Nuclear Systematics: III. Source of Solar Luminosity

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The Sun emits about 3 x 10^{43} ^{1}H per year in the solar wind (SW). Solar luminosity and the outflow of SW-protons come from the collapsed supernova core, a neutron star (NS), on which the Sun formed. The universal cradle of the nuclides indicates that the energy of each neutron in the Sun's central NS exceeds that of a free neutron by $\approx$ 10-22 MeV. Solar luminosity and SW-protons are generated by a series of reactions: a) escape of neutrons from the central NS, b) decay of free neutrons or their capture by heavier nuclides, c) fusion and upward migration of H$^+$ through material that accreted on the NS, and d) escape of H$^+$ in the SW.

Introduction

This is the third paper in a series using nuclear systematics to elucidate the Sun's origin, composition, and source of energy. The first paper [1] confirmed that Fe is the most abundant element and that, except for H, elemental abundance in the Sun is linked with nuclear stability [2] as might be expected of elements made near the core of a supernova. The second paper [3] identified a universal cradle of nuclear matter that is used here to clarify the source of the Sun's energy.

According to the Standard Solar Model (SSM) [4], the Sun formed as a homogeneous body. It consists mostly of the two lightest elements, H and He, and its energy comes from fusion of H into He in the core of the Sun [5]:

$$4\ ^1H^+ + 2\ e^- \rightarrow\ ^4He^{++} + 2\ \nu + 26.73\ \text{MeV} \tag{1}$$

According to this model, the Sun consumes 3.4 x 10^{38} ^{1}H$^+$ per second in order to generate its radiant energy.

The transformation of reactants into products is usually confirmed by showing that reactants are consumed and/or that products are generated. That has not been done for the above reaction. In fact, the results of several studies seem to conflict with predictions of the SSM and H-fusion as the source of solar energy:

1. One product of Eq. (1), the neutrino (ν), readily escapes from the solar core, but the measured output [5] of solar neutrinos is only a fraction of that expected if the Sun's

radiant energy comes solely from H-fusion. The other product has not been observed as excess ^{4}He and may still be trapped in the Sun's core.

2. The Sun apparently produces more ^{1}H than it consumes. Thus the reactant shown in Eq. (1) is actually emitted by the Sun. An emission rate of about 2.7 x 10^{43} ^{1}H/yr, i.e., an annual solar mass loss of $\approx$ 2 x 10^{-14} Mo, is required to produce the measured SW-flux [6] of 3 x 10^8 H$^+$ per cm^2 sec at 1 AU.

3. There is a systematic enrichment of the lighter mass isotopes of elements in the SW, as if an outward flow of ^{1}H from the Sun's interior selectively carries the lighter mass isotopes of each element to the solar surface [1].

4. When photospheric abundances of elements are corrected for the mass fractionation observed across the isotopes of SW-elements [7], the seven most abundant elements in the bulk Sun - Fe, Ni, O, Si, S, Mg and Ca - are those that comprise about 99% of the material in ordinary meteorites2 and nuclear stability is linked with elemental abundance, except for an obvious excess of ^{1}H (ref.1).

Thus, the H-fusion reaction shown in Eq. (1) may generate part of the Sun's radiant energy, but the Sun generates more ^{1}H than it consumes. The excess ^{1}H escapes from the surface of the Sun, apparently after moving upward through material with the elemental composition of ordinary meteorites. In the next section, these observations are combined with information in Papers I and II of this series [1, 3] to develop an alternative explanation for the Sun's radiant energy.

