The Possible Role of PeP Weak Interactions in the Early History of the Earth

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Abstract: The $p(pe^-, \nu)d$ reaction (Q = 1.442 MeV) is examined in view of the possible Gamow Factor Cancellation (GFC) theorized by Kim and Zubarev (1995). The lifetime for the pep reaction in a metal hydride environment, such as FeH in the core of the earth, was calculated to be 2.54E(+12) yrs. The duration of the earth's melting and degassing prior to the formation of the oceans can be calculated using the present ratio D/H = 1.5E(-4) for the oceanic value, the pep lifetime in Fe and the primordial ratio of D/H = 2.6E(-5). The time interval was calculated to be 630 ± 160 million years, yielding an oceanic formation age of 3.92 billion years ago. The $d(pe^-, \nu)t$ reaction (Q = 5.474 MeV) was also examined in view of the subsequent decay of tritium to ^3He and its possible role as a radiochronometer.

1. INTRODUCTION

The pep reaction lifetime in the sun is approximately 4.34E(+12) years because (a) the core temperature (energy < 1.35 keV), pressure and particle densities are sufficiently high to allow a substantial reaction rate between the three free particles, and (b) the effect of the quantum tunneling through the coulomb barrier of the two charged protons, the Gamow penetrability factor (Bahcall, 1989; Clayton, 1968). It is not at all obvious that this process should proceed in low temperature geologic settings. However, recent theoretical optical model investigations into ultra-low energy two- and three-body nuclear interactions by Kim and Zubarev (1995,1996,1997) indicate that a combination of Thomas-Fermi electronic shielding (Lindhard *et al.*, 1968; Zeigler *et al.*, 1985)

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coupled with a very weak long range attractive imaginary (elastic + fusion) scattering potential allows for the Gamow Factor Cancellation, the GFC effect. Additionally, mineral physics of the lattice vibrations thermally excited above the Debye temperature allow for particle-hole excitations within the electronic conduction band (Poirier, 1991; Kittel, 1986) uniquely producing highly mobile protons which share the electronic environment of the lattice. The added benefit of a long range attractive interaction (LRAI) in the imaginary scattering potential (Kim and Zubarev, 1995, 1996, 1997) is the formation of an internal electric field (E_{int}) in the lattice given by

$$E_{int} = -\nabla U_{sc} - \frac{\partial A_c}{\partial t} \qquad (1)$$

with U_{sc} the electronic screening potential and A_c the Fermi contact term or potential for the electron-proton at $r = 0$ (Yosida, 1996; Low, 1997), the LRAI. This form of the induced internal electric field is commonly known as a displacement potential.

In this paper I will apply the Kim-Zubarev GFC mechanism with a LRAI to investigate the pep and ped weak interaction decay lifetimes in the earth's early geological environment when melting, degassing and differentiation were occurring to create the first oceans and atmosphere. The premise is that the earth's primordial hydrogen, *chemically bound as hydrides* in either the Fe core or the Fe-silicate mantel, decayed into deuterium via pep weak interaction fusion during the time interval between the accretion of the earth 4.55 billion years ago and the degassing and formation of the early oceans and atmosphere. The basic assumption is that the majority of pep reactions occur in either the earth's Fe core or Fe-silicate mantel at thermal energies above the Debye temperature (470-750 K), and that the rate is largely determined by the Thomas-Fermi electron screening energy of the protons in Fe, the GFC effect and the proton density.

The $d(pe^-, \nu)t$ weak interaction fusion reaction was also examined because the subsequent tritium beta decay to ^3He has important consequences with regard to a possible radiogenic component. The question of whether radiogenic ^3He has contributed appreciably to the $^3He/^4He$ ratio anomalies observed between the atmospheric, oceanic seawater, Mid-Oceanic Ridge Basalts (MORE), Oceanic Island Basalts (OIB) and deep mantel "hot-spot" plumes is an interesting and timely one (see commentary Ladbury, 1999). The standard interpretation of helium isotopic anomalies reported over the past three decades has been based on a "primordial or protosolar" ^3He content of ocean basalts and deep mantle plumes (Clarke *et al.*, 1969; Craig *et al.*, 1975; Lupton and Craig, 1975; Kurz *et al.*, 1982; McKenzie and O'Nions, 1983; Kaneoka, 1983; Allegre *et al.*, 1983; O'Nions and Oxbugh,

1983; Jochum *et al.*, 1983; Porcelli and Wasserburg, 1995; Rocholl *et al.*, 1996; Patterson *et al.*, 1997; Niedermann *et al.*, 1997; Hoffmann, 1997; Kamijo *et al.*, 1998; Eiler *et al.*, 1998; Zhang, 1998; Hanyu *et al.*, 1999; Pedroni *et al.*, 1999). The interpretation of a possible radiogenic source of ^{3}He could help in resolving major differences between the atmospheric, MORB and plume helium anomalies and in better defining the D/H, U and Th abundances in the upper and lower crust (Wedepohl, 1995) and in the differentiated mantle (See references 1-13 in Jochum *et al.*, 1983).

