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ORIGINS OF CHEMICAL ELEMENTS FROM WATER

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ABSTRACT

Based on a literal interpretation of the Biblical account of creation, it is inferred that all the original matter available to the universe was water (Gen. 1:1-3). Employing this premise, a method is outlined demonstrating how various chemical elements might have been derived via nucleosynthesis processes. The mechanism commences with the hydrogen (H) and oxygen (O) nuclei provided by water, which are subjected to nuclear reactions. These reactions invoke classical collision theory as the mechanism for generation of new atomic nuclei at a given steady-state temperature.

For purposes of simplicity and time constraints, the study thus far has been limited to the production of only the most abundant, stable isotopes naturally present in the earth. There are still some seventy elements remaining to be accounted for. Furthermore, no attempt is made to address the distributions of elements, either in the earth, solar system, or cosmos. These questions must be deferred for future work. The emphasis of this study is solely on the mechanism of production.

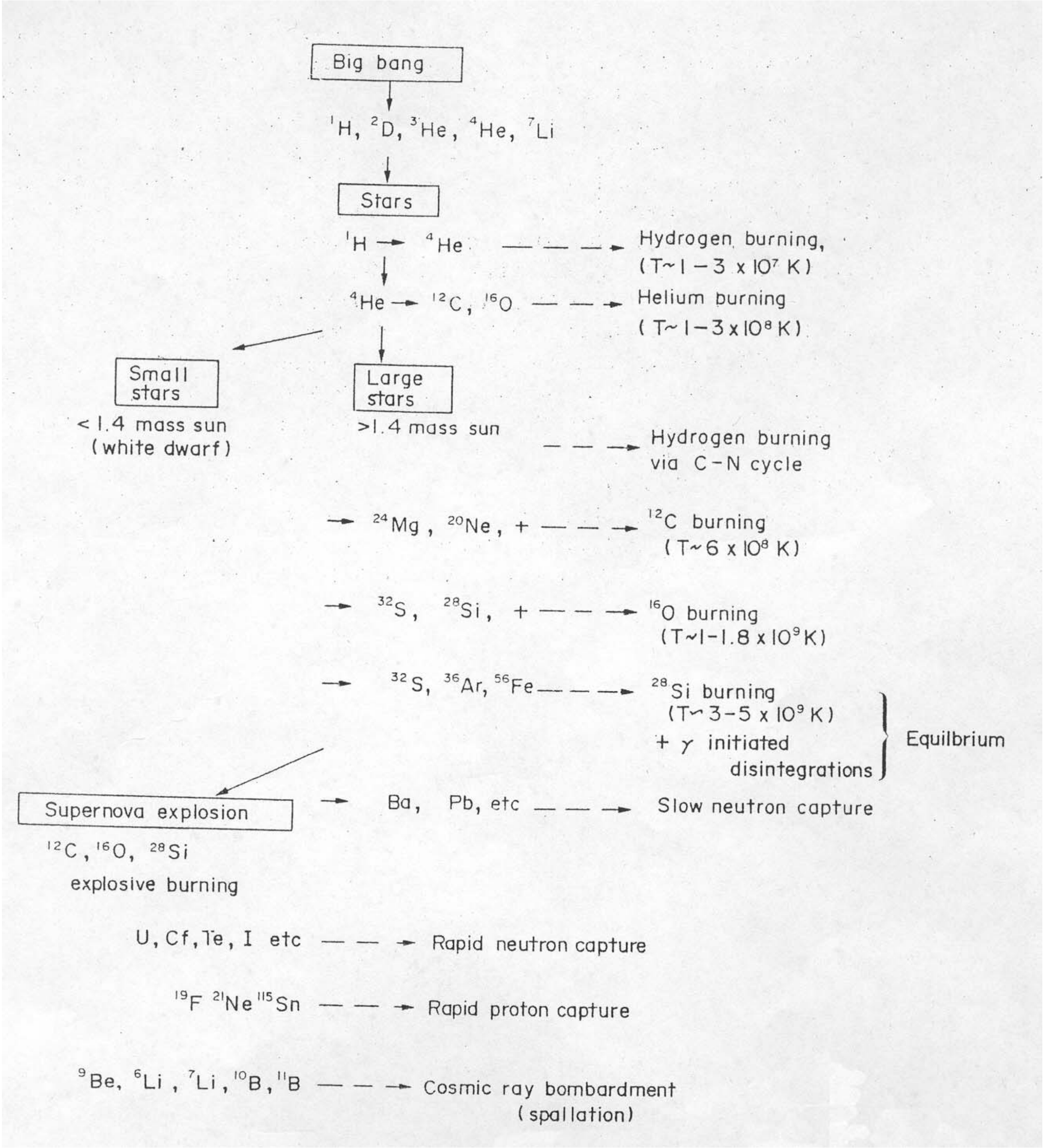
It is shown that dissociation of water would produce the necessary number of particles and all production times are short. A viable process is also presented which provides a tenable explanation for rapid energy release.

