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Primordial *LiH*: The Chemistry in a Collapsing Protocloud

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Primordial LiH : The chemistry in a collapsing protocloud ¹

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Abstract

We analyse and discuss the evolution of primordial molecules during the beginning stage of the early cloud formation using an updated primordial lithium chemistry. As Puy and Signore (1996, 1997), we consider a simple model of a collapsing protocloud after the recombination epoch but paying special attention to the LiH formation by radiative association from excited Li atoms. Because the rate of LiH destruction through collisions with H atoms is only estimated we find that, at present, *the percentage of primordial lithium converted to LiH is quite uncertain.*

1 Introduction

This paper deals with the chemistry of LiH in a model of a collapsing single isolated cosmological protocloud after the recombination epoch in an expanding Universe. In a first paper (Puy & Signore 1996), we have presented the basic processes of physics and chemistry, and in a second one (Puy & Signore 1997) we have analysed the thermal evolution and the influence of primordial molecules on the thermal history at the beginning of the collapse.

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Primordial molecules can play a role in observational cosmology, and more precisely the study of lithium and his chemical component, LiH molecules, can offer interesting perspectives for Cosmology (see for instance, Signore et al 1994). In the framework of the standard Big Bang model, the nucleosynthesis (SBBN) of the light elements took place at $t_{nuc} \sim 10^2$ sec after the Big Bang. Cosmologists compute and predict the abundances of deuterium, helium-3, helium-4 and lithium-7 as a function of the ratio of nucleus to photons η and predict also very tiny abundances of heavier elements, η or equivalently Ω_b , the density of baryons in units of the critical density, is the SBBN free parameter. In particular (Sarkar 1996):

$$\left(\frac{{}^7Li}{H}\right)_{SBBN} = 1.2 \times 10^{-11 \pm 0.2} < \eta >$$

where

$$< \eta > = \left[\left(\frac{\eta}{5. \times 10^{-10}} \right)^{-2.38} + 21.7 \left(\frac{\eta}{5. \times 10^{-10}} \right)^{+2.38} \right]$$

over the range: $\eta = 10^{-10} - 10^{-9}$. Although the comparison of the predicted elemental abundances with observational data is complicated by the fact that the primordial abundances may have been significantly altered during the lifetime of the Universe by, in particular, nuclear processing in stars, astrophysicists identify the primordial 7Li abundance with the observed average value in the hottest most metal poor stars :

$$\left(\frac{{}^7Li}{H}\right)_{pop.II} = 10^{-9.78 \pm 0.2} \quad (92\% \text{ cl})$$

Moreover, the observation that:

$$\left(\frac{{}^7Li}{H}\right)_{pop.I} \sim 10^{-9}$$

in young population I stars then requires the galactic $({}^7Li/H)$ ratio to rise by a factor of about 10 during the evolution of the Galaxy. In the framework of the inhomogeneous nucleosynthesis Big Bang models (IBBN), the nucleosynthesis occurs in an homogeneous medium, due to fluctuations generated by a first-order quark hadron phase transitions at $T_{QH} \sim 150 - 400$ MeV, i.e. at $t_{QH} \sim 10^{-5}$ sec after the Big Bang. These inhomogeneities may have created neutron-rich zones where extra lithium-7 and heavier elements may have been formed. In particular, in this opposite point of view, the primordial 7Li abundance may have been at the level of that observed in young population I stars, if, it has been depleted in the older population II stars, through some turbulent mixing driven by stellar rotation. For recent reviews on the status of the big bang nucleosynthesis (SBBN and IBBN) see Copi et al 1995, Sarkar 1996, Schramm and Turner 1997 and references therein. Let us only note that

observations of primordial level of the ${}^7\text{Li}$ nuclei would help to discriminate between SBBN and IBBN models and therefore to determine what our Universe looked like 10^{-5} seconds after the Big Bang.

