Isotopic Ratios: The Key to Elemental Abundances and Nuclear Reactions in the Sun

O. Manuel
Chemistry Department, University of Missouri, Rolla, MO 65401 USA

om@umr.edu

Abstract: Differences between the abundances of isotopes of elements in the planetary system, in the solar wind, and in solar flares suggest that a) the most abundant nuclear species in the sun is ^{56}Fe (the ash of violent thermonuclear reactions at equilibrium) rather than ^{1}H (the best fuel for thermonuclear reactions), and b) nuclear reactions in the outer regions of the sun produce ^{15}N by the $^{14}N(^{1}H, \beta^{+}\nu)^{15}N$ reaction. Diffusion in the sun enriches light-weight elements like H and He at the solar surface, where thermonuclear reactions occur, but the most abundant elements in the bulk sun are Fe, Ni, O, Si, S, Mg, and Ca.

1. INTRODUCTION

After cautioning that elemental abundances in the earth's crust and the sun's gaseous envelope may not represent the overall composition of these bodies, William Harkins (1917) used chemical analyses of 443 ordinary meteorites to show that iron is the most abundant element. He found that the seven most abundant elements (Fe, O, Ni, Si, Mg, S, and Ca) all have even atomic numbers, noted a relationship between elemental abundances and nuclear stability, and stated that the abundances of elements are related "*... to the structure of the nuclei of their atoms.*" (Harkins, 1917, p. 856).

Ida and Walter Noddack (1930) used the average density of the moon and the four inner planets (~ 5.1 g cm-3) to estimate a value for the ratio of iron : troilite : stone = 68 : 9.8 : 100. By assuming that stone meteorites contain 5.5% troilite (FeS), they used the results of analyses on 42 stone meteorites, 19 iron meteorites, and troilite grains from five iron meteorites to show that the seven most abundant elements are O, Fe, Si, Mg, Ni, S, and Ca. Although the order changed, Noddack and Noddack (1930) and Harkins (1917) concluded that the same seven abundant elements existed in the solar system.

About 99.8% of all the solar system's material is in the sun. Two publications in the late 1930s signaled basic changes in the scientific community's opinion of that body. Goldschmidt (1938) convinced the scientific community that meteorites and the inner planets are rich in elements, like Fe, O, Ni, Si, etc., because they lost volatile elements, like H, He, C, N, etc., and that the sun's atmosphere (Payne, 1925) better represents the overall abundance of the elements. Hans Bethe (1939) suggested that ^{12}C might serve

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as a catalyst for energy production in the sun and other stars by serving as the initial target for a chain of four proton-capture reactions that return the ^{12}C nuclide and convert $4\,^{1}H \rightarrow {}^{4}He + 2\,\beta^{+} + 2\,\nu$ + energy.

Goldschmidt's 1938 idea remains in vogue even today, but Bethe's CNO cycle lost favor in the scientific community before elements from the sun became available for study. Neutrinos from two intermediate nuclides in Bethe's CNO cycle, ^{13}N and ^{15}O, may exceed the 0.86 Mev threshold of the ^{37}Cl detector (Davis, 1955). The embarrassingly low flux of solar neutrinos convinced Davis *et al.* (1972) that Bethe's CNO cycle produces little, if any, of the sun's energy. This is now widely attributed to the proton-proton chain with $E_{\nu} \leq 0.41$ Mev.

2. MEASURED ISOTOPIC RATIOS OF THE SUN

About 30 years after the publications by Goldschmidt and Bethe, the Apollo mission returned with lunar soils and breccias containing abundant volatile elements from the solar wind (LSPET, 1969). The solar wind (SW) implanted component masks any indigenous hydrogen, nitrogen, and the noble gases. Subsequent studies also revealed a component of solar flare (SF) elements buried more deeply in the lunar samples (Rao *et al.*, 1991).