INTRODUCTION

The currently accepted understanding of the origin of chemical elements has its genesis in Big Bang cosmology, in which subatomic particles are initially produced. The electrons, protons and neutrons comprising the most stable entities among the initial products of this process, undergo high energy fusion reactions called nucleosynthesis, producing atomic isotopes of hydrogen and helium. The remaining chemical elements are produced by a variety of nucleosynthesis mechanisms, taking place in the evolution of stars. Of course, the earth and remainder of the solar system are produced subsequent to stellar formations. The process is proposed to be a condensation of the debris produced during the stellar evolution. However, this is contrary to the Biblical account, which states that the earth is created initially and the rest of the cosmos subsequent to that event.

More specifically, the initial nucleosynthesis process producing helium (^{4}He) from hydrogen (^{1}H) is initiated some 700,000 years after the singularity explosion of the Big Bang. It is maintained that more than a billion years were involved in this initial process, called **hydrogen burning**. But the next elements in sequence Li, Be, B, cannot be produced via hydrogen burning because the isotopes produced are unstable and decay into ^{4}He, which is stable. It is proposed that Li, Be and B are produced via a **spallation** process involving cosmic ray bombardment of heavier elements already produced by other mechanisms [10]. However, actual process is far from settled. In fact, it has been stated in reference to the origin of Li, Be, and B, "*there is no theory for their production that has been generally accepted*" [1].

An analogous **helium burning** process is said to occur in the 1-3x10^8K temperature range, producing C, N and O. A sequence of carbon and oxygen and silicon burning processes in the 6x10^8K to 3x10^9K temperature range are proposed for generating Mg, Ne, S, Si, Ar, P. A combination of fusion reactions can produce Fe, having the most stable nuclear binding energy of all elements. All elements heavier than Fe are believed to be produced via more energy efficient **neutron capture** processes. These are divided into **s** (slow) and **r** (rapid) mechanisms. The former is favored in proton-rich isotopes, while the latter is favored in neutron-rich isotopes. There are also **proton-capture** mechanisms which appear to be assigned rather arbitrarily to certain isotopes regardless of their neutron/proton ratios [10]. The myriad of nucleosynthesis processes described above appear to be predicated upon a "whatever seems feasible" basis, rather than grounded on good scientific evidence. Selbin has summarized these processes as depicted in the following diagram [9].