In standard Big Bang Theory, chemistry took place around the epoch of recombination. Many researchers have studied the evolution of the primordial LiH molecule (Lepp and Shull 1984, Dalgarno and Lepp 1987, Latter and Black 1991), have searched for it (de Bernardis et al 1993) and have shown that thanks to its possible prominence one can have a tool to analyse the ${}^7\text{Li}$ abundance at a progalactic level (de Bernardis et al 1994, Melchiorri and Melchiorri 1994, Maoli et al 1994, 1996, Signore et al 1994, 1997). In these papers, they have analyzed in detail, the main molecular radiation processes between CBR photons and primordial molecules in the context of two cosmological environments, in one hand during the expansion of the Universe and in the second hand during the gravitational collapse phase of the structures of the Universe. In particular, they have determined the conditions for blurring of primary CBA (cosmic background anisotropies) and for creation of secondary CBA. In fact Dubrovich (1993) suggested that the presence of molecules, particularly LiH molecules, can create a *curtain* that blurs the primordial spatial fluctuations of the cosmic background radiation (CBR), and moreover imprint on CBR from the resonant enhancements of the Thomson scattering process. In this context Signore et al (1997) pointed out that maps made by the PLANCK SURVEYOR mission (formerly referred to as the COBRA-SAMBA mission 1996) -the major space mission of the next decade dedicated to the CBR- should be excellent tools for discovering and analyzing anisotropies from resonant scattering of primordial molecules with CBR photons.

In summary one can say that primordial LiH signals are important not only as diagnostic tools for primary nucleosynthesis models and therefore for information on the physical conditions of the Universe at some 10^{-5} seconds after the Big Bang but also as tracers of protostructure later in the evolution of the Universe. In order to predict the observability of the LiH lines at high redshifts -or more generally of the effects of LiH molecules on CBR- let us consider the evolution of our new lithium chemistry and therefore let us estimate the final LiH abundance during the gravitational collapse of protostructure.

The chemistry of the primordial gas after the recombination epoch has been studied by several groups (Lepp and Shull 1984, Dalgarno and Lepp 1987, Latter and Black 1991, Puy et al 1993). More recently Stancil et al (1996) have developed a new model of lithium chemistry in the early Universe. They include, in particular, new quantal rate coefficients for the radiative association of lithium and hydrogen (Dalgarno, Kirby, Stancil 1996).

In this paper, we propose to extend the previous study in our simple model of a collapsing protocloud, and to include the new chemistry of Stancil et al (1996) and additional results obtained by Gianturco and Gori Giorgi (1996) on the radiative association of LiH from electronically excited lithium atoms. In section 2, we describe the new lithium chemistry in the early Universe; In section 3,

we present the evolution of the new lithium chemistry during the gravitational collapse of a protostructure, then we discuss the results and give conclusions.

2 The lithium Chemistry in the early Universe

In Standard Big Bang theory, primordial chemistry took place around the epoch of recombination. At this stage, the chemical species essentially were H , H^+ , D , D^+ , He and Li (Lepp and Shull 1984, Dalgarno and Lepp 1987, Latter and Black 1991, Puy et al 1993). Then with the expansion and adiabatic cooling of the Universe, different routes led to molecular formation.

In spite of the absence of dipole moment for H_2 and the slowness of direct radiative association of two atoms (there are no grains), Shchekinov and Entel (1983) and Saslaw and Zipoy (1967) brought out two ways of formation for H_2 molecules through associative detachment with H^- and by the creation of H_2^+ by radiative association, followed by charge transfer. Lepp and Shull (1984) and Puy et al (1993) shown that HD molecules mainly form through collision with H_2 molecules. The situation is very different concerning LiH molecules. Lepp and Shull (1984) suggested that the formation was provided by the only reaction:

Knowing that the ionisation potential of $Li(I)$ is shorter than that of hydrogen ($Li(I) = 5.392$ eV), Dalgarno and Lepp (1987) suggested the existence of Li^+ ions after the recombination of hydrogen, which permit to Stancil et al (1996) to develop a model of lithium primordial chemistry in the early Universe. Following these authors, one can say that LiH molecules are formed mainly through:

These reactions are coupled with the following destructions:

Recently Gianturco and Gori-Giorgi (1996) have carried out a fully quantum mechanical treatment of the reaction:

They have found that the radiative association of LiH molecule starting from lithium atoms that are electronically excited, $Li(2p)$, is much more efficient than the one starting from lithium atoms in their ground state, $Li(2s)$. The rate coefficients of this reaction is six order of magnitude greater than the one of reaction (28). The problem concerns the possibility to find cosmological epochs and scenarios for which electronically excited lithium exist. This question deserves some comments depending on the cosmological environments and on the evolution of the primordial chemistry:

- Just after the short period in the expansion of the Universe referred to as the epoch of recombination
- Later in the evolution of the Universe, during the phase of the gravitational collapse of protostructure.