Nuclear Systematics

EVANS[8] notes that "*Any pair of nuclei which can be made from each other by interchanging all protons and neutrons are called mirror nuclei.*" (p. 33). Thus, each pair of isobaric intercepts shown on the cradle of nuclear matter [3] at Z/A = 0 and Z/A = 1 are mirror nuclei. None of these mirror nuclei actually exist in nature, except for the ^{1}n, ^{1}H pair at A = 1. Before using the cradle of the nuclides [3] to explain the source of the Sun's energy, it is instructive to compare the properties of real nuclides with cradle predictions for nuclides with extreme charge densities. For that purpose, data from the sixth edition of Nuclear Wallet Cards [9] were first used to compute negatron-decay energies for the light-weight, odd-A, mirror nuclides close to the line of β-stability. These are shown in the familiar plot [8] of β-decay energies versus A$^{2/3}$ in Figure 1 for values A = 1-41.
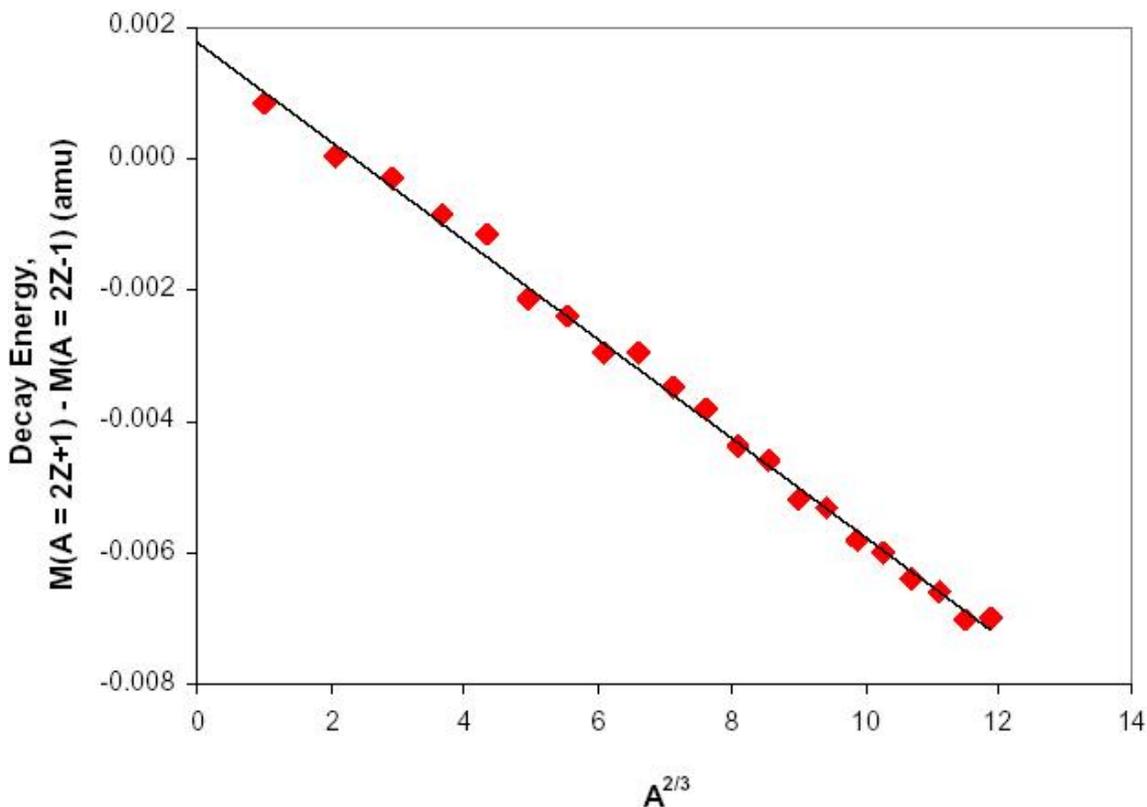
Figure 1: The negatron decay energy, E_β = M(A=2Z+1) - M(A=2Z-1), versus $A^{2/3}$ for the real, mirror image nuclei with A = 1 - 41 amu. The slope of the line for these light-weight nuclei near the line of β-stability yields a reasonable value for the coefficient of the Coulomb energy term, a_c = 0.702 MeV.