In contrast to the stellar evolutionary scenario of nucleosynthesis, the data presented in this paper are based upon a literal Biblical interpretation. Gen. 1:1-3, *"In the beginning of God's preparing the heavens and the earth - the earth hath existed waste and void, and darkness is on the face of the deep, and the Spirit of God fluttering on the face of the waters, and God saith, 'Let light be', and light is*" [11]. The words *"waste and void"* may refer to a state lacking specific composition and physical form, *"fluttering"* is the word **rakap** in Hebrew meaning to shake, agitate, or stir; *"waters"* is ***mayim*** in Hebrew which is normal water in its liquid state. The water may have been transformed by the "agitation" (of the Holy Spirit) into a high energy fluid plasma. Under this condition the H_2O molecular structure would decompose into its component H and O atoms. Furthermore, these atoms would be stripped of all their electrons producing bare nuclei. Thus these are nuclei under conditions amenable to nucleosynthesis reactions This is further substantiated by the rest of the verse, *"let light be."* The Hebrew word used for light is ’***ôr***. This word has numerous uses implying a variety of statements relating to light. However, in this context of Gen. 1, the sense is to produce light or "illumination" or even "to set fire to" something. The connotation here is to impart energy to the environment which was previously in darkness (absence of illumination or luminosity due to energy). From 2 Pet. 3:5, *"—and the earth out of water and through water standing together by the word of God"* [11]. The Greek word for water is ***hudatos,*** meaning liquid water in the normal sense. The implication could be that God created the earth from water, but there was still water remaining from which the earth was separated. Furthermore, Psalm 148:4 says *"Praise ye Him, heaven of heavens and ye waters that are above the heavens"* [11]. Russell Humphreys has proposed an interesting analysis of this scripture, plus other scriptures relating to *"stretching the heavens"* [2]. This investigation is in agreement with Humphreys, in that the stretching of the heavens relates to expanding the water to the outermost edge of the universe (some 10 billion light years away).

In conclusion, the six primary points made by Humphreys [2] are reiterated:

1. Matter in the universe is bounded.
2. The universe has expanded.
3. The earth is near the center of the universe.
4. The universe is young as measured by clocks on earth.
5. **The original matter God created was ordinary liquid water.** (bold emphasis added)
6. **God transformed the water into various elements by compaction.** (bold emphasis added)

Pure water is composed of two chemical elements, hydrogen (H) and oxygen (O). It is proposed in this study that all other chemical elements might be efficiently and rapidly produced from the two elements provided by water.

BASIS AND MECHANISM

If, as related in the introduction, it is assumed that the only matter initially present in the universe was water, and if it is further assumed that all the matter and energy in the present universe were derived from this original water, then the following considerations provide the foundational basis of this proposed model for elemental synthesis.

Restricting the production of elements to the earth alone, the total effective mass of the water would have been 6.026×10^{24} kg. (see Table 1). It is commonly accepted that the total mass of free and bound water in the earth is some $2.3 \pm 0.4 \times 10^{21}$ kg, so this amount of water would not be converted to other elements. This still allows 6.02×10^{24} kg of water to produce other elements. This mass of water provides 2.013×10^{50} O atoms and 4.026×10^{50} H atoms. Each H atom ionizes its electron to produce 13.5 eV and each O produces 871.4 eV if all eight of the, electrons are ionized. The O atoms providing 1.754×10^{53} eV, plus 5.44×10^{51} eV from the H atoms, yield a total of 1.808×10^{53} eV, or 1.808×10^{47} MeV.

The work done in decomposing all 6.026×10^{24} kg of H_2O into H and O nuclei plus their electrons, followed by their chemical recombination to form $2.3 \pm 4 \times 10^{21}$ kg of liquid water, is derived from the following expression; based upon the relations given later on in equation (3):

$$W = 2\left[\frac{E_{(dec)}}{E_{(rec)}}(MeV)\right]\frac{M_W M_E}{(M_W + M)} \tag{1}$$

where E(dec) = 1.808×10^{47} MeV (decomposition in energy), E(rec) = $6.91 \pm 1.20 \times 10^{43}$ MeV (recombination energy), M_E = 6.026×10^{24} kg (mass of water converted into non-aqueous earth), M_w = $2.3 \pm 0.4 \times 10^{21}$ kg (mass of water remaining in the earth). Substitution of the data into equation (1) yields 2.0×10^{24} MeV. The temperature equivalent of this energy is 2.3×10^{10}K, thus conforming to conditions of a high temperature plasma. The pressure to drive nuclide collision is a property of the plasma.