Let us briefly consider these two different chemical evolutions:

2.1 molecular evolution after recombination

As it was already pointed out by Lepp and Shull (1984) LiH formation through radiative association (reaction 28) becomes effective when the photodestruction (reaction 29) decreases, i.e. for $z < 400$. On the other hand, to obtain, at these redshifts, the first electronic excitation of lithium atoms:

photons (with $\lambda \sim 0.69\mu\text{m}$ or $E_\nu \sim 1.75 \text{ eV}$) are needed. Since the de-excitation of lithium atoms through spontaneous emission

occurs in times of the order of 10^{-6} sec; a bath of such photons ($\lambda \sim 0.69\mu\text{m}$, $E_\nu \sim 1.75\text{eV}$) would have maintain lithium atoms in the first electronically excited state $Li(2p)$. Gori Giorgi argues that (private communication 1996) if this background of photons is a black body ($\lambda \sim 0.69\mu\text{m}$, $T \sim 3020\text{K}$) the abundances of lithium atoms would have been such as:

$$Li(2p) \sim 10^{-3} Li(2s)$$

because the rate constant of reaction (51) is 10^6 greater than this of reaction (28) the final LiH abundance is more important. Moreover, one must also note

that photons (with $\lambda < 0.50\mu m$, $E_\nu > 2.5$ eV) could destroy LiH through photodissociation. Therefore Gori Giorgi concludes that the best opportunity would be the existence of a background of photons such as:

$$0.50\mu m < \lambda < 0.69\mu m$$

or

$$1.70eV < E_\nu < 2.25eV$$

What are the possible scenarios which could have led, at these redshifts $z < 400$, to a background of photons ? One can already said that, at these redshifts: the existence of the first "light" from primordial objects (VMO, SMO ...) is a hypothetical possibility, the existence of a line at $\lambda \sim 0.69\mu m$ is very difficult to imagine, but the existence of particle decay could be a plausible scenario.

2.2 molecular evolution during the gravitational collapse of protostructures

In Puy & Signore (1996), we have seen that, in the framework of our very simple model, the collapse of a protocloud with a mass of $10^9 M_\odot$ or $10^{10} M_\odot$ took place at a redshift of $z \sim 55$ or 25 . At these redshifts, a primordial object (population III star for example) could have emitted photons in the interval $[1.75 \text{ eV} , 2.25 \text{ eV}]$. On the other hand, let us introduce the following reaction:

which releases a photon at 1.85 eV. In the homogeneous case of the expansion of the Universe this reaction was only effective around a redshift of $z \sim 2000$ (see Black 1990) and therefore too earlier to excitate the lithium atoms.

But, during the gravitational collapse of protoclouds (at redshifts $z \sim 25 - 55$) while the density increased, the reaction (51) could have been effective. Therefore one can suppose that, during the collapse, the main part of lithium atoms $Li(2s)$ could have been excited into $Li(2p)$ through the reaction:

leading to the reaction:

which is more rapid than the reaction:

In the following and, in particular, in the new network, we will introduce two opposite cases for LiH formation:

- CASE 1: All lithium atoms are $Li(2s)$; LiH formation is mainly given by reaction (28).
- CASE 2: All lithium atoms are $Li(2p)$; LiH formation is mainly given by reaction (51) with its rate coefficient which is six orders of magnitude greater than the ones of reaction (28).

