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THE $^3H(\alpha, \gamma)^7Li$ REACTION IN THE ENERGY RANGE FROM 0.7 TO 2.0 MeV

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Abstract: Differential cross sections for the $^3H(\alpha, \gamma)^7Li$ (g.s.) and the $^3H(\alpha, \gamma)^7Li$ (0.478 MeV) reactions have been measured at 0° in the alpha-particle energy range from 0.7 to 2.0 MeV. A Ge(Li) detector has been used to measure the gamma rays. The results have been compared with recent theoretical calculations of Mertelmeier and Hoffman employing the resonanting group method and a good agreement has been found.

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NUCLEAR REACTIONS $^7Li(\alpha, \gamma)$, $E = 0.7$–2.0 MeV; measured $\sigma(\theta_\gamma = 0°)$. Comparison with resonating group method predictions.

1. Introduction

Among direct capture reactions the $^3H(\alpha, \gamma)$ reaction is particularly interesting because of the large energy range over which it is nonresonant. As the nucleosynthesis occurring during the Big Bang seems to be an only plausible source of ^7Li formation [1]) (cosmic ray spallation of interstellar gas can account for a few percent of ^7Li in the universe [2]), the ^7Li abundance can be compared with the Big Bang predictions based on the assumed S-factor which contains the $^3H(\alpha, \gamma)^7Li$ capture cross section. Measurements of this cross section can thus provide a direct comparison with the S-value assumed in Big Bang theories. The mirror reaction $^3He(\alpha, \gamma)^7Be$ is of some interest in nuclear astrophysics as it may serve as a ^3He burning reaction for the termination of the proton-proton chain:

$$^3He(\alpha, \gamma)^7Be(e^-, \nu)^7Li(p, \alpha)^4He\,,$$

$$^3He(\alpha, \gamma)^7Be(p, \gamma)^8B(\beta^+)^8Be(\alpha)^4He\,.$$

The measurements on the $^3H(\alpha, \gamma)$ reaction which have been reported are in marked disagreement with each other. Total cross sections obtained by Holmgren and Johnston [3]) in the α-particle energy range from 0.5 MeV to 1.3 MeV are over most of the energy range measured about a factor of 2 to 2.5 lower than those of Griffith *et al.* [4]) in the α-particle energy range from 0.35 MeV to 1.83 MeV.

Theoretical studies of α-particle capture reactions on light nuclei have been undertaken with a direct capture model [5,6]) which takes into consideration only

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asymptotic extremes of the wavefunctions. Many-body reaction theories like the resonating group method (RGM) or the generator coordinate method (GCM) are specially suitable for studying reaction involving a small number of nucleons at low energies, i.e. at few open reaction channels. Those microscopic approaches have described successfully light radiative capture reactions at the expense of the adjustment of the nucleon-nucleon potential parameters [7-10]). A microscopic potential model has also been applied [11]). It combines the many-body wavefunction generated by the RGM or GCM into the flexibility of a phenomenological potential containing the parameters which account for physically relevant input data.

The present experiment has been carried out to resolve the existing discrepancies in the reported values for the cross section and to supply new data to check microscopic predictions of the direct capture theory involving no free parameters and based on the resonating group method. Quite recently Mertelmeier and Hoffman [12]) have shown that this method is particularly suitable for calculations of electromagnetic transitions in which, due to the long range Coulomb forces, one probes the wavefunctions beyond the nuclear interaction range.

2. Experimental procedure

The experiment has been carried out with a singly-charged helium ion beam from a 3 MeV Van de Graaff accelerator of the Institute for Nuclear Studies. The beam is analysed by a 90° magnet and collimated to a 5 mm diameter spot onto a target. Tritium absorbed in a thin layer of titanium evaporated onto a copper plate composed the target. The copper plate itself formed the bottom of a Faraday cup. With an intense water cooling the target was capable of withstanding beam currents of up to 15 μA without any noticeable loss of yield.