The data obtained in this work are based upon the following assumptions:

1. Conventional nucleosynthesis theory as applied to the production of chemical elements in the evolution of star formation is not considered in this model.
2. All nucleosynthesis processes are treated in terms of the energy transferred according to inelastic classical collision theory of hard spheres. In this model, collision cross sections are not a function of energy, but are confined to particle dimensions.
3. The total energy provided for each fusion process is a function of the masses of pertinent nuclides and the Q (excess energy) of each reaction (see following section on rate of production).
4. For purposes of simplicity and time constraints, this study as completed thus far, is limited to the production of only the most stable abundant isotopes of product elements. An extension to various other isotopes, particularly for heavier elements, is planned in a continued extension of this study.
5. Although more than one process may be applicable for the production of a specific element, for purposes of consistency, only the most energy efficient options have been selected.
6. Because of the limitations of this present work, no comments can be made about relative elemental abundances in the earth, much less in the solar system or universe.

RATE OF PRODUCTION

It has been pointed out in the introduction that the mechanism of stellar nucleosynthesis requires time in excess of a billion years for even the initial reaction time of ^1H producing ^4He. More specifically, $2\,^1H+2n^o \rightarrow 2H$ (1.4x10^{10} yr.); $^2H+^1H \rightarrow ^3He$ (0.6 sec.); $2\ ^3He \rightarrow ^4He+2\ ^1H$ (10^6 yr.). Obviously, even if the production of subsequent elements involve variable short and long time intervals, the overall time spent will be quite long.

Further comments pertinent to the time issue include the following quote concerning isotope ratios $^{238}U/^{235}U$, $^{238}U/^{232}Th$ and $^{187}Re/^{187}Os$:

> "The present vs. r-process-production values of these ratios imply that the present mean age of the r-process elements is about 6.8x10^9 yr. Since 4.6x10^9 of this is the age of the solar system, during which no additional synthesis took place, the mean time scale for synthesis was 2.3x10^9 yr. This is surely not less than half the total time during which synthesis took place, implying an age for the universe of at least (4.6+2x2.2) x 10^9 or 9x10^9 yr" [10, p. 891].

Hence, if the age of elemental production is an important chronometer regarding the age of the universe, then the same is equally true with regard to the age of the earth.

This model incorporates time dependent collision theory between projectile-target, hard sphere nuclides. According to standard collision theory of hard spheres, the collision rate between pairs of unlike particles is given:

$$R_{(1,2)} = \pi N_1 N_2 \bar{d}^2_{(1,2)} \left(v^2_{(1)}\ v^2_{(2)}\right)^{1/2} \tag{2}$$

where the collision rate is $R_{(1,2)}$ for collisions /m^{-4} s^{-1}, N = number of collisions /m^{-4}, $\bar{d}$ = average diameter (m) of colliding particles, v^2= the root mean square velocities of colliding particles. The average collision diameter, $d^2_{(1,2)}$ is equal to $\sqrt{\pi}(r_1 + r_2)^2$, where r are nuclear radii. Also, v^2 = 3 kT/M, where k = 1.382 x 10^{-23} J/K, T = temperature in K, and M = mass in kg. The magnitude of the temperature in these processes is deduced as follows. The average energy transferred in a two-body hard sphere collision between particles (1) the projectile, and (2), the target, is $E_{(1,2)}$ given by the equation:

$$E_{(1,2)} = \frac{1}{2} KE_{(\max)}(1,2) = \frac{2KE_{(\min,1)} M_{(1)} M_{(2)}}{\left(M_{(1)} + M_{(2)}\right)^2} \tag{3}$$

where $KE_{(max)}$ is the maximum kinetic energy for collision, $KE_{(min,1)}$, the minimum kinetic energy for the projectile is given by:

$$KE_{(\min)} = \left[1 + \frac{M_{(1)}}{M_{(2)}} \right] |Q| \qquad (4)$$

where Q is the energy excess of a given nuclear reaction. In both equations (3) and (4), M is the particle mass in kg. The critical energy for reaction is E $_{(1,2)}$ for which the temperature equivalent of the energy if 1 MeV = $1.16\text{x}10^{10}$ K. The required Q are provided in Table 3. Upon substituting the appropriate data for evaluating equations (3) and (4) for all reactions in Table 3, it is found that T ranges from $7.68\text{x}10^{9}$ to $3.57\text{x}10^{10}$ K with the average value T = $2.17\pm0.80\text{x}10^{10}$. This is the temperature used to evaluate v^2 for equation (2).