3 Results and discussions

We have chosen the same model of gravitational collapse developed in Puy and Signore (1996) from Lahav (1986). The evolution equations are described in this paper, these equations for a collapsing cloud, characterized by the mass M , are:

$$\begin{aligned} & \text{(conservation of the matter)} \\ \bullet \quad \frac{dn}{dt} &= -3\frac{n}{r} \frac{dr}{dt} + \left(\frac{dn}{dt}\right)_{chem} \end{aligned}$$

(evolution of the temperature T_m of the collapsing cloud)

$$\bullet \quad \frac{dT_m}{dt} = -2\frac{T_m}{r} \frac{dr}{dt} + \frac{2}{3nk} (\Xi_{molec} + \Theta_{chem})$$

(evolution of the radius r)

$$\bullet \quad \frac{d^2r}{dt^2} = \frac{5k}{\mu m_H} \frac{T_m}{r} - \frac{GM}{r^2}$$

where n is the density, t the time, $\left(\frac{dn}{dt}\right)_{chem}$ the chemical contribution, k the Boltzmann constant, Ξ_{molec} the thermal function due to the primordial molecules H_2 , HD and LiH , Θ_{chem} the thermal chemical function due to the enthalpy of the reactions, μ the mean molecular weight, m_H the mass of hydrogen and G the gravitational constant. All these equations are coupled with the equations of the chemical kinetic due to the chemical network given in the Appendix. The calculations of the thermal function (molecular and chemical) are well-described in Puy and Signore (1997) which deals with the thermal analysis of this gravitational collapse. We recall that we consider a homologous collapse and the beginning of the collapse (i.e. for times lower than free-fall time), thus we neglect the effects of possible shock waves.

We consider protoclouds of masses $M=10^{10} M_\odot$ and $M=10^{11} M_\odot$. Table 1 gives the dynamical initial conditions at the turn-around redshift i.e. at the beginning of the collapse (see Padmanabhan 1993, and also Puy and Signore 1996, 1997). Table 2 shows the initial abundances at the beginning of the collapse phase. As in Puy and Signore (1996) (1997), we have chosen the initial abundances predicted by Inhomogeneous Big Bang Nucleosynthesis (IBBN).

3.1 $10^{10} M_{\odot}$ protocloud

Fig. 1 describe, at the beginning of the collapse ($t < t_{ff}$) the dynamical and chemical evolution of a $10^{10} M_{\odot}$ protocloud. For this mass the turn-around redshift z_{ta} is at 25 K (see Tables 1 and 2).

The abundances are calculated in the framework of non-excited lithium (Stancil et al 1996, Case 1), the initial abundances are given in Table 2. We note (Fig. 1c) that the abundance of LiH decreases slightly mainly due to the destructions:

Fig. 2 represent the evolution of the abundance in the framework of excited lithium (Gianturco and Gori Giorgi 1996, Case 2). We note (Fig. 2c) that the situation is very different than the Case 1 (non-excited lithiums), the abundance increases significantly which shows the importance of the associative reaction with excited lithium.

In Figures 1 and 2 the evolution of the abundances of H_2 and HD are similar than in our precedent article (Puy and Signore 1996), the abundances of species having lithium are too low to participate to the modification of the abundances of H_2 or HD . In these two cases (Case 1 and Case 2) the dynamical evolution, characterized by the figures (1e), (1f), (1g), (1h) is similar. The abundance of lithium hydride is too low to affect the dynamic through the thermal function (cooling or heating) produced by LiH molecules. As we have seen in Puy and Signore (1997), the main cooling agent is the HD molecules (Fig. 1g).

3.2 $10^{11} M_{\odot}$ protocloud

In this case, we have only considered the case with excited lithium (Case 2). We note (Fig. 3c) a similar evolution for the abundance of LiH in the sense that LiH abundance fastly increases then decreases. Nevertheless the abundance of LiH have globally increased.

Concerning the dynamical evolution, the situation is close to $10^{10} M_{\odot}$. At the turn-around redshift, the temperature of the background radiation is greater than the temperature of matter inside the collapse. Thus at the beginning of the collapse, the molecules heat the medium. Then the temperature increases and reaches the value of the temperature of the background radiation, leading to the efficiency of the molecular cooling (dotted line in Fig. 3g) mainly due to HD molecules.

Finally, we note in this study the importance of the radiative association to form the LiH molecules. Moreover the exchange reactions (47), (48), (49) and (50) play an important role concerning the ways of destruction of LiH . Like Stancil et al (1996) have mentionned, these gas-phase reactions and particularly

which reduces the abundance of LiH , the rate coefficients are uncertain and probably too large but not unreasonable (Dalgarno 1995 private communication). Nevertheless the trend concerning the evolution of LiH abundance inside the collapse is not clear (increases or decreases ?) and more importantly the percentage of primeval lithium converted to LiH is quite uncertain (before and during the collapse phase). Therefore the importance of the role of the LiH molecule as a tracer of protostructure evolution cannot be definitively determined.