The capture γ-rays were measured with a 80 cm^3 Ge(Li) detector of 2.7 keV FWHM resolution for the ^{60}Co 1.33 MeV peak. The detector was placed at a distance of 20 mm from the target at 0° to the beam axis. Because of the low γ-ray yield great care was taken to reduce the background, particularly from the $^{13}C(\alpha, n)^{16}O$ reaction. All parts of the beam line which could be struck by the beam were thoroughly cleaned and a liquid nitrogen trap was placed just in front of the target. The runs at different α-particle energy were interspaced with the runs at $E_\alpha = 2.0$ MeV to establish the stability of the tritium content of the target. No noticeable loss of the yield was observed within an accuracy of 5%.

Standard electronics was employed for accumulation of singles γ-ray spectra over 2048 channels in the Nuclear Data 4420 System.

2.1. THE Ge(Li) DETECTOR EFFICIENCY

The efficiency of the Ge(Li) detector for the α capture γ-rays has been determined with γ-ray sources. The geometry γ-source–Ge(Li) detector strictly reproduced the geometry beam spot–Ge(Li) detector employed in the ^{4}He runs. The determined efficiency, e, comprises thus the intrinsic efficiency of the Ge(Li) detector, ε, and the factor of the solid angle subtended at the target by the detector:

$$e = \frac{d\Omega}{4\pi}\varepsilon .$$

The relative efficiency of the detector as a function of γ-ray energy has been determined with ^{56}Co and ^{226}Ra γ-sources. The energies of γ-rays from those sources span the energies of α-capture γ-rays detected in the experiment. Relative intensities of relevant γ-lines were taken for ^{56}Co from refs. [13-15]) and for ^{226}Ra from refs. [16-18]).

For determination of the absolute efficiency the sum peak method with ^{60}Co γ-source has been applied. Denoting the photopeak efficiency, for the γ-1 line (1173.34 keV) by e_1 and for the γ-2 line (1332.50 keV) by e_2 and the corresponding numbers of counts in the detector by N_1 and N_2 we obtain in first-order approximation:

$$N_1^0 = e_1^0 b_1 n ,$$

$$N_2^0 = e_2^0 b_2 n ,$$

where n is the number of decays of ^{60}Co and b_1 and b_2 are the numbers of γ_1 and γ_2 quanta per decay, respectively. Let us denote by r_1 that fraction of γ_1 quanta which feeds the γ_2 transition and by r_2 that fraction of γ_2 quanta which is in cascade with the feeding γ_1 quanta. The products $b_1 r_1 = b_2 r_2$ are then the fractions of all the decays followed by the cascade.

As in ^{60}Co there is no transition of an energy $E = E_1 + E_2$ the number of counts of the summed line (2505.84 keV) will then be

$$N_{12} = e_1^0 e_2^0 b_1 r_1 n = e_1^0 e_2^0 b_2 r_2 n .$$

the first-order approximation yields:

$$e_1^0 = \frac{N_{12}}{N_2^0 r_2} ,$$

$$e_2^0 = \frac{N_{12}}{N_1^0 r_1} .$$

These "first-order efficiencies" have to be corrected for events resulting in a loss of counts from the photopeaks of the γ-lines which are due to

(i) summation of the two full energy pulses

(ii) summation of one full energy pulse with a Compton pulse of another line.

Corrected numbers of counts will then be

$$N_1 = N_1^0 - N_{12} - N_2^C e_1^0 r_2 ,$$

$$N_2 = N_2^0 - N_{12} - N_1^C e_2^0 r_1 ,$$

where N_i^C is the number of Compton counts produced in the detector by the γ-line i. To obtain the numbers of Compton counts N_i^C a theoretical total cross section for Compton scattering σ^C was calculated from formula given in ref. [21]) and the N_i was then taken as a fraction of the total number of Compton counts produced by both γ-lines in the whole measured spectrum, N_{tot}^C

$$N_i^C = \frac{b_i \sigma_i^C}{b_1 \sigma_1^C + b_2 \sigma_2^C} N_{tot}^C .$$

The corrected efficiencies were then calculated from formulae:

$$e_1 = \frac{N_1^0}{N_1} e_1^0 ,$$

$$e_2 = \frac{N_2^0}{N_2} e_2^0 ,$$

with the following values of the constants [19,20]): $b_1 = 0.9974$; $b_2 = 1.0$; $r_1 = 1.0$; $r_2 = 0.9974$. Absolute calibration with the sum peak method and the energy dependence of the efficiency determined with ^{56}Co and ^{226}Ra γ-sources yielded the efficiency curve shown in fig. 1. The curve has been obtained as a least squares fit to the measured efficiencies with a normalization factor obtained from the absolute calibration. The error bars comprise the statistical errors and the uncertainties in relative intensities. An overall normalization error of the Ge(Li) efficiency in the relevant γ-ray energy has been estimated to amount to 6% with the main contribution from the uncertainty in reproducing the beam spot–Ge(Li) geometry.

2.2. THE THICKNESS OF TRITIUM TARGET

To determine the thickness of tritium target the $^3H(d, n)^4He$ reaction at $E_d = 1.0$ MeV has been employed. The cross section for this reaction is well known.

Neutrons were detected with a proton recoil spectrometer set at an angle of 90° to the deuteron beam and at a distance of 28 cm from the beam spot on the target. Protons recoiled at angles $0° \pm 13°$ from a CH_2 foil of a thickness of 66.6 mg/cm^2 were detected in a CsJ(Tl) crystal coupled to a 6097 phototube. The thickness of the crystal slightly exceeded the range of recoiled protons and amounted to 1.2 mm. The distance between the radiator and the crystal was 49 mm. The background due to neutron induced reactions in the crystal and in the walls of the spectrometer was measured in a separate run taken without the radiator.

If the number of detected recoil protons is N_p, the thickness of the tritium target in at/cm^2 is

$$n_t = \frac{N_p}{n_d d_H \int (d\sigma(d, t)/d\Omega) d\Omega_t \int (d\sigma(n, p)/d\Omega) d\Omega_s} ,$$

where n_d is the number of deuterons inducing the reaction and d_H is the number of H atoms per cm^2 in the radiator.

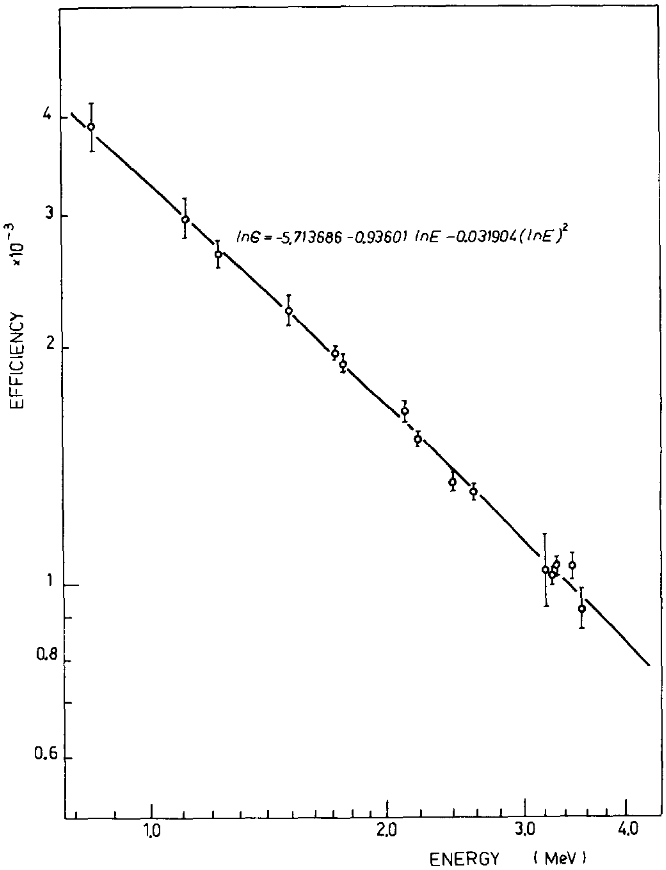

Fig. 1. Gamma-ray efficiency for the Ge(Li) detector as determined in the in-beam geometry.