It is apparent from equations (3) and (4) that the nuclide collision energy for effective fusion is a function of the reaction Q. But, the latter is not derivable from kT alone, and the application of equation (2) to obtain the desirable collision rates is not totally adequate. Thus the rate expression incorporating the nuclear activation energy (critical energy) for the collision process is:

$$Rate = d_{(1,2)} \left[\frac{8kT}{\pi\mu} \right]^{1/2} \exp\left(- E^* / kT \right) N_{(1)} N_{(2)} \qquad (5)$$

where μ = $M_{(1)}M_{(2)}/M_{(1)}+M_{(2)}$, the reduced mass, and E* is the activation energy. This energy of activation is taken to be $E_{(1,2)}$ from equation (3).

The actual collision rate is, of course, dependent on the total number of actual collisions. Hence, it is desirable to know what portion of particles involved in the collisions do not collide. This is given by exp(-t/f), where t is the time interval for the collisions and f is the ratio of the average velocity to the mean free path. For the collision rates presented in this paper, it is found that when t = 1s, 33% of the particles do not collide. But, as the time increases this ratio fall off very rapidly, i.e., at t = 40s, 10^{-20}% do not collide; at t = 0.5 days, $<10^{-2000}$% do not collide. Thus it seems safe to conclude that essentially all particles involved in pair-wise collisions do indeed collide within a very short period of time.

It is now necessary to estimate the number of those collisions which are likely to be effective in producing a nuclear fusion product. The initial rate, $R_{(1,2)}$, provides the total number of collisions within given volume per unit length per second (m^{-4} s^{-1}). To attain an estimate of the effective number of collisions per average number of particles within the given volume per second, the following transformation is incorporated. $R_{(1,2)}\cdot(V/\lambda N_1N_2)$ where λ is the average mean free path for target and projectile (m units of length); V is the volume in m^3 units; N_1 and N_2 are the numbers of projectiles and targets respectively. The factor $(V/\lambda VN_1N_2)^{1/2}$=C.E.F., the collision efficiency factor. Since $R_{(1,2)}$, is in units of collisions/m^4s, $R_{(1,2)}$(C.E.F.)=R* the reduced rate, in units of collisions/(m^3)(particles)(second). The time for each collision induced nucleosynthesis is t=1/R*(1,2). These and all other pertinent data are listed in Table 4.

CONCLUSION

It has been shown that the production of chemical elements from hydrogen through calcium can be accomplished in principle, from the complete dissociation of water into H and O nuclei. These are incorporated in nucleosynthesis reactions producing other elements which also engage in further nucleosynthesis. The number of H and O atoms available from the initial water are $4.030\text{x}10^{50}$ and $2.013\text{x}10^{50}$ respecitively. As shown in Table 2, there are no other atoms in the sequence considered which exceed 10^{50} in number. All subsequent elements will be limited to even smaller numbers of atoms.

Thus far in reactions involving O atoms, the numbers of these other atoms produced do not exceed the total O atoms initially available.

Similarly, for those reactions involving H atoms there are no product elements exceeding 10^{50} in number. Thus the amount of H initially available is more than sufficient. The total number of He atoms required for all reactions presented here is $8.8\text{x}10^{49}$. Since the amount of He now present in the earth is less than $8\text{x}10^{46}$ atoms (see Table 2), it is reasonable to conclude that all of the He generated for producing those elements through potassium (and even beyond), has been more than sufficient for the nucleosyntheses.

It is important to point out that the above relations have nothing to do with the helium and hydrogen present in the sun and stars, which must have been produced by a different process. Recall that this limited study is confined only to the earth.