For all these reasons an important work remains to do concerning the specific calculations of the reaction rates, and particularly the knowledge of the complete chemical network of LiH in the excited states: $LiH(A^1\Sigma^+)$ and $LiH(B^1\Pi)$.

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Figures 1: Dynamical and chemical evolution of collapsing protocloud $M=10^{10} M_{\odot}$ in the framework of non-excited lithium (Case 1). (1a) represents the evolution of H_2 molecule abundance normalised to the abundance of H_2 at z_{ta} the turn-around redshift. (1b) represents the evolution of HD abundance normalised to the abundance of HD at z_{ta} . (1c) characterizes the evolution of LiH abundance normalised to 10^{-17} cm^{-3} . (1d) represents the evolution of H^+ normalised to the abundance of H^+ at z_{ta} . The series of curves (1e),(1f),(1g),(1h) represents respectively the evolution of radius and density normalised to their respective value at Z_{ta} , cooling (dotted line) and heating (solid line) normalised to $10^{30} \text{ erg cm}^{-3} \text{ s}^{-1}$, temperature.

Figures 2: Dynamical and chemical evolution of collapsing protocloud $M=10^{10} M_{\odot}$ in the framework of excited lithium (Case 2, Gianturco and Gori Giorgi 1996). (2a) represents the evolution of H_2 molecule abundance normalised to the abundance of H_2 at z_{ta} the turn-around redshift. (2b) represents the evolution of HD abundance normalised to the abundance of HD at z_{ta} . (2c) characterizes the evolution of LiH abundance normalised to 10^{-17} cm^{-3} . (2d) represents the evolution of H^+ normalised to the abundance of H^+ at z_{ta} .

Figures 3: Dynamical and chemical evolution of collapsing protocloud $M=10^{11} M_{\odot}$ in the framework of excited lithium. (3a) represents the evolution of H_2 molecule abundance normalised to the abundance of H_2 at z_{ta} the turn-around redshift. (3b) represents the evolution of HD abundance normalised to the abundance of HD at z_{ta} . (3c) characterizes the evolution of LiH abundance normalised to 10^{-17} cm^{-3} . (3d) represents the evolution of H^+ normalised to 10^{-3} cm^{-3} . The series of curves (3e),(3f),(3g),(3h) represents respectively the evolution of radius and density normalised to their respective value at z_{ta} , cooling (dotted line) and heating (solid line) normalised to $10^{30} \text{ erg cm}^{-3} \text{ s}^{-1}$, temperature.

M (in $M_\odot$)	z_{ta}	T_r (in K)	T_{init} (in K)	n_{init} (in 10^5 cm^{-3})	r_{ta} (in 10^{20} cm)
10^{11}	11	33	6	$1.23 \cdot 10^{-4}$	633.2
10^{10}	25	72	25	$1.23 \cdot 10^{-3}$	136.4

Table 1: Dynamical parameters at the beginning of the collapse (rotation and magnetic field are neglected), z_{ta} is the turn-around redshift, T_r the temperature of the radiation at z_{ta} , T_{init} the initial temperature of the collapse, n_{init} and r_{init} respectively the initial density and initial radius of the collapsing protocloud.

M (in $M_\odot$)	z_{ta}	H_2 (in 10^{-6} cm^{-3})	HD (in 10^{-8} cm^{-3})	LiH (in 10^{-17} cm^{-3})	H^+ (in 10^{-5})
10^{11}	11	8.4	5.21	0.3	3
10^{10}	25	8.4	5.21	0.3	3

Table 2: Initial relative abundances for $10^{10} M_\odot$ and $10^{11} M_\odot$ protoclouds (i.e. at $z = z_{ta}$).

Appendix: Table of chemical reactions

The reaction rates are $k = \gamma \left(\frac{T}{300} \right)^\alpha \exp\left(\frac{-\beta}{T}\right)$, where γ is in cm^3s^{-1} , β in Kelvin.