Mass Fractionation Enriches Lighter Nuclides at Solar Surface

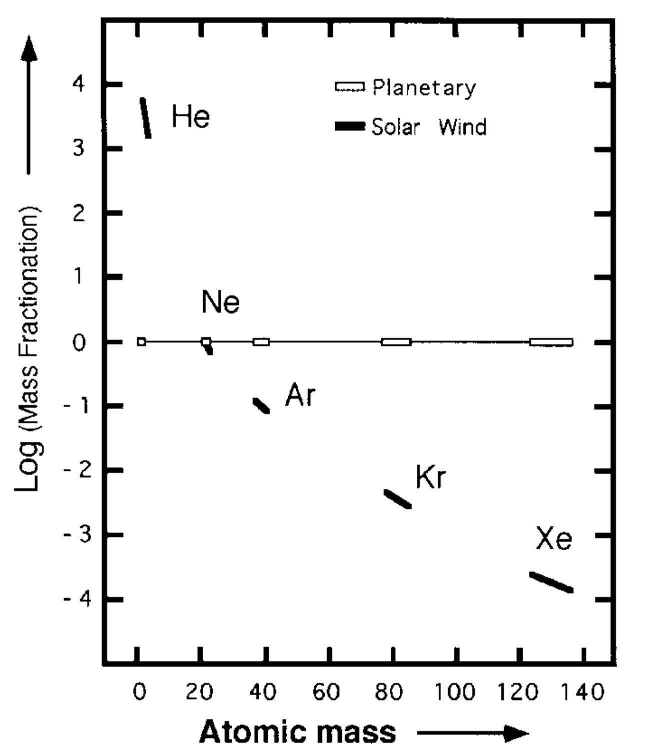

Figure 1. Isotope ratios of solar-wind implanted gases show a smooth, mass-dependent fractionation, as expected if intrasolar diffusion enriches lighter nuclides at the solar surface. Mass fractionation is shown relative to ^{20}Ne.

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Manuel and Hwaung (1983) noted a systematic enrichment of the lighter weight isotopes of hydrogen and the noble gases in the SW-implanted component. The percent enrichment per mass unit decreases in a regular manner as the mass increases across the series: H, He, Ne, Ar, Kr, and Xe. The mass fractionation for the five noble gases is about 200% per amu for SW-He, 27% per amu for SW-Ne, 9% per amu for SW-Ar, 6% per amu for SW-Kr, and 3.5% per amu for SW-Xe. This is shown in Figure 1, where empty rectangles show the relative abundances of noble gas isotopes in planetary material, and filled rectangles show those in the solar wind.

If the sun and its planetary system formed out of the same batch of elements, then deuterium burning in the sun might have increased the values of the $^{1}H/^{2}H$ and $^{3}He/^{4}He$ ratios by converting ^{2}H into ^{3}He (Geiss, 1993). This would explain the two largest isotopic anomalies in SW elements, but it does not explain the excess light-weight isotopes for other SW elements. Alternatively, the smooth, mass-dependent fractionation pattern (Figure 1) may mean that ˜ 9-stages of mass fractionation have altered the abundance of any nuclide of mass, m, relative to that of ^{20}Ne in the solar wind. Empirically, Manuel and Hwaung (1983) found that:

$$\text{Mass fractionation} = (20/m)^{4.56} \qquad (1)$$

where each theoretical stage of mass fractionation alters the isotopic abundance by a factor of $\sqrt{20/m}$.

The light weight isotopes of He, Ne, and Ar are less enriched in solar flare particles than in the solar wind (Rao *et al.*, 1991). Isotopic ratios of Mg in the solar wind (Boschler *et al.*, 1996) also vary systematically with velocity and the heavier mass isotopes become increasingly abundant at higher velocities and most abundant in solar flares (Selesnick *et al.*, 1993). Manuel and Ragland (1997) displayed these isotopic ratios of SW and SF elements in the manner shown in Table 1.

Table 1. Isotopic ratios of He, Ne, Mg and Ar in the solar wind and in solar flares.

Isotopic Ratios	Solar Wind	Solar Flares	SW/SF	?m/$m_{avg.}$
$^{3}He/^{4}He$	4.1×10^{-4}	2.6×10^{-4}	1.58	0.29
$^{20}Ne/^{22}Ne$	13.6	11.6	1.17	0.095
$^{24}Mg/^{26}Mg$	7.0	6.0	1.17	0.080
$^{36}Ar/^{38}Ar$	5.3	4.8	1.10	0.054

In Table 1, column 2 shows isotopic ratios in the solar wind, column 3 shows those in solar flares, and column 4 shows the fractional change in these ratios. If these shifts are caused by partial disruption of the mass fractionation seen in SW-implanted elements (Figure 1), then the fractional changes in the column 4 should scale with the values of ? m/$m_{avg.}$ tabulated in column 5. That this is true can be seen by comparing values in column 4 with the sum of one plus twice the value in column 5. Differences between the isotopic ratios of SW and SF elements suggest that SF elements come from deeper within the sun, effectively by-passing ≈ 3.5 stages of mass-dependent fractionation (Ragland and Manuel, 1998).