The integration of the (d, n) cross section over the solid angle subtended by the radiator at the target $d\Omega_t$ and of the (n, p) cross section over the spectrometer solid angle $d\Omega_s$ has been carried out using Monte Carlo technique. The angular dependence of the $^3H(d,n)^4He$ cross section was taken from ref. [22]) and for the (n, p) elastic scattering the angular distribution at a relevant neutron energy was obtained from a phenomenological expression due to Gammel [23]) with the np total cross section equal to of 673 mb [ref. [24])]. The absolute value of the $^3H(d,n)^4He$ cross section at $E_d = 1.0$ MeV was taken to be 19.2 mb/sr and the (n, p) scattering cross section at 0°–218.8 mb/sr. The determined thickness was $1.084 \cdot 10^{17}$ at/cm^2. The exact thickness of the titanium layer in the target was difficult to measure. The tritium to titatnium ratio in T-Ti targets is usually close to 1 which would correspond to a titanium thickness of 8.6 μgm/cm^2. For this thickness the energy losses of particles in the T-Ti target amount to 12, 9, 8 and 7 keV at incident energies of 700, 1000, 1500 and 2000 keV, respectively.

The beta decay of tritium has been utilized to measure the uniformity of the tritium content in the target. The surface of the target has been scanned with a thin windowed (10 μm berylium) Si(Li) gamma detector provided with a 1 mm diameter collimator to look at the bremsstrahlung radiation of beta particles. Maximum deviations of the counting rates in the relevant parts of the target did not exceed 10%.

The error of the tritium content determined in this way has been estimated to amount to 12% with the following contributions: tritium content nonuniformity - 10%, counting statistics - 3%, radiator thickness - 2%, collected beam charge - 2%, proton spectrometer geometry - 3%, (d, t) cross section - 4%, (n, p) cross section - 2%.

3. Results and discussion

The γ-ray spectrum obtained under bombardment with 1 MeV He ions is shown in fig. 2. The energy calibration corresponds roughly to 2 keV per channel. The total accumulated charge amounted to 700 mC. For the transition to the ground state of ^{7}Li the full energy peak and the first escape peak lying close to the full energy peak of α-capture to the first excited state of ^{7}Li are clearly seen. The capture peaks exhibit a Doppler shift amounting to 30 keV and 22 keV for the transition to the ground and the first excited state, respectively. The width (FWHM) of the capture

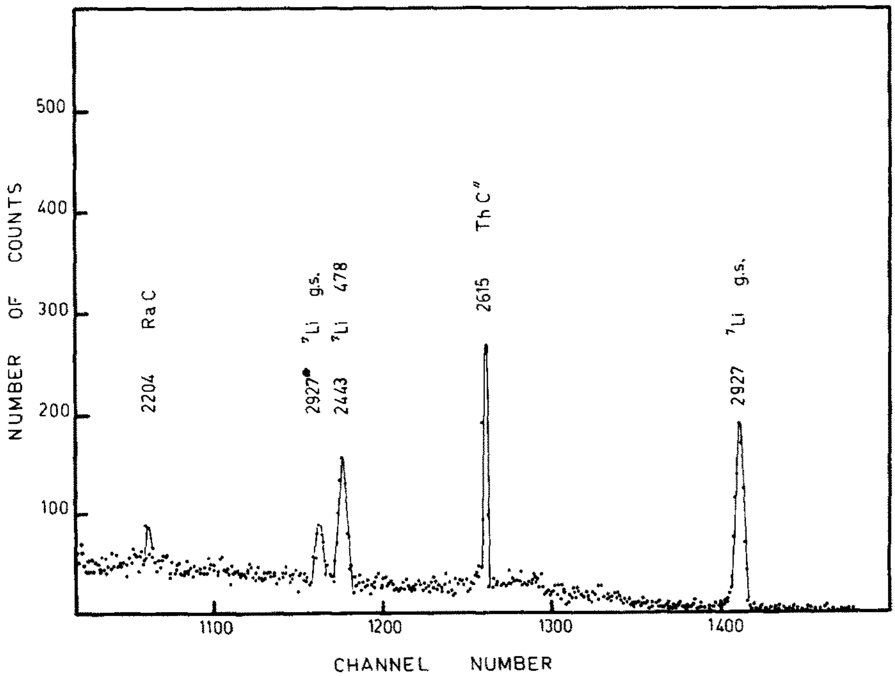

Fig. 2. $^3H(\alpha, \gamma)^7Li$ spectrum at a bombarding energy of 1.0 MeV. Asterisk denotes a single escape peak.