For negatron emission of these real nuclides with Z/A ≈ 0.50, the parent has A = 2Z+1, the daughter has A = 2Z-1, and the difference in Coulomb energies of these mirror nuclei determine their decay energy [8], E_β = M(A = 2Z+1) - M(A = 2Z-1). The slope of the least-squares line in Figure 1 yields a value of a_c = 0.702 MeV for the coefficient of the Coulomb energy term, where

$$\text{Coulomb Energy} = a_c \, {}^1 Z^2 / A^{1/3} \qquad (2)$$

To show that the cradle of the nuclides [3] yields reasonable values for the mass per nucleon of hypothetical nuclides with extreme charge densities, Z/A = 0 and Z/A = 1, the average negatron decay energy per nucleon, E_β/A = M(A,0)/A - M(A,A)/A, is plotted versus $A^{2/3}$ for this set of mirror image nuclei in Figure 2.
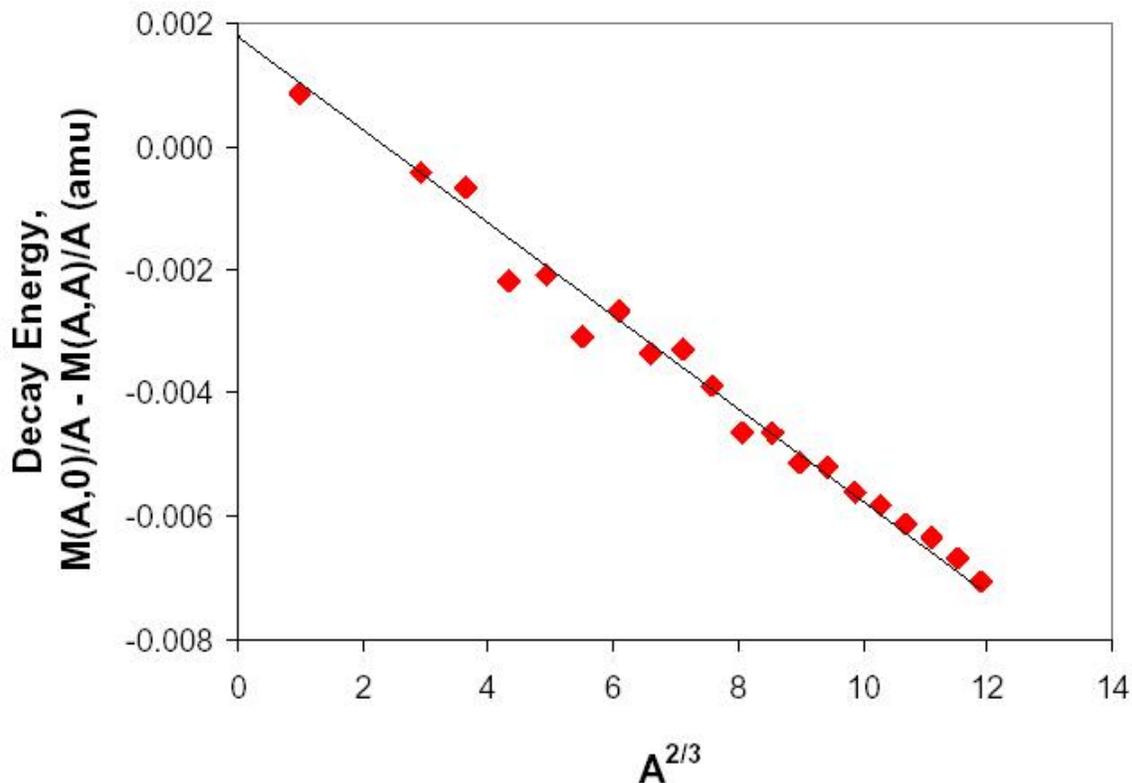
Figure 2: The average negatron decay energy per nucleon, $E_\beta/A = M(A,0)/A - M(A,A)/A$, versus $A^{2/3}$ for the set of mirror image nuclei with A = 1 - 41 amu and extreme charge densities of Z/A = 0 and Z/A = 1.0. Except at A =1 all the members of this set of nuclides are hypothetical. The values M(A,0)/A and M(A,A)/A were obtained by extrapolation of isobaric parabolas through the cradle of the nuclides [3,10]. The β-decay energies of these hypothetical nuclei lie along the same line defined by the data for real nuclei from Figure 1.

Except at A = 1 all members of this set of mirror nuclei are hypothetical, with values M(A,0)/A and M(A,A)/A extrapolated from isobaric parabolas through the cradle of the nuclides [3, 10]. As in Figure 1, the data in Figure 2 are for A = 1-41.