The total energy released for the sum total of nuclides from H through Ca is about $9\text{x}10^{49}$ MeV.This horrendously large amount of energy waxes small in light of the $1.68\text{x}10^{71}$ MeV energy equivalent for the $3\text{x}10^{51}$kg mass of the universe. The Big Bang scenario maintains that in just 10^{-43} seconds after the onset of the Big Bang event, this 10^{71} MeV of energy ($2 \text{ x } 10^{81}$ K temperature equivalent) instantaneously dissipates with the simultaneous production of matter. But Big Bang cosmology offers no viable scientific basis for this nearly instantaneous energy dissipation, other than that it is a requirement for the evolution of a stable universe. However, the total $9\text{x}10^{49}$ MeV associated with the reactions noted here, could have been rapidly reduced according to the mechanism proposed by Humphreys [4]. This is based on the principal that temperature of an isolated system (ex. earth) varies indirectly with the square of the radius of curvature of space, as shown in the following equation:

$$\frac{T_t}{T_0} = \left(\frac{R_0}{R_t}\right)^2 \tag{6}$$

Humphreys has also provided the following expression for evlauating the time associated with the expansion of radius of curvature of a spherical body [3]:

$$t = \frac{R_0}{c\pi}\left(\arccos\left(2\frac{R_t}{R_0} - 1\right) + 2\left[R_t / R_0 - \left(R_t / R_0\right)^2\right]^{1/2}\right) \tag{7}$$

in which t is the absolute proper time, c the speed of light, and the arccos function is in π radians.

The application of these relations to the heat problem in question is based on the following considerations. Geophysical conditions currently existing in the earth indicate a pressure down to the core depth of the order of 10^{10} Pa and a maximum temperature of about 5000K. Combining these data with a $1.1\text{x}10^{21}$ m^3 volume yields a PV/T constant of $2.2\text{x}10^{27}$ Pa m^3/K.

The 10^{60}K temperature associated with the nucleosynthesis processes would account for a pressure increase to $4.2\text{x}10^{18}$ Pa, if the initial environment had expanded to a spherical volume consistent with the accepted $1.4\text{x}10^{23}$ m radius of curvature. If this pressure were initially confined within a reduced volume equivalent to that of the earth ($1.1\text{x}10^{21}\text{m}^3$), the temperature would have been $2.1\text{x}10^{12}$ K.

Application of equation (6) with an initial temperature, T_o=2. $1\text{X}10^{12}$ K and a present, average whole-earth temperature of the order of 10^3 K, plus a radius of curvature, R_t=$6.4\text{x}10^6$m, the earth's current radius, then R_o=$2.9\text{x}10^{11}$ m. Subsequent substitution of these data into equation (7) provides a time, **t=16 min**. This suggests that less than one half hour would have been required to cool the earth to its current temperature state.

There is, of course, much work remaining to be done in deriving syntheses of remaining elements. However, the various factors pertinent to the mechanism should be essentially equivalent to those already presented. Hence, it appears that a reasonable scheme for elemental syntheses from water is tenable.

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TABLE 1
CRITICAL EARTH DATA

Region	Mass (kg)	Volume (m^3)
Core	1.94×10^{24} (?)[a]	1.76×10^{20} (?)[a]
Lithosphere (crust plus mantle)	4.086×10^{24}	9.102×10^{20}
Hydrosphere	1.41×10^{21}	1.38×10^{18}
Atmosphere	5.10×10^{18}	3.95×10^{18} (ave)

[a] True chemical composition of core is not known

MAJOR ELEMENTAL ABUNDANCES (% kg wt)[b]

Element	Lithosphere	Hydrospere	Atmosphere
H	2.82	10.6	
He	0.012	6.8×10^{-10}	
Li	8.9×10^{-4}	1.8×10^{-5}	
Be	1.9×10^{-5}	5.9×10^{-11}	
B	3.3×10^{-4}	4.5×10^{-4}	
C	0.16	2.7×10^{-3}	0.013 (CO_2)
N	9.0×10^{-4}	4.9×10^{-5}	75.65 (N_2)
O	63.1	83.9	23.05 (O_2, CO_2)
F	2.2×10^{-3}	1.3×10^{-4}	
Ne	1×10^{-10}	1.4×10^{-8}	
Na	2.51	2.03	
Mg	1.58	0.34	
Al	6.10	1×10^{-6}	
Si	20.3	2.9×10^{-4}	
P	7.4×10^{-2}	6.8×10^{-6}	
S	4.0×10^{-2}	8.7×10^{-2}	
Cl	2.1×10^{-4}	2.86	
Ar	9.3×10^{-7}	5.9×10^{-5}	1.28
K	1.03	3.7×10^{-2}	
Ca	1.06	3.9×10^{-2}	

