About the reactions $^{3}H(\alpha,\gamma)^{7}Li$ and $^{3}He(\alpha,\gamma)^{7}Be$

About the reactions $^3H(\alpha,\gamma)\,^7Li$ and $^3He(\alpha,\gamma)\,^7Be$

Wolfgang Löffler†

Institut für Theoretische Physik, Universität Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

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Abstract. In this article the current experimental and theoretical status of the radiative alpha capture reactions $^3H(\alpha,\gamma)\,^7Li$ and $^3He(\alpha,\gamma)\,^7Be$ and their relations to primordial nucleosynthesis and the solar neutrino problem are reviewed.

Zusammenfassung. Es wird ein Überblick über den aktuellen experimentellen und theoretischen Wissensstand der beiden Alpha-Einfangreaktionen $^3H(\alpha,\gamma)\,^7Li$ und $^3He(\alpha,\gamma)\,^7Be$ und deren Zusammenhang mit der primordialen Nukleosynthese und dem solaren Neutrino Problem gegeben.

1. Introduction

The large scale evolution of the Universe would appear to be governed by very few principles: two of which are gravitational attraction and the concept of nucleosynthesis. The latter one describes the creation of the elements in a network of reactions taking place in the interior of stars. Today, the way in which the elements are synthesized is qualitatively understood, but many quantitative questions are still unanswered, and several problems possibly arising from unknown reaction rates are unsolved.

One of the basic problems of nuclear astrophysics is that in most cases it is not possible to determine reaction rates at astrophysically relevant energies by direct observation, because at these low energies the cross sections are far too small to be observable in accelerator experiments. Therefore theoretical models are essential to extrapolate the observed data from higher down to almost zero energy. A review of the basic experimental and theoretical concepts can be found in the book of Rolfs and Rodney [1], a more detailed presentation of the standard theoretical methods and models involved are given by Langanke [2] and by Oberhummer and Staudt [3].

The rates of the two mirror reactions $^3H(\alpha,\gamma)\,^7Li$ and $^3He(\alpha,\gamma)\,^7Be$ are both important in astrophysics. One application concerns nucleosynthesis in the early Universe: The amount of ^7Li produced in the Big Bang is a function of the nucleon to photon ratio (or baryon abundance) $\eta = n_N/n_\gamma$, with the rates of the reactions $^3H(\alpha,\gamma)\,^7Li$ and $^3He(\alpha,\gamma)\,^7Be$ as parameters. In the reverse way, the fundamental cosmological parameter η can in principle be determined by the observation of today's ^7Li abundance. The other context in which the reaction rate of $^3He(\alpha,\gamma)\,^7Be$ plays an important role in is the solar neutrino problem: in the Homestake detector, which—with a threshold of $E_{thres} = 814\,keV$—is mainly sensitive to the high-energy neutrinos produced by the decay of ^8B in the Sun, only about one third of the expected number of events is observed (table 1). The SAGE collaboration [4], using a detector with a threshold of $E_{thres} = 233\,keV$ which makes it also sensitive to neutrinos from the p–p reaction, observed a neutrino rate consistent with zero. In the GALLEX experiment [4] with the same threshold about two thirds of the predicted neutrino rate was observed.

The following two sections give a review of the two major applications in which the reactions $^3H(\alpha,\gamma)\,^7Li$ and $^3He(\alpha,\gamma)\,^7Be$ play an important role: the Big Bang nucleosynthesis and the solar neutrino problem. In the last section the current knowledge from experimental and theoretical investigations on both reactions are presented.

2. Big Bang nucleosynthesis

The standard Big Bang model assumes a homogeneous and isotropic expansion in a radiation dominated Universe without degenerate matter or exotic particles. As reviewed by Yang *et al* [5], at a temperature of $kT \simeq 10\,MeV$ the Universe is dominated by a relativistic gas of photons, electron–positron pairs and light neutrinos which is 'contaminated' by a trace amount of baryons with a ratio of baryons to photons

† Present address: Astronomisches Institut der Universität Basel, Venusstrasse 7, Ch-4102 Binningen, Switzerland.

of $\eta \simeq 10^{-10}$–10^{-9}. At this temperature the neutral-current weak interactions

$$e^+ + e^- \rightleftharpoons \nu_i + \bar{\nu}_i \quad (i = e, \mu, \tau, \ldots)$$

are sufficiently rapid to ensure thermal equilibrium between all neutrino species. The charged-current weak interactions

$$p + e^- \rightleftharpoons n + \nu_e$$

$$n + e^+ \rightleftharpoons p + \bar{\nu}_e$$

$$n \rightleftharpoons p + e^- + \bar{\nu}_e$$

maintain equilibrium between neutrons and protons. In this surrounding, proton–neutron collisions lead to the formation of deuterons at a high rate. However, because of their weak binding energy, most of the deuterons are immediately destroyed by the high-energy photons and therefore further nucleosynthesis is blocked.