The least-squares line from Figure 1 has been arbitrarily inserted in Figure 2. This line was obtained from the β -decay of mirror nuclides close to the line of β-stability, with Z/A ≈ 0.50. It can be seen in Figure 2 that the β-decay energies of hypothetical mirror nuclei with extreme charge densities of Z/A = 0 and Z/A = 1.0 lie along this same line. This suggests that the cradle of the nuclides [3, 10] yields reasonable values for the average potential energy, or mass per nucleon, even for nuclides with extreme charge densities.

The average potential energy, or mass per nucleon, for nuclides composed only of neutrons can be obtained by extrapolating isobaric parabolas through the cradle of nuclides to Z/A = 0. These values of M(A,0)/A are shown in Figure 3.
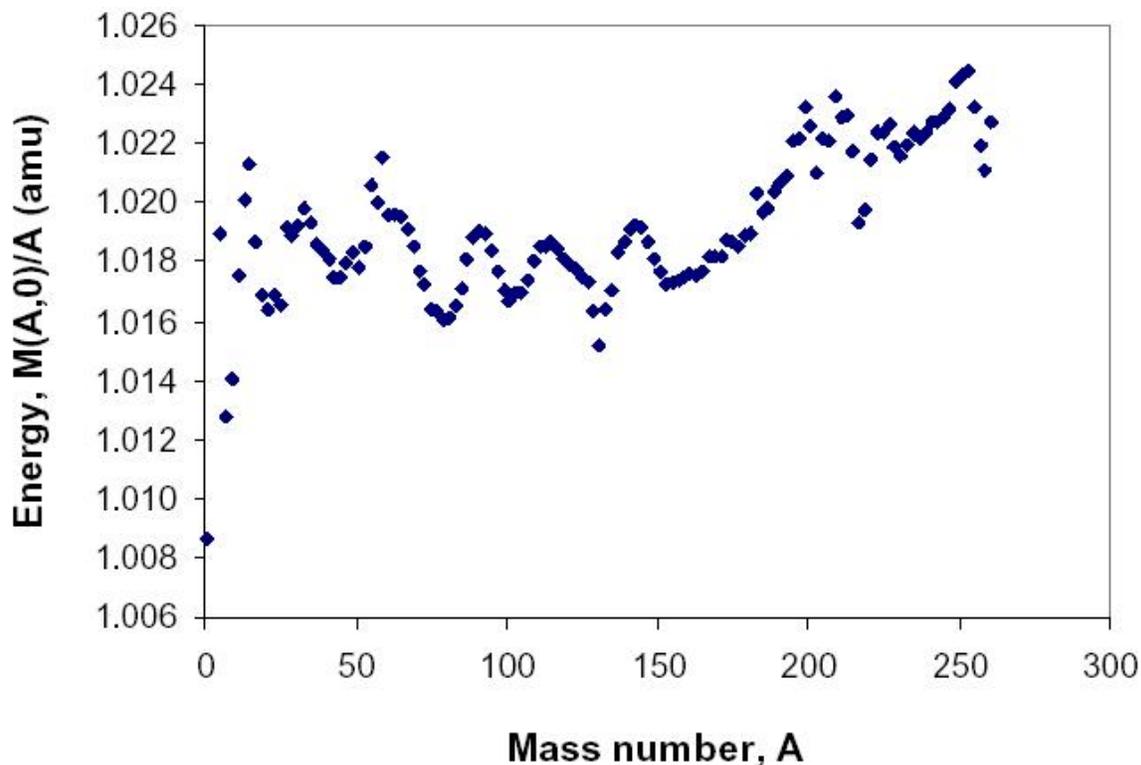
Figure 3: The average potential energy, or mass per nucleon, for nuclides composed only of neutrons. The values shown here were obtained by extrapolating odd-A isobaric parabolas through the cradle of nuclides to Z/A = 0. Even-A nuclides at Z/A = 0 follow the same trend shown here but clutter the graph with separate values for odd-odd and even-even nuclides at each value of A. This figure is reproduced from ref. 10.