[b] Compiles from references [5-8]

TABLE 2
MAJOR TERRESTRIAL ELEMENTS

Element	Total Composite (kg)[a]	Total Number of Atoms
H	1.152×10^{23}	6.88×10^{49}
He	4.9×10^{20}	7.37×10^{46}
Li	3.64×10^{19}	3.16×10^{45}
Be	7.76×10^{17}	5.19×10^{43}
B	1.35×10^{19}	7.52×10^{44}
C	6.54×10^{21}	3.28×10^{47}
N	4.07×10^{19}	1.75×10^{45}
O	2.583×10^{24}	9.72×10^{49}
F	8.99×10^{19}	2.85×10^{45}
Ne	7.06×10^{13}	2.11×10^{39}
Na	1.03×10^{23}	2.7×10^{48}
Mg	6.46×10^{22}	1.6×10^{48}
Al	2.49×10^{23}	5.57×10^{48}
Si	8.29×10^{23}	1.78×10^{49}
P	3.02×10^{21}	5.8×10^{46}
S	1.63×10^{21}	3.06×10^{46}
Cl	4.89×10^{19}	8.3×10^{44}
Ar	1.04×10^{17}	1.57×10^{42}
K	4.21×10^{22}	6.48×10^{47}
Ca	4.33×10^{22}	6.51×10^{47}

[a] All components of the earth

TABLE 3
PERTINENT NUCLEOSYNTHESIS REACTIONS[a]

$^{1}H + e^{-} = n^{o} + 0.78$ MeV

$^{1}H + {}^{o}n = {}^{2}H + 2.22$ MeV

$^{16}O + {}^{2}H = {}^{14}N + {}^{4}He + 3.11$ MeV

$^{14}N + {}^{2}H = {}^{12}C + {}^{4}He + 13.57$ MeV

$^{12}C + {}^{2}H + 1.34$ MeV $= {}^{10}B + {}^{4}He$

$^{10}B + n^{o} = {}^{11}B + 8.44$ MeV

$^{11}B + {}^{2}H = {}^{9}Be + {}^{4}He +8.03$ MeV

$^{9}Be + {}^{2}H = {}^{7}Li + {}^{4}He + 7.15$ MeV

$^{14}N + n^{o} + 10.8$ MeV $= {}^{15}N$

$^{15}N + {}^{4}He = {}^{19}F + 4.01$ MeV

$^{16}O + {}^{4}He = {}^{20}Ne + 4.73$ MeV

$^{19}F + {}^{4}He = {}^{23}Na + 4.01$ MeV

$^{20}Ne + {}^{4}He = {}^{24}Mg + 4.73$ MeV

$^{23}Na + {}^{4}He = {}^{27}Al + 10.47$ MeV

$^{24}Mg + {}^{4}He = {}^{28}Si + 0.31$ MeV

$^{27}Al + {}^{4}He = {}^{31}P + 9.67$ MeV

$^{28}Si + {}^{4}He = {}^{32}S + 9.99$ MeV

$^{31}P + {}^{4}He = {}^{35}Cl + 7.00$ MeV

$^{35}Cl + {}^{4}He = {}^{39}K + 7.22$ MeV

$^{39}K + n^{o} = {}^{40}K +7.80$ MeV

^{40}K(unstable) $= {}^{40}Ar + e^{+} + 1.51$ MeV

^{40}K(unstable) $= {}^{40}Ca + e^{-} + 1.32$ MeV

$^{32}S + {}^{4}He = {}^{36}Ar + 6.64$ MeV

$^{36}Ar + {}^{4}He = {}^{40}Ca + 7.04$ MeV

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[a] All reactions were derived from the data in reference [12]