At a temperature kT of a few MeV, the neutral-current weak interaction rates become too slow to maintain equilibrium. The neutrino gas decouples and cools adiabatically as the Universe further expands. At a slightly lower temperature the charged-current weak interactions follow, and the neutron-to-proton ratio is said to 'freeze out'. Finally the photon gas cools below 100 keV, so that the photodisintegration of deuterium stops. As soon as the deuterium abundance becomes significant, nucleosynthesis sets in. Because of the increasing Coulomb barrier and the dropping temperature, nucleosynthesis becomes more and more difficult with higher nuclear charges involved, and finally is stopped by the mass gaps at $A = 5$ and $A = 8$.

The resulting abundances of the four most important nuclides ^2H, ^3He, ^4He and ^7Li synthesized in the Big Bang are determined by the reaction cross sections, the baryon-to-photon ratio η, the neutron half-life $\tau_{1/2}$ and the number N_ν of neutrino species. The predicted abundances depend on these parameters as follows.

Since ^4He is the most stable nucleus produced in Big Bang nucleosynthesis, almost all neutrons available are incorporated into ^4He. Its primordial abundance by mass Y_p therefore essentially is determined by the neutron-to-proton ratio at the time nucleosynthesis sets in:

$$Y_p \approx 2\frac{n}{p}\left(1 + \frac{n}{p}\right)^{-1}.$$

This ratio n/p is given by the competition between the weak interaction rate, which varies as $\tau_{1/2}^{-1}$, and the universal expansion rate. A stronger weak interaction leads to higher weak reaction (and decay) probabilities and therefore to a shorter neutron half-life. If one now assumes or measures a longer neutron half-life the weak reactions will freeze out at a higher temperature, when there are more neutrons relative to protons, leading to the production of more ^4He.

A faster expansion rate also results in an earlier freezing out of the weak interactions—and therefore to the production of more ^4He. In a radiation dominated Universe, the expansion rate is determined by the effective number of relativistic degrees of freedom [5]

$$t(\mathrm{s}) = 2.42 g_{\mathrm{eff}}^{-1/2} T_{\mathrm{MeV}}^{-2}$$

where

$$g_{\mathrm{eff}} = \sum_B g_B\left(\frac{T_B}{T_\gamma}\right)^4 + \tfrac{7}{8}\sum_F g_F\left(\frac{T_F}{T_\gamma}\right)^4.$$

g_B and g_F are the number of boson and fermion helicity states and T_B and T_F the temperature ($\leqslant T_\gamma$) of the various species. From the equations above it is clear that the addition of more light particles—a further neutrino species for example—increases g_{eff} and, therefore, leads to a faster expansion.

Finally, although the resulting abundance of ^4He is rather insensitive to changes in the baryon-to-photon ratio η, Y_p slowly increases with increasing η. With a larger η the 'deuterium bottleneck' can be overcome earlier, when the neutron-to-proton ratio is higher.

The relative abundances of ^2He, ^3He and ^4He are determined by the competition between the reaction rates, which themselves depend on η, and the expansion rate. The higher η is, the higher the reaction rates and the faster ^2H and ^3He are destroyed. A faster expansion rate permits more ^2H and ^3He to survive (table 2).

The mass gaps at $A = 5$ and $A = 8$ inhibit nucleosynthesis of heavier nuclides: temperatures drop too fast to overcome the Coulomb barriers of the reactions necessary to bridge these gaps. Nevertheless, a small amount of ^7Li is produced in the Big Bang. For a low baryon abundance ($\eta \leqslant 3 \times 10^{-10}$), ^7Li mainly is produced via

$$^4He + {}^3H \rightarrow {}^7Li + \gamma.$$

For a higher baryon abundance, most of the ^7Li comes from the decay of ^7Be produced via

$$^4He + {}^3He \rightarrow {}^7Be + \gamma.$$

This leads to a ^7Li abundance function with a predicted minimum for $2 \times 10^{-10} \leqslant \eta \leqslant 4 \times 10^{-10}$ which by chance just covers the expected range of η. This

Table 1. Predicted and observed solar neutrino detection rates for three experiments. 1 SNU (solar neutrino unit) is defined as 10^{-36} neutrino captures per second per target atom. For the observed rates of SAGE and GALLEX, first the statistical and then the systematical error is listed.