peak amounts to 10 keV and is roughly equal the calculated energy loss of the α-particle in the target. The background under the peaks was obtained by a linear extrapolation from the region outside the peaks. The uncertainty introduced by this procedure was estimated from different extrapolations and found to be much lower than the statistical error of the number of counts under the peaks. The yields measured have been corrected for the absorption of γ-rays in the target holder, the correction ranged from 2.5% to 3.3%, depending on the γ-ray energy. The correction for the Ge(Li) efficiency yields the numbers of α-capture γ-quanta. As mentioned in sect. 2.1 the Ge(Li) efficiency determined in the present experiment, e, comprises the solid angle subtended at the target by the detector, thus providing immediately $d\sigma/d\Omega = N_\gamma / N_\alpha N_T 4\pi e$, where N_γ is the number of registered γ-quanta, corrected for the absorption in the target material, N_α the number of α-particles on the target, N_T the number of tritium atoms per cm^2.

The measured differential cross sections transformed into the c.m. system are given in table 1. The listed c.m. energies correspond to the mean α-particle energies in the target. The errors are only statistical with the error due to background subtraction included. The error of overall normalization has been estimated to amount to 14% with the contribution from the target tritium content at 12%, Ge(Li) efficiency at 6%, beam charge at 2%. Our results are in a very good agreement with the results of Griffith *et al.* [4]). In fig. 3. the total capture cross sections are compared with theoretical calculations of Mertelmeier and Hoffman for the E1 capture [12]). To obtain the total cross sections an isotropic γ-emission (capture from α-particle s-waves only) for incident energies of 700 and 1000 keV has been assumed. The assumption seems to be justified in view of isotropic γ-emission observed at $E_\alpha =$ 800 keV and small anisotropy found at $E_\alpha = 1600$ keV [ref. [4])]. For incident energies of 1500 and 2000 keV a small correction factor accounting for nonisotropic yield, κ has been introduced and the total cross section has been obtained from formula $\sigma_{tot} = \kappa (d\sigma/d\Omega)_{0°} 4\pi$. The correction factor has been estimated from anisotropy measured by Griffith *et al.* [4]) at an incident energy of 1600 keV and found to be $\kappa = 0.88 \pm 0.04$. The same correction factor has been applied for incident energy of 1500 keV and 2000 keV and for the ground state and the first excited state transitions. The amount of anisotropy should be higher at $E_\alpha = 2000$ keV but as there are no

TABLE 1

Differential c.m. cross sections at 0° for the $^3H(\alpha, \gamma)^7Li$ reaction

α-particle c.m. energy (MeV)	$d\sigma/d\Omega$ ground state	(μb/sr) 0.478 MeV state
0.297	0.094 ± 0.005	0.044 ± 0.005
0.427	0.141 ± 0.005	0.077 ± 0.006
0.641	0.190 ± 0.007	0.099 ± 0.007
0.856	0.224 ± 0.007	0.111 ± 0.007