The enthalpy ΔH is in eV.

	reactions	γ	α	β	ΔH	references
(1)	$\text{H} + \text{e} \rightarrow \text{H}^- + \text{h}\nu$	$3 \cdot 10^{-16}$	1	0		Prasad & Huntress (1980)
(2)	$\text{H}^- + \text{H} \rightarrow \text{H}_2 + \text{e}$	$1.5 \cdot 10^{-9}$	0	0	3.71	Launay <i>et al</i> (1991)
(3)	$\text{H}^+ + \text{H} \rightarrow \text{H}_2^+ + \text{h}\nu$	$1.8 \cdot 10^{-18}$	1.5	0		Dalgarno & Lepp (1987)
(4)	$\text{H}_2^+ + \text{H} \rightarrow \text{H}_2 + \text{H}^+$	$6.4 \cdot 10^{-10}$	0	0	1.81	Karpas <i>et al</i> (1979)
(5)	$\text{H}_2 + \text{h}\nu \rightarrow \text{H} + \text{H}$					Latter & Black (1991)
(6)	$\text{H}^- + \text{h}\nu \rightarrow \text{H} + \text{e}$					Wishart (1979)
(7)	$\text{H}_2^+ + \text{h}\nu \rightarrow \text{H}^+ + \text{H}$					Von Busch & Dunn (1972)
(8)	$\text{H}^+ + \text{H}^- \rightarrow \text{H} + \text{H}$	$2.3 \cdot 10^{-7}$	-0.5	0	12.84	Prasad & Huntress (1980)
(9)	$\text{H}^+ + \text{H}^- \rightarrow \text{H}_2^+ + \text{e}$	$8.83 \cdot 10^{-15}$	-0.32	0	1.9	Poulaerts <i>et al</i> (1978)
(10)	$\text{H}_2^+ + \text{H}^- \rightarrow \text{H}_2 + \text{H}$	$2.3 \cdot 10^{-7}$	-0.5	0	14.66	Prasad & Huntress (1980)
(11)	$\text{H}^+ + \text{e} \rightarrow \text{H} + \text{h}\nu$	$3.5 \cdot 10^{-12}$	-0.70	0		Prasad & Huntress (1980)
(12)	$\text{H}_2^+ + \text{e} \rightarrow \text{H} + \text{H}$	$1.68 \cdot 10^{-8}$	-0.29	0	10.95	Nakashima <i>et al</i> (1987)
(13)	$\text{H}^+ + \text{D} \rightarrow \text{D}^+ + \text{H}$	10^{-9}	0	41	-0.01	Watson (1976)
(14)	$\text{H} + \text{D} \rightarrow \text{HD} + \text{h}\nu$	10^{-25}	0	0		Lepp & Shull (1984)
(15)	$\text{D}^+ + \text{H}_2 \rightarrow \text{H}^+ + \text{HD}$	$1.7 \cdot 10^{-9}$	0	0	0.06	Smith <i>et al</i> (1982)
(16)	$\text{D}^+ + \text{H} \rightarrow \text{HD}^+ + \text{h}\nu$	$1.8 \cdot 10^{-18}$	1.5	0		Dalgarno & Lepp (1987)
(17)	$\text{H}^+ + \text{D} \rightarrow \text{HD}^+ + \text{h}\nu$	$1.8 \cdot 10^{-18}$	1.5	0		Dalgarno & Lepp (1987)
(18)	$\text{HD}^+ + \text{H} \rightarrow \text{H}^+ + \text{HD}$	$6.4 \cdot 10^{-10}$	0	0	1.85	Karpas <i>et al</i> (1979)
(19)	$\text{HD} + \text{h}\nu \rightarrow \text{H} + \text{D}$					Latter & Black (1991)
(20)	$\text{HD}^+ + \text{h}\nu \rightarrow \text{H}^+ + \text{D}$					Von Busch & Dunn (1972)
(21)	$\text{HD}^+ + \text{h}\nu \rightarrow \text{D}^+ + \text{H}$					Von Busch & Dunn (1972)
(22)	$\text{D}^+ + \text{e} \rightarrow \text{D} + \text{h}\nu$	$3.5 \cdot 10^{-12}$	-0.70	0		Prasad & Huntress (1980)
(23)	$\text{HD}^+ + \text{e} \rightarrow \text{D} + \text{H}$	$1.39 \cdot 10^{-8}$	-0.29	0	10.93	Nakashima <i>et al</i> (1987)
(24)	$\text{D}^+ + \text{H} \rightarrow \text{H}^+ + \text{D}$	10^{-9}	0	0	0.01	Watson (1976)
(25)	$\text{H}^+ + \text{HD} \rightarrow \text{D}^+ + \text{H}_2$	$1.7 \cdot 10^{-10}$	0	462	-0.06	Smith <i>et al</i> (1982)
(26)	$\text{H}_2^+ + \text{D} \rightarrow \text{D}^+ + \text{H}_2$	$6.4 \cdot 10^{-10}$	0	0	1.81	Karpas <i>et al</i> (1979)