Experiment	Threshold (keV)	Detection Rate (SNU)	
		Predicted	Observed
Homestake	814	8.0 ± 1.0	2.10 ± 0.30
SAGE	233	131.5^{+7}_{-6}	$20^{+15}_{-20} \pm 32$
GALLEX	233	131.5^{+7}_{-6}	$83 \pm 19 \pm 8$

Table 2. Primordial abundances of ^{2}H, ^{3}He and ^{7}Li as given by Yang et al [5].

$10^{10}\eta$	$10^5(^2\mathrm{H/H})$	$10^5(^2\mathrm{H}+{}^3\mathrm{He})/\mathrm{H}$	$10^{10}(^7\mathrm{Li/H})$
1	49	53	4.4
2	16	28	1.1
3	8.1	9.7	0.76
4	5.1	6.5	1.0
5	3.6	4.8	1.7
6	2.7	3.8	2.7
7	2.1	3.1	3.9
8	1.7	2.6	5.3
9	1.4	2.3	6.9
10	1.1	2.0	8.6
15	0.48	1.2	17
20	0.23	0.87	25

unique feature makes the ^{7}Li abundance especially interesting: small deviations in the baryon abundance η in either direction lead to large changes in the observable ^{7}Li abundances.

The cross sections, the neutron half-life, and the number of neutrino species can be determined experimentally, so that the primordial abundances given by the standard Big Bang model depend on one free parameter only, the baryon abundance.

As reported by Malaney [6], a new technique based on the storage of ultra-cold neutrons has been developed to determine the neutron half-life. From these experiments the neutron half-life is inferred to be $\tau_{1/2} = 10.28 \pm 0.05$ min. This is to be compared with the previously used value of $\tau_{1/2} = 10.6 \pm 0.2$ min.

The maximum number of light neutrino species was an open question for a long time. Astrophysical arguments favoured three species, but could not strictly exclude a fourth one. The determination of the width of the Z^0 resonance at $E = 91$ GeV carried out at LEP [7] could finally restrict the number of neutrino species with a mass $m_\nu < \frac{1}{2}m_{Z0}$ to three.

With the experimentally known values for the reaction cross sections, the neutron half-life, and the number of neutrino species it is theoretically possible to calculate a numerical value for η which reproduces the observed elemental abundances. From this value of η then the universal baryonic mass density can be determined [6] as

$$\Omega_B = 3.73 \times 10^{-3} h_0^{-2} \left(\frac{T_0}{2.75\,\mathrm{K}}\right)^3 10^{10}\eta$$

where the present value of the Hubble parameter is $H_0 = 100 h_0\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ with $0.4 < h_0 < 0.9$ [8, 9], and T_0 is the present temperature of the microwave background $T_0 = 2.735 \pm 0.06$ K [10]. Present knowledge gives $0.02 \leqslant \Omega_B \leqslant 0.12$. If this value is compared with the limit on the mass density of the visual (luminous) matter $\Omega_{vis} \leqslant 0.01$ and with the ranges estimated from dynamical studies $0.1 \leqslant \Omega_{dyn} \leqslant 0.3$, it must be concluded that a significant amount of the baryons build up some form of dark matter. However, this mass density is far away from the critical value $\Omega_0 = 1$, for which the Universe would be critical, and which is predicted by the inflationary Big Bang models.

As reviewed by Malaney [6] and Thielemann *et al.* [11], there has been great interest in the past few years in the nucleosynthesis resulting from inhomogenous Big Bang models. These models predict that the Universe shifted by a first-order QCD phase transition from a quark–gluon plasma to a meson gas when it was roughly 10 μs old. By this transition baryon density inhomogeneities can be produced and survive until nucleosynthesis sets in. The vastly different mean free paths of protons and neutrons create, after decoupling, a very proton-rich environment in the initially high-density regions, while the low-density regions are almost entirely filled with diffused neutrons. Due to the shifted neutron-to-proton ratios, the abundances of ^{2}H, ^{3}He and ^{4}He are expected to be lower in the high-density regions and higher in the low-density regions. Because the high-density regions dominate, a higher average baryon density is required to explain the observed abundances. This led to the hope that in inhomogenous scenarios the critical mass density of the Universe could be reached by baryonic matter only. Detailed calculations seem to show this is possible, with the exception of a problem associated with ^{7}Li, which is overproduced by a factor 5–100 times over its observed value.