Isotopic abundances of one element from the sun, N, do not follow the trend shown in Figure 1. Currently, SW-N is enriched in the heavier isotope, ^{15}N, although the lighter mass isotope, ^{14}N, was enriched in the early SW-N. Nitrogen is unique in that its isotopic abundances in the sun have changed over geologic time (Kerridge, 1975). Differences in the isotopic abundances of SW-N and SF-N are also unlike the pattern shown in Table 1. The $^{14}N/^{15}N$ ratio in the solar wind is *lower* than that in solar flares (Kerridge, 1993), whereas the light/heavy isotopic ratio for magnesium and the five noble gases in the solar wind is *higher* than that in solar flares (Table 1). This anomalous behavior of nitrogen isotopic ratios in the sun may be the first experimental observation that confirms the existence of a nuclear reaction, and identifies its location, in the sun.

2.1 Implications for elemental abundances in the sun

If solids condensed from H, He-rich material of the sun's atmosphere (Payne, 1925), they would likely incorporate only a small fraction of its H and He (Goldschmidt, 1938). The obvious validity of that assertion has led many to accept that planetary solids formed in this way, despite numerous isotopic ratios that directly falsify this view (Manuel, this volume). Nolte and Lietz (this volume) explain why deuterium burning in the sun (Geiss, 1993) is an unlikely explanation for the high $^{3}He/^{4}He$ ratio in the solar wind. Manuel and Hwaung (1983) gave six reasons for rejecting planetary fractionation in favor of solar fractionation as the cause of the mass-dependent fractionation pattern shown in Figure 1. They concluded that diffusion inside the sun is selectively moving lighter elements and the lighter isotopes of individual elements to solar surface. They corrected the photospheric abundances of Ross and Aller (1976) with the empirical mass fractionation effect given by Equation (1) and concluded that the seven most abundant elements in the bulk sun are in decreasing order: Fe, Ni, O, Si, S, Mg, and Ca.

These are the same seven elements that Harkins (1917) and Noddack and Noddack (1930) found as the major constituents of meteorites. However, the paper of Manuel and Hwaung (1983) has been largely ignored, probably because these authors failed a) to mention the earlier work by Harkins (1917) and Noddack and Noddack (1930), and b) to point out how unlikely it is that the empirical mass fractionation pattern of isotopes in the solar wind would select seven trace elements from the solar photosphere that are identical to those which Harkins (1917) and Noddack and Noddack (1930) found to be most abundant in hundreds of ordinary meteorites.

If the observations (Figure 1) defined empirically by Equation (1) are not the result of diffusion in the sun, what are the chances that this misunderstanding would select the same seven elements from the solar photosphere that Harkins (1917) found to comprise about 99% of the material in hundreds of meteorites? The probability that Equation (1) would by chance select Harkins' set of seven elements from the 83 in the sun would be about $7!(83-7)!/83! = 2 \times 10^{-10}$ if each element had an equal chance for selection. Since Fe, Ni, O, Si, S, Mg, and Ca are trace elements in the H, He-rich solar photosphere, with atomic abundances of only 3.0×10^{-5}, 1.9×10^{-6}, 6.5×10^{-4}, 4.2×10^{-5}, 1.5×10^{-5}, 3.8×10^{-5}, and 1.9×10^{-6}, respectively (Ross and Aller, 1976), the probability for the chance selection of Harkins' set of seven elements would be much less if their probability of selection depended on their atomic abundances in the solar photosphere.

All of the elements in Figure 1 are volatile, and isotopic analysis of a refractory element like Mg was one of three tests that Manuel and Hwaung (1983) advanced for their proposal of diffusion inside the sun. The data in Table 1 confirm correlated shifts in the isotopic ratios of He, Ne, Mg, and Ar, as expected if energetic events at the solar surface disrupt ~ 3.5 stages of diffusive mass-fractionation (Ragland and Manuel, 1998) possibly by dredging up less mass fractionated material from the solar interior.

2.2 Implications for nuclear reactions in the sun

The value of the $^{15}N/^{14}N$ ratio in the SW has increased over geologic time (Kerridge, 1975). This observation suggests that the $^{14}N(^{1}H, \beta^{+}\nu)^{15}N$ part of the CNO cycle proposed by Bethe (1939) may occur in the outer regions of the sun, producing solar neutrinos, violent activity at the solar surface, and increasing the value of the $^{14}N/^{15}N$ ratio over geologic time. Among volatile elements trapped in lunar surface material, Geiss and Bochsler (1982) found that nitrogen is unique in showing isotopic variations = 30%, but they decided against thermonuclear production of ^{15}N at the solar surface.

