(p,α)^{4}He led [18] to a $S(0)$ value significantly lower than the recommended value [8]. Thus, ^{7}Li will be produced with larger abundances in primordial nucleosynthesis. This tightens [19] the lower bound on the baryon density of the Universe and thus strengthens the arguments for the maximum number of possible neutrino species. Quantitative consequences have to await the results of complete calculations [19].

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