2. RESULTS AND DISCUSSIONS

Mineral Physics and Lattice Vibrations. At temperatures above the Debye temperature (θ_D) of a metal or ceramic hydride, hydrogen becomes mobile as a proton hole state with the electrons occupying the conduction band. The ceramic perovskites with oxygen vacancies created at elevated temperatures readily absorb water, followed by the hydroxyl groups filling the vacancies thus creating mobile protons at temperatures above $\theta_D \approx 750\ K$ (Navrotsky, 1999; Kreuer, 1997,1996; Norby, 1990; Nowick and Du, 1995; Bose and Navrotsky, 1998). The high density and short O-O distance in MgSiOxides favors hydration and proton migration. Thermally excited proton-electron particle-hole continuum states with hopping frequencies > 1E(+13) per sec are effectively developed by electronic screening potentials of the order of a keV in the vibrational lattice of Fe materials commonly found in geological settings, such as the earth's Fe core or in the mantle perovskites, Mg(Fe)SiOxides. The screening potential yields an "effective energy or temperature" for the pep or ped reactions in the metal or metal-silicate. The electronic screening potential for protons in Fe was calculated to be 2.496 keV (See equation 5 below), a value greater than the equivalent central core temperature of the sun (< 1.35 keV).

Optical Model Formulation of Ultra-Low Energy Fusion Reactions. For non-resonance reactions which are relevant to primordial and stellar nucleosynthesis at low energies (a few keV), as in the weak interaction fusion reactions, the cross-section for production is given by the following very well known formula (Kim and Zubarev, 1995, 1996, 1997; Bahcall, 1989; Clayton, 1968),

$$\sigma_a(E) = \frac{S(E)}{E} e^{-2\pi\eta(E)} \qquad (2)$$

where $\eta(E) = Z_a Z_b e^2/\hbar v$ an $e^{-2\pi\eta(E)}$ is the Gamow factor representing the probability of bringing two charged nuclei to zero separation distance, and

S(E) is expected to be a slowly varying function of E. The GFC effect results from the appearance of a very weak long range attractive interaction (LRAI) in the imaginary part of the T-matrix of the Optical Model. The proof of separability of the imaginary part of the T-matrix, $T_{Im} = \mathrm{Im}\langle r|\, T|\, r'\rangle = -U_l(r,r')$, for the S-wave $(l=0)$ elastic and fusion channels is given in the theory by Kim and Zubarev (1995, 1996, 1997) with further formulation given below. $U_0(r,r')$ can be further parameterized by λ (strength/length) and β^{-1} (range) in a separable form for estimating the S-wave cross-section, $\sigma_0(E)$, for the two-channel case, as in $U_0(r,r') = \lambda g(r)g(r')$. Thus, using $g(r) = e^{-\beta r}/r$, the low energy zero energy cross-section, Equation (2), becomes

$$\sigma_0(E) = \frac{4\pi\lambda}{kE}\left[\int_0^\infty dr\psi_0^c(r)e^{-\beta r}/r\right]^2 = \frac{4\pi^2\lambda}{E}R_b\frac{(e^{-2\phi\eta}-1)^2}{(e^{2\pi\eta}-1)}e^{4\phi\eta} \qquad (3)$$

where $e^{4\phi\eta} = exp\left[4\alpha\frac{\mu c^2}{\hbar c}(Z_aZ_b/k)tan^{-1}\left(\frac{k}{\beta}\right)\right]$, $\phi = \tan^{-1}(k/\beta)$, and the

Bohr radius of the system is $R_B = \hbar^2/(2\mu Z_aZ_be^2)$. The energy dependence of λ is expected to be weak and several general forms of g(r) also lead to the same enhancement factor $e^{4\pi\eta}$, with the following result for $\sigma_0(E)$,

$$\sigma_0(E) = \frac{S_0(E)}{E}e^{4\phi\eta}e^{-2\pi\eta} \qquad (4)$$

The enhancement factor $e^{4\phi\eta}$ is $e^{2/R_B\beta}$ at zero energy and decreases, as E increases, to $e^{\pi/kR_B} \approx 1$ for large E. The important result is that in the limit $\beta \to 0, \phi = tan^{-1}(k/\beta) = \pi/2$, and $e^{4\phi\eta} = e^{2\pi\eta}$ which just cancels the Gamow factor, $e^{-2\pi\eta}$, for zero energy reactions.