One of the goals of astrophysics is—using the experimentally determined neutron half-life, the number of neutrino species and the reaction cross sections together with the observed elemental abundances—to build up a consistent picture of the primordial nucleosynthesis leading to one single (average) value of the baryon abundance η. Because of the critical role the ^{7}Li abundance plays in this process, it is important to know to what extent the experimentally determined reaction cross sections for the reactions $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ and $^3\mathrm{H}(\alpha,\gamma)^7\mathrm{Li}$ are reliable.

3. The solar neutrino problem

Because neutrinos are sensitive to the weak interaction only, Sun and Earth essentially are transparent to them. This feature makes them interesting on one hand, because neutrino detection is a way to directly 'look' into the solar interior where the stellar processes take place. On the other hand the same feature makes their detection enormously difficult.

As reviewed by Rolfs and Rodney [1] and Bahcall and Davis [12], the first technically feasible and financially affordable detector is based on the principle of the inverse β-decay and consists of a tank of 610 t of $\mathrm{C_2^{37}Cl_4}$ with an admixture of ^{36}Ar or ^{38}Ar as carrier gas. It was built between 1964 and 1968 by Davis *et al* 1500 m underground in the Homestake gold mine at Lead, South Dakota. The placement in the depth of a mine was chosen to reduce the cosmic-ray effects below those expected from the solar neutrinos.

The inverse β-decay reaction

$$\nu_e + {}^{37}Cl \rightarrow {}^{37}Ar + e^-$$

which this detector is based on, has a threshold of $E_\nu = 814$ keV and a cross section of the order of 10^{-44} cm^2. Since the latter steeply increases with neutrino energy, the detector is mainly sensitive to the high-energy neutrinos produced by the ^8B-decay in the Sun. The detector has no directional sensitivity, so that it has to be assumed that all observed neutrinos are from the Sun. It is believed that the neutrino flux from the rest of the Universe roughly bears the same relation to the solar neutrino flux as starlight does to sunlight. A known exception to this are the neutrinos ejected by type II supernovae.

The detection process starts with the neutrino induced inverse β-decay of ^{37}Cl to ^{37}Ar. This rare gas atom which reverts to ^{37}Cl with a half-life of 35 d is ejected from the C_2Cl_4 molecule and mixes into the non-radioactive carrier gas. After an accumulation time of about a month, the tank is flushed with large quantities of helium to collect the argon and bring it into a proportional counter. When the ^{37}Ar decays, the produced ^{37}Cl de-excites by emitting a 2.8 keV Auger electron which then is detected by the counter.

Due to the extraordinarily small neutrino capture rates, a special unit has been introduced for solar neutrino detection:

$$1\ \text{SNU} = 1\ \text{solar neutrino unit}$$
$$= 10^{-36}\ \text{neutrino captures per second per target atom.}$$

Based on the solar model and reaction rates available at the time, Bahcall *et al* [13] predicted a counting rate of $R_{th} = 8.0 \pm 1.0$ SNU, which is larger by more than a factor of three than the rate observed by Davis *et al* during the years 1969–1983, i.e. $R_{obs} = 2.1 \pm 0.3$ SNU. This rate is equivalent to the production of one ^{37}Ar atom in the entire tank about every three days. This disagreement between observation and standard theory is known as the 'solar neutrino problem'.

There have been three basic theoretical approaches in trying to solve this problem: the first one assumes an incorrect standard solar model, the second suggests new neutrino physics and the third one is based on inaccurate reaction cross sections.

The alternative solar models try to change the properties of the solar centre without changing the Sun's outer appearance to get a lower flux of high energy neutrinos. However, drastic or exotic deviations from the standard solar model are constrained by the implications of helioseismology [14].