The heavier nitrogen isotope, ^{15}N, is more abundant in SW than in SF nitrogen (Kerridge, 1993), which is an inversion of the isotopic anomaly patterns observed for SW and SF magnesium and the noble gases. The heavier isotopes of He, Ne, Mg, and Ar are more abundant in SF than in SW elements. These observations suggest that solar flares which dredge up less mass-fractionated He, Ne, Mg, and Ar (Manuel and Ragland, 1997) also bring up nitrogen with less of the $^{14}N(^{1}H, \beta^{+}\nu)^{15}N$ product.

Recently, Kim et al (1995, p. 383) note that "*... the long-term trend in the $^{15}N/^{14}N$ signature, rather than being simply a linear increase with time as originally proposed, has experienced two excursions, to minimum (< -28%) and maximum (> +16%) $d^{15}N$ values in a roughly 3.5 Gyr time frame.*" These observations offer a test for the suggestions that the $^{14}N(^{1}H, \beta^{+}\nu)^{15}N$ reaction occurs in the outer regions of the sun and that solar flares carry nitrogen with less of this $^{14}N(^{1}H, \beta^{+}\nu)^{15}N$ product. If so, then fluctuations in values of the $^{15}N/^{14}N$ ratio will be accompanied by excursions in the isotopic ratios of noble gases and magnesium, but in the opposite direction.

3. CONCLUSIONS

The Apollo mission returned samples from the moon in 1969. Analyses on the isotopic abundances of elements implanted there from the sun suggest two errors in the mid-20th Century: 1) Acceptance of the proposal that the sun's photosphere (Payne, 1925) represents elemental abundances for the solar system; and 2) Rejection of Bethe's (1939) proposal that the CNO cycle serves as a path for hydrogen fusion in the sun.

Seventeen years into the 20th Century, Harkins (1917) used the wet chemical analyses of hundreds of meteorites to conclude that Fe, O, Ni, Si, Mg, S, and Ca are the seven most abundant elements in the solar system. Seventeen years before the start of the 21st Century, Manuel and Hwaung (1983) combined measurements of isotopic ratios in the solar wind (Eberhardt et al., 1972) with line spectra of elements in the solar photosphere (Ross and Aller, 1976) to conclude that Fe, Ni, O, Si, S, Mg, and Ca are the seven most abundant elements in the sun itself.

The probability that an empirical fit to the abundance pattern of SW isotopes, mass-fractionation = $(20/m)^{4.56}$, would by chance select these seven "trace" elements from the solar photosphere is about one in 5×10^{9}.

In terms of nuclear physics, ^{56}Fe and ^{1}H are opposites: One is the ash and the other the best fuel for thermonuclear reactions at equilibrium. Among stable nuclides ^{56}Fe has the

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lowest mass per nucleon; ^{1}H has the highest. Manuel and Sabu (1975, 1977) explained the origin of such an Fe-rich sun. Additional details are given in this volume by Hwaung and Manuel.

Geiss and Bochsler (1982) used the weak correlation of excess ^{13}C with excess ^{15}N in the solar wind (Becker, 1980) to set the following limits on thermonuclear production of ^{15}N at the solar surface: $2 \times 10^8 K < T < 5 \times 10^8 K$; $\rho \sim 0.03$ g cm^{-3}; reaction time of $\sim 10^2$ s followed by fast quenching. These nuclear reactions at the sun's surface and the elemental abundances concluded above for its interior are inconsistent with the standard solar model (Dar and Shaviv, 1996).

Harkins (1917) analyzed hundreds of ordinary meteorites to conclude that the most abundant elements are Fe, O, Ni, Si, Mg, S, and Ca. Recent studies have focused instead on elemental abundances in a very rare meteorite group, the CI type carbonaceous chondrites. The results are enigmatic. Some minerals of CI chondrites contain isotopically anomalous elements; others have undergone aqueous alteration (Ebihara *et al.*, this volume). Although they contain only a small fraction of the volatile elements (H, He, C, N, etc.) that are dominant at the sun's surface, nevertheless it is reported that elemental ratios among the remaining ~ 75 nonvolatile elements are remarkably similar to those in the solar photosphere. This remains as a major puzzle.

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Note added in proof: As this paper went to press, two papers appeared in the 18 November 1999 issue of Nature about elemental abundances and nuclear reactions in the sun.

- *Owen et al. (1999) report that abundances of heavy noble gases are much greater in Jupiter than first thought. The high abundances of heavy elements may indicate formation of Jupiter at low temperatures, as suggested by the authors, or this may confirm diffusion in the sun that enriches lighter elements at the solar surface.*
- *Chaussidon and Robert (1999) report evidence for the nucleosynthesis of lithium in the outer regions of the sun.*