Above the Debye temperature of the material the mobile protons share the electronic environment of the host lattice and the S-factor becomes modified accordingly, $S_G(E) = f_U(E)S(E)$ where an enhancement factor $f_U \approx \exp(\pi\eta U_{sc}/E)$ is due to the electron screening effect on the protons in the host metal hydride. U_{sc} is the Thomas-Fermi (Lindhard *et al.*, 1968; Zeigler *et al.*, 1985) screening energy which is given by

$$U_{sc} = 30.7Z_aZ_b(Z_a^{2/3} + Z_b^{2/3})^{1/2}eV \qquad (5)$$

with $Z_a = 1$ and $Z_b = 26$, yielding a screening potential energy of 2.496 keV for the three body system, ppe^-, in Fe or Fe-Silicate lattice. Note the two

body reactions, $pp \rightarrow dve^{+}$ and $pd \rightarrow {}^{3}Hey$, are not allowed since the screening potential between the two protons without the assistance of the electronic Fermi contact potential in Fe, is only 43.4 eV. This "effective energy or temperature" is insufficient to produce a noticeable GFC effect, $e^{-2\pi\eta} \approx 1.4E(-21)$ compared with 1.3E(-4) with shielded protons in Fe.

The pep reaction rate at "effective energies or temperatures" comparable to the solar plasma, 3-15(E+6) *K* (260-1300 eV), is given by:

$$R_{pep} \cong 1.102E(-4)\left(\rho/\mu_e\right)T_6^{-1/2}(1+0.02T_6)R_{pp} \tag{6a}$$

or reduced to,

$$R_{pep} = \chi_{pep} R_{pp} \tag{6b}$$

where μ_e is the mean molecular weight per electron, ρ the local density (Bahcall, 1989) and χ_{pep} is understood to represent the quantities in front of R_{pp} in equation(6a). The proton-proton rate, R_{pp}, is given by:

$$R_{pp} = \frac{n_a n_b}{1+\delta ab}\langle \sigma v \rangle \tag{7}$$

where $n_{a,b}$ are the particle densities, $1 + \delta_{ab}$ is the Kronecker delta which prevents double counting and the average cross section times velocity is approximated by $\langle \sigma v \rangle = \sigma v$ with $\sigma(E)$ given by equation (4). Equation (4) is modified appropriately to include the electron screening enhancement factor, $f_e \approx e^{2\pi\eta U_{sc}/E}$, for mis comparison of the rates in the earth $(E_e = U_{sc})$ and the sun (E_{sun}).

The comparison of the rates, $R_{pep\ (earth)}/R_{pep\ (sun)}$, reduces to the following equation:

$$R_{pep}^{earth} = \frac{1}{1.01E(+10)yrs}\left(\frac{\chi_{earth}}{\chi_{sun}}\right)\left(\frac{n_{a,b}^{e}}{n_{a,b}^{s}}\right)\left(\frac{E_{sun}}{U_{sc}}e^{2\pi\eta U_{sc}/E_{sun}}\right)\left(\frac{v_e}{v_s}\right) \tag{8}$$

The energies are converted to T_6 temperatures, $U_{sc} = k_b T_6$, the mean molecular weight per electron (earth) = 2, average mantle density ranging between $\rho = 3.56$ to $4.11\ g/cm^3$ and the mantle proton particle density $n_{a,b}^{e} =$ 1.44 to 1.65E(+22), equivalent to one conduction electron or particle-hole state per perovskite molecule, a 0.6% proton fraction. The solar parameters were taken from Bahcall (1989). See his tables 4.4 and 4.5. The final result is a calculated pep weak interaction fusion lifetime in the mantle of the earth

of 2.54(38)E(+12) years which is comparable to the lifetime in the sun, 4.34E(+12) years. The uncertainty, in parentheses is approximately **± 15%** based on a 10% uncertainty in the overall pep solar rate (Bahcall, 1989) and the range of mantle densities (Poirier, 1991).