The main idea of new neutrino physics is the existence of neutrino oscillations. According to some grand unified theories, neutrinos may have a finite mass, and then it would be possible, starting with one species of neutrinos, to wind up with an equal number of all three species. Because in the Homestake experiment only electron-neutrinos can be detected, the missing of two thirds of the expected neutrino number would be explained, if the electron-neutrinos were transformed into μ- or τ-neutrinos during the eight-minute flight from the Sun to the Earth. The postulation of the Mikheyev–Smirnov–Wolfenstein (MSW) effect of matter-enhanced neutrino oscillations made this hypothesis even more popular. At present, in earthbound experiments, only upper limits for neutrino masses and no direct experimental evidence for neutrino oscillations have been found.

To shed some light on the observational situation, other neutrino detectors have been built. The Japanese Kamiokande detector detects bursts of Čerenkov radiation produced by the recoil electrons of elastic neutrino–electron scattering in a large underground water tank.

Since 1990 two international collaborations SAGE and GALLEX aimed to detect low energy solar neutrinos originating from the p–p reaction using detectors based on the inverse β-decay reaction

$$\nu_e + {}^{71}Ga \rightarrow {}^{71}Ge + e^-$$

with a threshold of $E_\nu = 233$ keV and a similar detection process to Homestake. The Soviet–American SAGE collaboration at the Baksan neutrino observatory in the north Caucasus uses a detector made of 30 t of liquid metallic gallium and yielded after six months operation a result—within the experimental error—consistent with zero (20^{+15}_{-20}[stat] $\pm$ 32[sys] SNU) [15]. The multinational GALLEX collaboration uses 30 t of gallium in the form of 101 t gallium chloride ($GaCl_3$) in large tanks mounted in the Gran Sasso automobile tunnel. On the basis of 14 runs covering 295 days of exposure a neutrino detection rate of 83 $\pm$ 19[stat] $\pm$ 8[sys] SNU was reported, about two thirds of the predicted $132 \pm^{21}_{17}$ SNU [15]. The implications of this result on the standard solar model and neutrino physics are discussed in [4].

Again all reasoning is based on the assumption that the cross sections of the important reactions in the different neutrino producing reaction chains and cycles in the Sun are well known. In this context, the reaction $^3He(\alpha,\gamma)^7Be$ plays an important role for the pp-II and pp-III reaction chains.

4. The *S* factors of the reactions $^3H(\alpha,\gamma)^7Li$ and $^3He(\alpha,\gamma)^7Be$

For charged particle induced nuclear reactions the cross section drops rapidly for energies below the Coulomb barrier

$$\sigma(E) \propto \exp(-2\pi\eta)$$

where η is the Sommerfeld parameter. Another non-nuclear energy-dependent term involves the de

Table 3. The S factors for the reaction $^3He(\alpha,\gamma)^7Be$ used by Kajino to derive a theoretical average value. In the left column are the values empirically derived from the experimental data. The right column shows the values theoretically extrapolated by Kajino [16].

Experiment	Empirical extrapolation	Theoretical extrapolation
Prompt capture γ-ray measurement		
Parker and Kavanagh (1963) [17]	0.47 ± 0.05	0.514 ± 0.054
Nagatani *et al* (1969) [18]	0.58 ± 0.07	0.588 ± 0.071
Kräwinkel *et al* (1982) [19]		0.322 ± 0.033
Osborne *et al* (1982) [20]	0.52 ± 0.03	0.521 ± 0.030
Alexander *et al* (1984) [21]	0.47 ± 0.04	0.478 ± 0.041
Activation measurement		
Osborne *et al* (1982) [20]	0.55 ± 0.05	0.573 ± 0.050
Robertson *et al* (1983) [22]	0.63 ± 0.04	0.660 ± 0.036
Volk *et al* (1983) [23]	0.56 ± 0.03	
Average (excluding Kräwinkel and Volk)		0.560 ± 0.03 keVb

Broglie wavelength

$$\sigma(E) \propto \pi\lambda\!\!\!^{-2} \propto 1/E.$$

Using both relations, the cross section can be written as

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)S(E).$$

The function $S(E)$ defined by this equation is called the astrophysical S factor and contains all nuclear effects. Contrary to the cross section, the S factor varies slowly with decreasing energy, what makes it much more useful in extrapolating measured cross sections down to the astrophysically interesting energies near zero.

4.1. The reaction $^3He(\alpha,\gamma)^7Be$

The reaction $^3He(\alpha,\gamma)^7Be$ was experimentally investigated by many independent groups (table 3), whose results—with one exception—roughly agree with each other. These experiments are based on direct observation of the prompt capture γ-rays or on the observation of the 478 keV γ-rays due to the transition from the $j = \frac{3}{2}^-$ excited state to the ground state in ^7Li following a positron decay of the ^7Be ground state (activation measurement). Because of this experimentally viable situation, theoretical work concentrated on finding accurate descriptions of these experimental data to extrapolate them down to zero energy.