	reactions	γ	α	β	ΔH	references
(27)	$D + H_2 \rightarrow HD + H$	$1.09 \cdot 10^{-18}$	0	0	0.05	Zhang & Miller (1989)
(28)	$Li + H \rightarrow LiH + h\nu$	$3.8 \cdot 10^{-20}$	0	0		Stancil et al (1996)
(29)	$LiH + h\nu \rightarrow Li + H$					Kirby & Dalgarno (1978)
(30)	$Li^+ + e^- \rightarrow Li + \nu$	$3.01 \cdot 10^{-12}$	-0.68	0		Stancil et al (1996)
(31)	$Li + \nu \rightarrow Li^+ + e^-$					see Stancil et al (1996)
(32)	$Li^+ + H^- \rightarrow Li + H$	$1.2 \cdot 10^{-7}$	-0.36	-16500		Stancil et al (1996)
(33)	$Li + H^+ \rightarrow Li^+ + H$	$4.0 \cdot 10^{-20}$	6.8	1800		Stancil et al (1996)
(34)	$Li + H^+ \rightarrow Li^+ + H + \nu$	$2.3 \cdot 10^{-14}$	0.55	10000		Stancil et al (1996)
(34)	$Li + e^- \rightarrow Li^- + \nu$	$1.85 \cdot 10^{-15}$	-0.62	9300		Stancil et al (1996)
(35)	$Li^- + \nu \rightarrow Li + e^-$					see Stancil et al (1996)
(36)	$Li^- + H^+ \rightarrow Li + H$	$1.2 \cdot 10^{-7}$	-0.36	-16500		Stancil et al (1996)
(37)	$Li^+ + H \rightarrow LiH^+ + \nu$	$8.0 \cdot 10^{-23}$	-0.9	7000		Stancil et al (1996)
(38)	$LiH^+ + \nu \rightarrow Li^+ + H$					see Stancil et al (1996)
(39)	$Li + H^+ \rightarrow LiH^+ + \nu$	$3.25 \cdot 10^{-15}$	-0.49			Stancil et al (1996)
(40)	$LiH^+ + \nu \rightarrow Li + H^+$					see Stancil et al (1996)
(41)	$LiH^+ + e^- \rightarrow Li + H$	$2.6 \cdot 10^{-8}$	-0.47			Stancil et al (1996)
(42)	$LiH^+ + H \rightarrow Li + H_2^+$	$9.0 \cdot 10^{-10}$		66400		Stancil et al (1996)
(43)	$LiH^+ + H \rightarrow Li^+ + H_2$	$3.0 \cdot 10^{-10}$				Stancil et al (1996)
(44)	$LiH^+ + H \rightarrow LiH + H^+$	$1.0 \cdot 10^{-11}$		67900		Stancil et al (1996)
(45)	$Li + H^- \rightarrow LiH + e^-$	$4.0 \cdot 10^{-10}$				Stancil et al (1996)
(46)	$Li^- + H \rightarrow LiH + e^-$	$4.0 \cdot 10^{-10}$				Stancil et al (1996)
(47)	$LiH + H^+ \rightarrow LiH^+ + H$	$1.0 \cdot 10^{-9}$				Stancil et al (1996)
(48)	$LiH + H \rightarrow Li + H_2$	$2.0 \cdot 10^{-11}$				Stancil et al (1996)
(49)	$LiH + H^+ \rightarrow Li^+ + H_2$	$1.0 \cdot 10^{-9}$				Stancil et al (1996)
(50)	$LiH + H^+ \rightarrow Li + H_2^+$	$1.0 \cdot 10^{-9}$				Stancil et al (1996)

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