The Formation Age of the Oceans. The formation interval **(Ξ)** between the accretion of the earth 4.55 Gyr ago and the degassing and formation of the early oceans and atmosphere was calculated assuming the difference between seawater, D/H = 1.5(l)E(-4), and the best estimate (Geiss and Reeves, 1972) for protosolar gas, D/H = 2.5E(-5), or the measured Jovian atmospheric isotope ratio (Nieman *et al*., 1996), D/H = 2.6(7)E(-5), resulted from the pep reaction in the earth's early history. The formation interval equation is given as:

$$\delta(D/2H) = (1\text{-}e^{-\lambda\Xi}) \qquad (9)$$

where $\lambda = \tau_{pep}^{-1}$ and $\tau_{pep} = 2.54(38)E(+12)$ years and $\delta(D/2H) = 2.48(32)\,E(-4)$. Using the Jovian measurement value (Nieman *et al*., 1996) yields, $\Xi = 630 \pm 160$ Myr. Half of the estimated uncertainty is from the measured uncertainties in the D/H ratios and the remainder from the pep lifetime calculation (Bahcall, 1989). The formation age of oceans can be estimated using the accretion age of the solar system of **4556 ± 2.0** Myr (Lugmair and Shukolyukov, 1998) and the formation interval calculated above, yielding 3.92 Gyr before the present. This age agrees well with the appearance of the first ancient continental crust or cratons and other geologic evidence such as the water-lain sediments dated approximately to 3.8 Gyr ago (Titayeva, 1994).

The $d(pe^-,\nu)t$ Lifetime and the Helium Anomalies. Following the formation of the oceans and the development of a differentiated core, mantle and crust the pep and ped weak interactions would continue to produce radiogenic deuterium and tritium (and subsequently **^{3}He**). The ped reaction lifetime is much shorter than the pep lifetime due to the greater beta decay energy. The nuclear beta matrix elements are constant and the decay constant follows the well known power law, $\tau^{-1} \propto E_\beta^{4.697}$. The ped lifetime compared with the pep reaction is estimated to be $[(E_{pep}/E_{ped})^{4.697} = 9.5E(-4)]\ 1/2\ \tau_{pep} = 2.43E(+9)$ years and is expected to be in secular equilibrium with the pep reaction.

Comparing the **^{3}He/^{4}He** ratios for the atmosphere **($R_{air} = 1$)** to the average MORB **($R/R_{air} = 8.18 \pm 0.73$)** (c*f* compilation by Kerr, 1999) one could infer that the upper mantle has been degassed and the MORB source represents a depleted upper/lower mantle. The increased He ratio would therefore represent a decreased average U and Th abundance relative to D/H. Using the averaged crustal values (Wedepohl, 1995) of 2.7 ppm U and 8.5 ppm Th the MORB ratio would decrease these values to 333 ppb and 1039 ppb,

respectively. Alternatively Jochum *et al.* (1983) have measured N-type MORB concentration averages of 75 ppb U and 189 ppb Th. This approach warrants further investigation.

The deep mantle plumes with $R_{plume}/R_{air} \approx 30\text{-}43$ would seem to indicate that either "primordial" ^3He locked within the undegassed deep mantle (the accepted theory) or a further depletion of U and Th abundances (less likely) was occurring to increase the ratio substantially to what is now observed for MORB. Recent models (Kerr, 1999; van der Hilst and Karason, 1999; Kellogg *et al.*, 1999; Kaneshima and Helffrich, 1999) indicate that the deep mantle may be isolated from the upper portions over periods of several billion years and is not depleted relative to the upper portions of the mantle and crust. If that is the case, then the weak interaction fusion reactions considered here could provide a new radiogenic point of view. Assuming the difference in R/R_{air} of the plumes and MORB is not due to U, Th and D/H concentration changes but rather that MORB is degassed whereas the deep mantle plumes are not, then one can calculate the increased concentration of radiogenic ^3He over the past 4.55 Gyr in the deep mantle. The plume to MORB ratio is calculated to be $R_{plume}/R_{MORB} = 5.40 \pm 1.35$ using the pep(dep) lifetime. Correcting for the decay of U and Th over the last 4.55 Gyr yields a plume ratio of $R_{plume}/R_{air} \approx 44 \pm 11$, a value in good agreement with what is observed experimentally.

3. SUMMARY

The pep and ped hydride lifetimes in the earths interior were calculated using the Kim-Zubarev optical model approach. A LRAI in the imaginary potential results in the GFC effect and a screening potential enhancement factor for protons in Fe. The pep lifetime was calculated to be 2.54E(+12) years which together with the net D/H ratio in seawater was used to calculate the time interval between the earth's accretion 4.55 Gyr ago and the formation of the first oceans and atmosphere. The time interval was calculated to be $\Xi = 630$ Myr, yielding a formation age of 3.92 Gyr ago. The He anomalies associated with the MORB, OIB and deep mantle plumes can be accounted for by assuming a radiogenic ^3He component and a combination of mantle depletion of U and Th and degassing of the upper/lower mantle. A well separated deep mantle which has not been degassed since the first differentiation into deep and upper/lower mantle components has a much larger He isotopic anomaly than the MORB values.

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