The approach developed by Kajino *et al* [24] is based on the resonating group method (RGM). The results obtained this way depend only on the adopted nuclear forces and nuclear radii. The best choice for the nuclear forces was found to be the modified Hasegawa Nagata force (MHN) [25]. Using the nuclear matter radius measured by Tanihata *et al* [26], the limiting range for the S factor was calculated to be

$$0.36 \text{ keV b} \leqslant S(0) \leqslant 0.63 \text{ keV b}.$$

Normalizing the energy dependence of the $S(E)$ factor obtained by this approach to each of the experimental data sets available, and then averaging the extrapolated S factors, Kajino *et al* [16] recommended the absolute value

$$S(0) = 0.560 \pm 0.03 \text{ keV b}.$$

The microscopic potential model developed by Langanke and Koonin [27] is a combination of the qualitative results obtained by microscopic many-body theories—like the resonating group method (RGM) and the generator coordinate method (GCM)—and phenomenological potential models with adjustable parameters. In this approach experimental properties (energy positions and widths of resonances) of the nuclei involved can be reproduced with high accuracy. The resulting S factor is exactly the value recommended by Kajino *et al*.

The value of $S(0) = 0.56$ keV b is therefore expected not to be substantially changed by further experimental or theoretical investigations. Based on today's knowledge, the solar neutrino problem is believed not to arise from uncertainties in the $^3He(\alpha,\gamma)^7Be$ reaction rate.

4.2. The reaction $^3H(\alpha,\gamma)^7Li$

Contrary to this, there are severe problems concerning the cross sections of the reaction $^3H(\alpha,\gamma)^7Li$. Almost all theoretical model predictions disagree with the only data set available covering the low-energy range of interest.

The first experiment on $^3H(\alpha,\gamma)^7Li$ was carried out by Griffiths *et al* [28] in 1961. The observed smooth energy dependence indicated the reaction to be dominated by a direct capture process into the $j = \frac{3}{2}^-$ excited state at $E_x = 478$ keV and into the $j = \frac{1}{2}^-$ ground state. The branching ratio was found to be nearly energy independent with a mean value of 0.40 ± 0.05. Because the data suggested an energy-independent S factor, the value at zero energy

$$S(0) = 0.064 \pm 0.016 \text{ keV b}$$

was obtained by simply averaging over all data points.

Later, the theoretical models developed by Kajino *et al* [25] and Langanke *et al* [27] predicted a rising S factor with decreasing energy. Using this new energy dependence the data of Griffiths *et al* now extrapolated to

$$S(0) = 1.00 \pm 0.025 \text{ keV b}.$$

To shed more light on the situation, Schröder *et al* [29] carried out a further experiment in 1987 covering a lower energy range. Their observations confirmed a rising S factor with decreasing energies, but with an appreciably higher absolute value than predicted by Kajino *et al* and Langanke *et al*. Their extrapolation led to

$$S(0) = 0.134 \pm 0.020 \text{ keV b}.$$

Again, the branching ratio was found to be energy independent, but with a much lower value of 0.32 ± 0.01 than expected and than that of Griffiths *et al*.

Although the S factor measured by Schröder *et al* was covered by the limiting range of

$$0.083 \text{ keVb} \leqslant S(0) \leqslant 0.15 \text{ keVb}$$

calculated by Kajino *et al* [26] in the same way as for the reaction $^3He(\alpha,\gamma)^7Be$, the validity of this value has been at least severely questioned, since in 1989 Kajino *et al* [30] used an indirect approach based on the mirror symmetry between the nuclei ^7Li and ^7Be to calculate the branching ratio of $^3H(\alpha,\gamma)^7Li$ theoretically. To do this, a kinematical direct capture model was adopted with the nuclear radius and the ratio of the reduced widths of the final states as free parameters. The nuclear radii were taken from the experiments carried out by Tanihata *et al*, whereas the reduced widths of ^7Be were adjusted to reproduce the undoubted branching ratio of the reaction $^3He(\alpha,\gamma)^7Be$. As a consequence of the mirror symmetry the ratio of the reduced widths is now the same for both nuclei, so that the branching ratio of $^3H(\alpha,\gamma)^7Li$ could be calculated the reverse way. The resulting value of 0.47 ± 0.07 agrees with Griffiths *et al* within 1σ, whereas the value of Schröder is clearly outside this range.