The scatter of data in Figure 3 does not reflect a problem in extrapolating isobaric parabolas to the extreme value of Z/A = 0. The rhythmic scatter shown in Figure 3 for the energy of nuclei composed only of neutrons is mirrored in a rhythmic scatter of data for the energy of nuclei composed only of protons (Z/A = 1.0). Yet differences in the energies of these extreme mirror nuclides (i.e., their b-decay energies) follow the trend line shown in Figures 1 and 2.

Note in Figure 3 that the mass or energy per nucleon for the free neutron at A = 1 is less than it is for any of the heavier nuclei composed only of neutrons. This is a source of potential energy in heavy nuclei with Z/A = 0.

Sources of the Sun's energy

Since the Sun apparently generates more H than it consumes, we look for a common source for the H emitted [6] in the SW, the anomalous excess of H identified [1] in the Sun, and the H consumed by fusion reactions that give rise to neutrino emission [5] from the Sun. Neutron decay is obviously one way to produce this H, but the half-life [11] for the decay of a free neutron is only about 10.61 min. Furthermore, the energy released in the decay of a free

neutron, 0.78 MeV, is much too small to account for the discrepancy [5]between the observed and the predicted flux of solar neutrinos.

However, evidence has been accumulating since 1975 that the solar system formed directly from the heterogeneous debris of a supernova (SN) and that the Sun formed on the collapsed SN core [12-14]. The prevailing view is that a neutron star (NS) is the collapsed core of a supernova, e.g., ref. 15. We suggest that a NS may be the source of the H emitted [6] by the SW, the excess H seen [1] in the Sun, and the H consumed [5] there by fusion reactions. Before describing how a central NS might produce solar luminosity and excess H, a brief review of the current state of understanding of neutron stars is appropriate.

In 1996, WALTER et al. [16] reported the discovery of an isolated NS. They noted that our Galaxy should contain between 10^8 and 10^9 neutron stars, but "*Only about 600 pulsars are known ...*" (p. 233). They estimated [16] that about 2,000 isolated NS (not in binary systems) should be detectable, but only one had been reported [17]. They concluded that "*The properties of isolated old neutron stars are very poorly understood theoretically, ...*" (p. 235) and suggested that "*Detailed study of isolated old neutron stars could determine the heating mechanism (or cooling times), and would help constrain the equation of state of neutron stars.*" (p. 235).

There have been several follow-up studies [18-22] showing, for example, an optical counterpart [18] to the isolated NS discovered by WALTER et al. [16], estimating its age [19] at 0.9-1.0 million years, and revealing spectral features [20] that are difficult to reconcile with an H- or He-rich surface but may be explained by black body radiation or an atmosphere rich in Fe and Si. These advances have not explained the NS shortage nor answered the other questions raised by WALTER et al. [16]. In fact, some observations suggest the possibility that the Sun and a NS may share two mysteries - excess H and unexplained luminosity.

For example, VAN KERKWIJK [22] states in one of the more recent reports that the surface temperature of the NS, RX J1856.5-3754, is about 700,000 °C. He questions how such an "old" NS could be so hot. He notes that it would be difficult for the NS to catch much interstellar matter that might heat the surface while the NS is moving at about 100 km/s. However, he reports faint Balmer emission lines from H and notes that the observed glow seems to indicate the presence of H atoms at a density that is at least 100 times that in the interstellar medium.

From the above, we conclude that the current understanding of neutron stars does not preclude the possibility that the Sun formed [12-14] on a collapsed SN core that had been compressed to the point of becoming a NS. This obviously requires a NS less massive than the Sun. ZEILIK [15] notes that a low mass NS can be "... *made in the pile-driver compression of a supernova explosion, ...*" (p. 495).