TABLE 4

Collision rate data for nucleosynthesis reactions

Projectile and Target	M^a	N^a	r^a	$d^2_{(1,2)}$	|Q|	$R_{(1,2)}$	λ (m)	C.E.F.	R^*	t (s)
n^0	1.657	6880	0.45	-	0.76	-	-	-	-	-
$n^0/^1H$	1.661	6880	1.21	0.865	2.22	$1.47x10^5$	0.912	$5.05x10^{-3}$	742	$1.3x10^{-3}$
^2H	3.345	6880	1.52	-	-	-	-	-	-	-
^4He	6.647	737	1.92	-	-	-	-	-	-	-
$^2H/^{16}O$	26.57	9720	3.05	6.56	3.11	$1.24x10^6$	0.112	$1.21x10^{-2}$	$1.50x10^4$	$1.7x10^{-5}$
$^2H/^{14}N$	23.25	0.175	2.91	6.17	13.57	10.3	0.374	1.56	16.1	$6.2x10^{-2}$
$^2H/^{12}C$	19.93	32.8	2.77	5.78	1.34	$4.07x10^3$	0.384	0.1112	4.56	$2.2x10^{-3}$
$n^0/^{10}B$	16.63	$7.5x10^{-2}$	2.61	2.94	8.44	4.84	1.83	1.07	5.28	0.19
$^2H/^{11}B$	18.23	$7.52x10^{-2}$	2.69	5.57	8.03	5.29	0.394	2.31	13.2	$7.6x10^2$
$^2H/^9Be$	14.97	$5.19x10^{-3}$	2.52	5.13	7.15	0.325	0.411	8.64	2.81	03.56
$n^0/^{14}N$	23.25	0.175	2.92	3.55	10.8	13.8	1.66	0.737	10.2	$9.8x10^{-2}$
$^4He/^{15}N$	24.91	0.175	2.98	7.54	4.01	$1.59x10^{-2}$	242	1.87	$2.97x10^{-2}$	34
$^4He/^{16}O$	26.57	9720	3.05	7.76	4.73	$8.67x10^2$	0.118	1.14	988	$1.0x10^{-3}$
$^4He/^{19}F$	31.55	0.285	3.23	8.33	4.01	$3.02x10^{-2}$	224	1.48	$4.47x10^{-2}$	22
$^4He/^{20}Ne$	33.20	$2.11x10^{-7}$	3.28	8.50	4.73	$2.17x10^{-10}$	236	$1.73x10^3$	$3.75x10^{-5}$	$2.7x10^4$
$^4He/^{23}Na$	38.18	270	3.44	9.03	10.47	0.195	3.43	0.400	7.80	0.128
$^4He/^{24}Mg$	39.85	160	3.49	9.20	0.31	0.260	4.49	454	11.8	$8.47x10^{-2}$
$^4He/^{27}Al$	44.84	557	3.63	9.68	9.67	0.500	1.53	416	20.8	$4.81x10^{-2}$
$^4He/^{28}Si$	46.50	1780	3.67	9.82	9.99	$1.62x10^2$	0.475	0.418	67.7	$1.5x10^{-2}$
$^4He/^{31}P$	51.48	5.80	3.80	10.3	7.00	69.4	83.7	0.552	0.383	2.61
$^4He/^{32}S$	53.14	3.06	3.84	10.4	6.64	3.83	116	0.645	0.247	4.05
$^4He/^{35}Cl$	58.12	$8.30x10^{-2}$	3.96	10.9	7.22	$1.08x10^{-2}$	204	0.487	$5.26x10^{-3}$	190
$^4He/^{36}Ar$	59.78	$1.57x10^{-4}$	3.99	11.0	7.04	$2.09x10^{-5}$	208	2.93	$6.12x10^{-5}$	$1.63x10^4$
$n^0/^{39}K$	64.76	64.8	4.10	6.50	7.80	0.129	10.5	0.466	6.01	0.166

[a]These data are for single particles and those to the **right** of the / mark.
M = particle mass ($x10^{-27}$ kg); N = numbers of particles ($x10^{46}$); r = particle radius ($x10^{-15}$ m); d^2 = collision cross section ($x10^{-29}$ m^2); Q = excess nuclear energy (MeV); $R_{(1,2)}$ = collision rate ($x10^{37}$ $m^{-4}s^{-1}$); λ = average mean free path per collision pair (m); C.E.F. = $(V/\lambda N_1N_2)^{1/2}$; R = effective rate (coll./part. m^3s); t = time (s)

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