As a possible explanation, Kajino *et al* suggested some inconsistencies between the excited state and ground state measurements of Schröder: If only the S factor to the $j = \frac{1}{2}^-$ excited state $S_{1/2}(0) = 0.036 \pm 0.006$ keV b, as reported by Schröder, is taken into account, the total S factor can be derived using the theoretical branching ratio $R = 0.47 \pm 0.07$ mentioned above

$$S(0) = S_{1/2}(0)\left(1 + \frac{1}{R}\right) = 0.11 \pm 0.03$$

which is in better agreement with the data of Griffiths *et al* and the theoretical predictions. However, the uncertainties concerning the S factor of the reaction $^3H(\alpha,\gamma)^7Li$ still persist.

The theoretical calculation of Chopovsky [31] presented in 1989 and the experiment carried out by Utsunomiya *et al* [32] in 1990 are qualitative tests of a new method, rather than quantitative contributions to this discussion. Based on the algebraic version of RGM, Chopovsky suggests a method to calculate the S factor directly at zero energy from 'first principles' as opposed to the current methods, in which first a model function $S(E)$ is calculated in at higher energies and then extrapolated down to zero. The values obtained for the S factors are

$$S(0) = 0.690 \text{ keV b}$$

for the reaction $^3He(\alpha,\gamma)^7Be$, and

$$S(0) = 0.154 \text{ keV b}$$

for the reaction $^3H(\alpha,\gamma)^7Li$. Both values are slightly outside the limiting ranges given by Kajino *et al* [26].

The main goal of the experiment by Utsunomiya *et al* was to test a new and promising experimental method suggested in 1986 by Baur, Bertulani and Rebel [33,34] for overcoming the principal difficulties of radiation capture experiments by using the reciprocity theorem. In this approach the reverse process of nuclear photodisintegration is measured and the observed cross sections then are converted into cross sections for the forward radiative capture process. Using this new technique, Utsunomiya *et al* studied the reaction $^3H(\alpha,\gamma)^7Li$. The $S(E)$ factor obtained in this way exhibits the same pronounced energy dependence as it was found by Schröder *et al*.

Table 4. The experimentally and theoretically determined S factors for the reaction $^3H(\alpha,\gamma)^7Li$.

Author	Experimental investigation	Theoretical investigation
Griffiths *et al* (1961)	0.064 ± 0.016	
Schröder *et al* (1987)	0.134 ± 0.020	
Kajino *et al* (1989)		1.00 ± 0.025

But because of some unsolved theoretical (nuclear and Coulomb interferences in the dissociation mechanism, final-state interaction) and experimental (particle-tracking capabilities) problems no absolute value for $S(0)$ is given.

The same technique has been used to study the alpha-capture reaction $d(\alpha,\gamma)^6Li$ [28] where a clear theoretical analysis of the problems mentioned above was possible and S factors down to an energy of $E_{cm} \simeq 100$ keV were obtained.

5. Conclusions

The astrophysical $S(E)$ factor of the reaction $^3He(\alpha,\gamma)^7Be$ has been experimentally investigated by many different groups. The empirically extrapolated $S(0)$ factors are in good agreement with each other. Extrapolations based on theoretical model calculations lead to an average value of

$$S(0) = 0.560 \pm 0.03 \text{ keV b}.$$

In the case of the reaction $^3H(\alpha,\gamma)^7Li$, the extrapolated $S(0)$ factors of the two experiments covering the low-energy range do not agree very well. However, a theoretical investigation based on the mirror symmetry between the reactions $^3H(\alpha,\gamma)^7Li$ and $^3He(\alpha,\gamma)^7Be$ reveals an internal inconsistency in one of the experiments. Extrapolations based on theoretical model calculations and using the mirror symmetry favour a value of

$$S(0) = 1.00 \pm 0.025 \text{ keV b}.$$

In both cases I believe that the values of $S(0)$ will not change substantially with new experimental or theoretical investigations. The solar neutrino problem (as far as it still exists) therefore cannot be explained by the remaining uncertainties in the S factor of the two reactions, neither do these uncertainties strongly affect the universal ^7Li abundance, whose reproduction is a crucial test for different scenarios of Big Bang nucleosynthesis.

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