Figure 3 provides a clue to the process by which a central NS might contribute to solar luminosity. The predicted energy or mass per nucleon at Z/A = 0 is greater for all heavy nuclei than it is for the free neutron. The potential energy of particles in a neutron star can be

estimated by extrapolating the values of M/A at Z/A = 0 from Figure 3 to a neutron star at $1/A \approx 0$. This is shown in Figure 4.
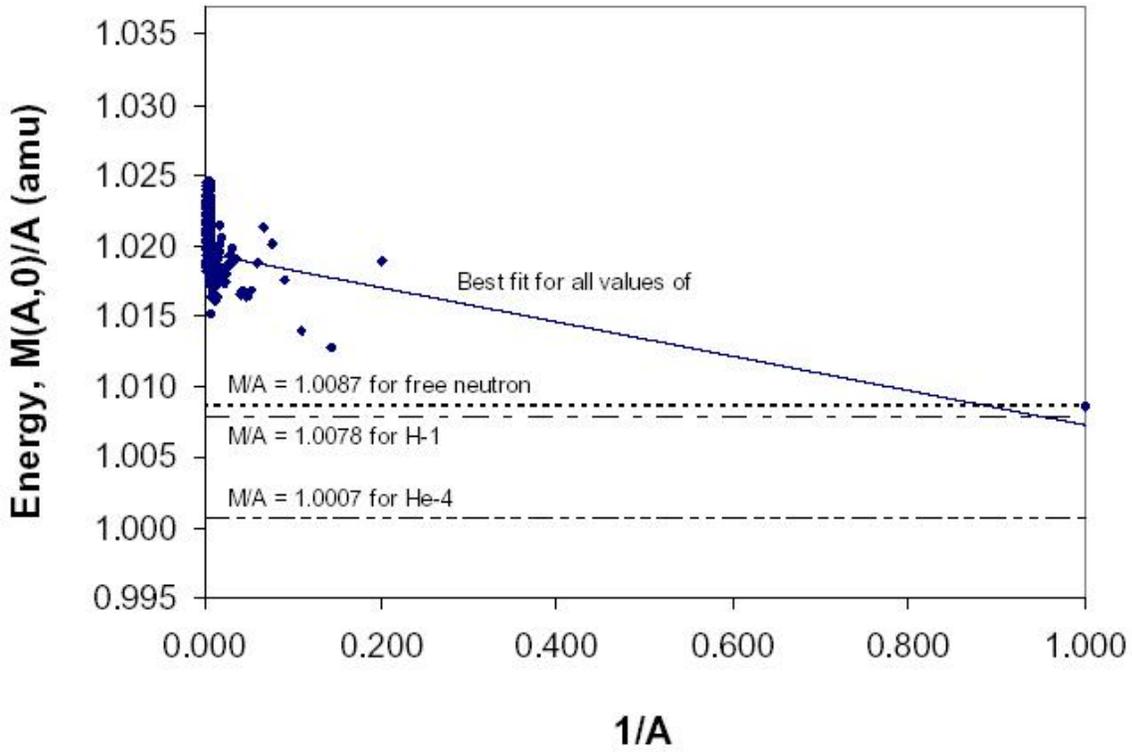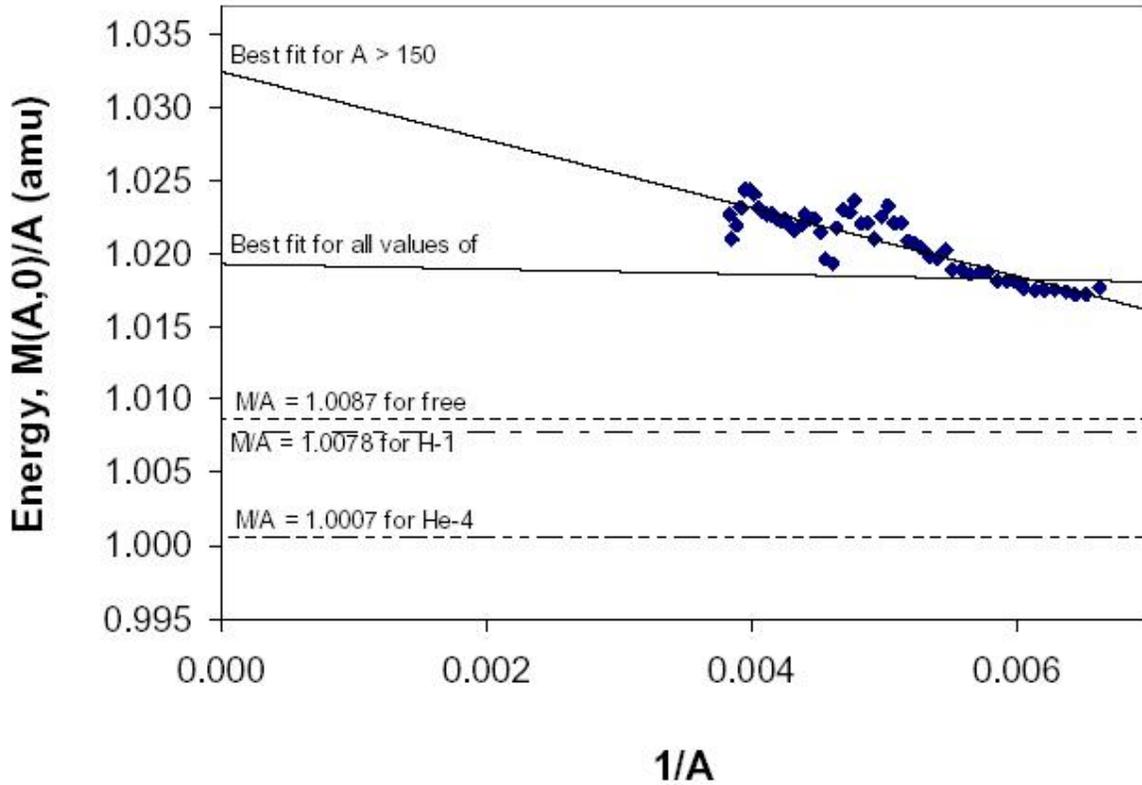