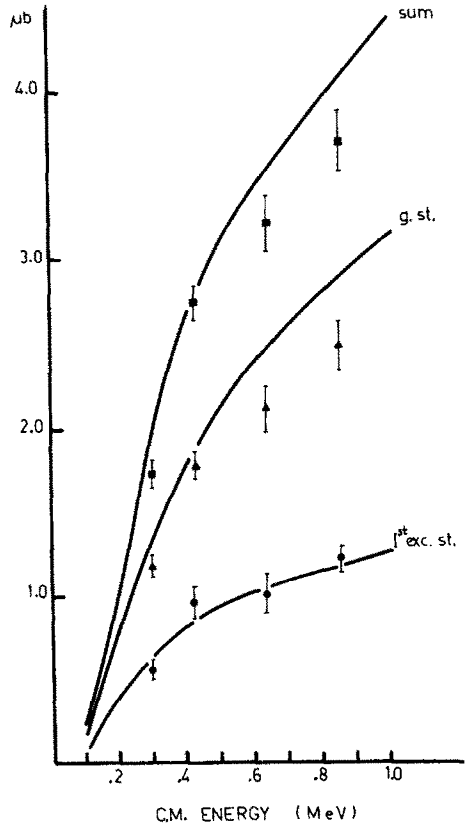

Fig. 3. Excitation functions for the $^3H(\alpha, \gamma)^7Li$ (g.s.) and the $^3H(\alpha, \gamma)^7Li$ (0.478 MeV) reaction. Curves represent results of calculations of Mertelmeier and Hoffman.

data on the angular distribution of γ-rays the same anisotropy correction has been maintained at that energy. The error bars for points at c.m. energies 297 keV and 427 keV are only statistical with the error of background subtraction accounted for. For the points at c.m. energies 641 keV and 856 keV the error in the determination of the κ-factor has been included. The error of overall normalization is 14%. Mertelmeier and Hoffman applied the refined resonating group method with an effective nucleon-nucleon potential without free parameters. This method allows to account for the influence of inelastic channels and distortion effects in addition to the cluster structure of a light nucleus. The two fragment scattering functions and the bound state wavefunctions are obtained by the vibrational Kohn-Hulthen principle and vibrational Ritz principle, respectively.

The agreement is very good with a certain overprediction by theory of the cross section for the capture to the ground state of ^7Li. These calculations show that the resonating group method is also suitable for calculations of electromagnetic transitions without free parameters.

A comparison of the astrophysical S-factor defined as

$$S(E) = \sigma(E)E \exp\left(2\pi Z_1 Z_2 \frac{e^2}{\hbar v}\right),$$

calculated by Mertelmeier and Hoffman with experimental results of this work is displayed in fig. 4. The dependence of S on energy exhibits a slight rise towards low energies but the error bars rather discourage an extrapolation which would provide a reliable value useful for theoretical calculations. It is worth noting that the extrapolation of the theoretical curve to low energies ($E = 0$) results in a higher S-factor than assumed in standard Big Bang theories of early universe. It would point to an underprediction of ^7Li formation rate assumed in Big Bang theories.

We are very much indebted to Drs Mertelmeier and Hoffman for providing us with the results of their theoretical calculations prior to publication.

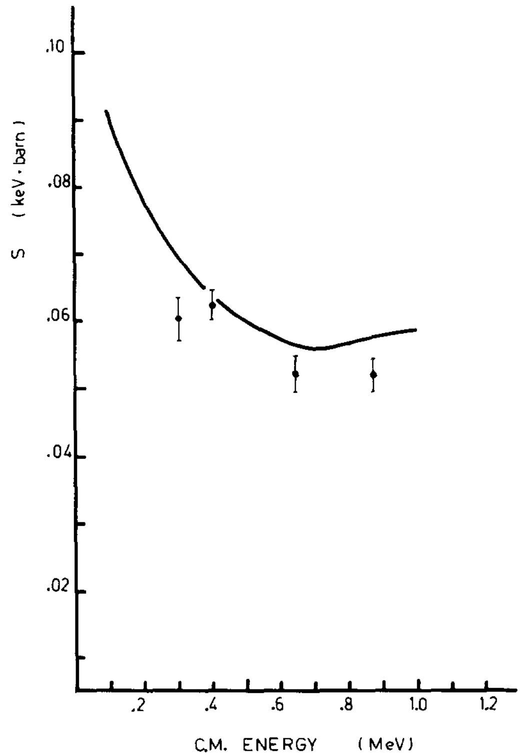

Fig. 4. The cross section S-factor for the $^3H(\alpha, \gamma)^7Li$ reaction. The curve represents results of calculations of Mertelmeier and Hoffman.

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