Figure 4: The potential energy of particles in a neutron star can be estimated by extrapolating values of M/A at Z/A = 0 from Figure 3 to a neutron star at $1/A \approx 0$. The "best fit" line through all values of A yields an intercept at $1/A = 0$ suggesting that these particles will have $\approx$ 10 MeV more energy than the free neutron. Values of M/A for the free neutron, ^{1}H, and [4]He are shown by the dashed lines. This figure is reproduced from ref. 10.

In Figure 4, the intercept at $1/A = 0$ for the "best-fit" line through all values of A implies that each neutron in a NS will have $\approx$ 10 MeV more energy than the free neutron. The dashed lines in Figure 4 show for comparison the mass per nucleon for the free neutron, ^{1}H, and [4]He.

Many data points near the intercept at $1/A = 0$ in Figure 4 lie above the "best-fit" line. The reason for this can be seen in Figure 3. The energy or mass per nucleon seems to scatter about some common value for 1<A<150 but then gradually increases for heavier nuclei with A > 150. The data points for A>150 appear as an almost vertical array in Figure 4.

For a neutron star, A>>150. The potential energy of particles there might be better estimated by considering only A > 150 and extrapolating values of M/A at Z/A = 0 to a neutron star at $1/A \approx 0$. This is shown in Figure 5.

Figure 5: The potential energy of particles in a neutron star can be estimated by considering only A > 150 and extrapolating values of M/A at Z/A = 0 from Figure 3 to a neutron star at 1/A ≈ 0. The intercept of this "best fit" line at 1/A = 0 suggests that these particles will have ≈ 22 MeV. The lines from Figure 4 are also shown in Figure 5 for comparison. This figure is reproduced from ref. 10.

In Figure 5, the intercept of the upper "best-fit" line through all values of A>150 suggests that each neutron in a NS will ≈ 22 MeV more energy than the free neutron. Also shown in Figure 5 is the "best fit" line from Figure 4 and the dashed lines showing the values of M/A for the free neutron, ^{1}H, and ^{4}He.

If a central NS is the source of the Sun's luminosity and excess H, then Figure 5 indicates that ≈ 10-22 MeV of energy may be released when the parent neutron departs the NS.

Thus, solar luminosity and SW-protons might arise from a series of reactions: a) escape of neutrons from the central NS, b) decay of free neutrons or their capture by heavier nuclides, c) fusion and upward migration of H$^+$ through the material that accreted on the NS, and d) escape of H$^+$ in the SW.

1. If the observed flux of solar neutrinos [5] comes solely from the pep cycle, then solar luminosity and excess H might be produced in the following manner:

  a. Neutrons escape from the NS, $<^1n> \rightarrow {}^1n$
  b. Free neutrons decay, ${}^1n \rightarrow {}^1H^+ + e- + \nu_{anti}$
  c. Hydrogen fusion, $4\ {}^1H^+ + 2\ e- \rightarrow {}^4He^{++} + 2\ \nu$
  d. Some H^+ reaches the surface and departs in the solar wind.

The relative amount of energy released in steps a, b, and c are indicated in Figure 5 by the vertical distances between the lines.

2. If solar neutrinos are produced by other proton capture reactions, then the process might be represented as:

  a. Neutrons escape from the NS, $<^1n> \rightarrow {}^1n$
  b. Free neutrons decay, ${}^1n \rightarrow {}^1H^+ + e- + \nu_{anti}$
  c. Proton capture, e.g., ${}^1H^+ + {}_zX \rightarrow {}_{z+1}Y \rightarrow {}^{A+1}X + \nu + \beta^+$
  d. Some H^+ reaches the surface and departs in the solar wind

3. If neutron capture reactions occur before all of the neutrons decay, then a summary might be represented by:

  a. Neutrons escape from the NS, $<^1n> \rightarrow {}^1n$
  b. N-capture, e.g., ${}^1n + {}^AX \rightarrow {}^{A+1}X \rightarrow {}^{A+1}Y + e- + \nu_{anti}$
  c. Free neutrons decay, ${}^1n \rightarrow {}^1H^+ + e- + \nu_{anti}$
  d. H-fusion as shown by reactions 1c or 2c.
  e. Some H^+ reaches the surface and departs in the solar wind

Conclusions

Solar luminosity, SW-protons [6], an abundance anomaly [1] of excess H in the Sun, and severely fractionated abundances [7] at the solar surface arise from a series of reactions: a) escape of neutrons from the central NS, b) decay of free neutrons or their capture by heavier nuclides, c) fusion and upward migration of H^+ through the iron-rich material [12] that accreted on the NS, and d) escape of H^+ in the SW.

Observations supporting our conclusion that neutrons escape from the Sun's central NS and decay into ${}^1H$ are summarized below:

  a. This neutron decay-product is emitted from the Sun's surface in the solar wind [6] at a rate equal to 2.7 x 10^{43} ${}^1H$/yr.
  b. The upward migration of ${}^1H$ through the Fe-rich material [1] that accreted onto the Sun's central NS offers a viable explanation for the observed enrichment [7] of lighter elements and lighter isotopes at the solar surface.
  c. The continuous emission of neutrons from the central NS might explain the anomalous abundance of H in the Sun [1], greatly exceeding that expected from the link seen between the abundance of other elements and their average values of M/A (See Figure 3 of ref. 1).

d. The measured flux of solar neutrinos [5] indicates that fusion of the neutron decay-product, ^{1}H, produces part of the Sun's luminosity. The presence of a central NS offers an explanation for the remainder of the energy.

A few other observations that may be related to the presence of a central NS in the Sun are as follows:

a. The homochirality in living organisms may have been initiated by the selective destruction [23, 24] of left- or right-handed molecules by circularly polarized light (CPL) from the neutron star that is now hidden in the interior of the Sun.
b. A constant climate for planets would indicate a long half-life for the NS. Gradual cooling of planets over the history of the solar system, as has recently been suggested [25] for Mars, might indicate a half-life value for the NS comparable to that of long-lived actinides like ^{238}U or ^{232}Th.
c. The paucity of observable neutron stars noted by WALTER et al. [16] may indicate that it is not unusual for an "ordinary" star to conceal a central NS.
d. Neutron emission and decay may contribute to the mysterious luminosity [22] observed in isolated neutron stars, as well as to that of the Sun.
e. Major solar flares, ejecting large amounts of material simultaneously in opposite directions, may arise from events near the high-density solar core.

Finally, we would like to call attention to the need for other measurements that might test for the presence of a high-density solar core, e.g. helioseismology, gravitational-field-gradient studies of the Sun, etc.

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