SOLAR ABUNDANCES OF LIGHT NUCLEI
AND MIXING OF THE SUN

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(Received 17 May, 1973)

Abstract. Radial profiles of the light nuclei ($A \leq 15$) are calculated in the non-mixing Sun, taking into account the changes of solar structure with time. The results are discussed in relation to models of solar mixing and compared with abundance determinations at the solar surface or in the solar wind. B cannot be depleted in the outer convective zone without producing a large increase in the He$^3$/He$^4$ ratio. A decrease in He$^3$/He$^4$ would be accompanied by changes in C$^{13}$/C$^{12}$ and N$^{15}$/N$^{14}$ of a magnitude which is not observed.

It is shown that boron could be depleted in the pre-main sequence period of the Sun, if mixing was on a time-scale of $10^9$ yr. The simultaneous small increase in He$^3$/He$^4$ does not contradict observation. However, Be would be depleted more strongly than B.

A He$^3$/He$^4$ decrease is always accompanied by large changes in N$^{15}$/N$^{14}$ and C$^{13}$/C$^{12}$. Since such changes are not observed, it is concluded that the He$^3$/He$^4$ ratio in the outer convective zone is a reliable upper limit for (He$^3$ + D)/He$^4$ in the solar nebula. Thus the D/H ratio in the protosolar material was much lower than it is in sea water or in carbonaceous chondrites.

Recently, increased attention has been given to the possibility of deep solar mixing. Several causes have been examined. The torque exerted by the solar wind at the surface of the Sun leads to a drainage of angular momentum progressing into the solar interior which is probably accompanied by mixing of the outer layers of the Sun (Schatzman, 1962; Dicke, 1970). If in the early Sun rotation was much faster than it is today, this type of mixing could have been particularly significant. Also the Eddington-Sweet circulation could become efficient, if solar rotation was much faster in the past (Cameron et al., 1973). The observed deficiency in the solar neutrino flux (Davis, 1972) has led Fowler (1972) to suggest still another mechanism: quasi-periodic mixing triggered by some instability.

Shaviv and Salpeter (1971) have discussed consequences of internal mixing on the evolution of stars. They found, that extended internal mixing, involving more than 40% of the stellar mass would lead to contradictions with the observations on clusters. Also Rood (1972) and Ulrich and Rood (1973) have argued, that sudden internal mixing of the Sun leads to difficulties and that other measures should be taken for explaining the neutrino deficiency, before our present picture of stellar structure and evolution is abandoned. Dilke and Gough (1972) and Ezer and Cameron (1972), on the other hand, discuss repeated mixing of the solar interior as the cause of the
present low neutrino flux and link this model with the recurring ice ages on Earth. Concrete models of solar mixing have definite implications as to changes in the abundances and isotopic composition of light elements \( (Z \leq 8) \) at the solar surface. It is the purpose of this paper to estimate radial profiles of various light nuclei in the Sun, to analyze the effects which certain types of mixing would have on abundance ratios at the solar surface, and to compare these findings with the experimental and observational evidence presently available.

We have calculated the development with time of the abundances of light nuclei in the non-mixing Sun. These calculations were based on Sears’ (1964) models of solar structure (cf. Strömgren, 1965). \( T, \rho, \) and \( X \) were linearly interpolated between his zero-age model and his model of the present Sun. The nuclear reaction parameters given by Fowler et al. (1972) were used. Figure 1 shows elemental abundances and isotopic compositions calculated for the present, non-mixing Sun, relative to the respective surface values. We can immediately deduce from this figure that mixing

![Graph showing relative abundances of various elements]

Fig. 1. Calculated radial profiles of present abundances of light nuclei in the non-mixing Sun. Abundances and abundance ratios are plotted relative to the respective (unchanged) surface values as a function of fractional mass \( M_r/M \). The solar wind value of \( 4 \times 10^{-4} \) was adopted for the \( \text{He}^3/\text{He}^4 \) ratio at the solar surface.
between the outer convective zone of the Sun and deeper layers could change elemental abundances and isotopic composition of He, Li, B, C and N. Before discussing the significance of such changes, we shall summarize the relevant observational data.

Elemental abundances in the solar nebula can be inferred from analyses of meteorites. However, this is not possible for such volatile elements as He, C, and N. The abundances of Li, Be and B in the Sun and in meteorites have recently been critically examined by Cameron et al. (1973), who concluded that these elements were depleted in solar surface material by factors of 250, 4 and >35 respectively, if solar abundance determinations are taken at face value.

For the purpose of quantitative comparison, isotopic ratios are preferable to elemental abundances because isotopes show very similar geochemical behaviour, and determinations of their solar surface ratios by spectroscopy or solar wind measurements are less model dependent than those of elemental abundances. Hall et al. (1972) found that the C\(^{13}/C^{12}\) ratio in sunspots is the same as the terrestrial or meteoritic ratio within ±15%, and they pointed out that this observation places a limit on solar mixing. The excess of C and N in lunar fines relative to lunar igneous rocks is evidence for an extralunar origin of most of the C and N found at the lunar surface. (cf. Epstein and Taylor, 1972; Hintenberger et al., 1970; Müller, 1972). A meteoritic or cometary origin of these elements could be postulated, but detailed investigations have shown that the C and N distribution in the lunar surface material resembles very much that of hydrogen and the noble gases (Epstein and Taylor, 1972; Müller, 1972; Goel and Kothari, 1972; Kaplan et al., 1973). Since the bulk of noble gases and hydrogen (Epstein and Taylor, 1972) is undoubtedly of solar origin, at least a significant fraction of C and N found in the fine material ought to be of solar origin as well. The relative concentrations of C, N, Kr and Xe in lunar fine material are similar to the cosmic abundance ratios. However, the light noble gases are depleted relative to C and N. Actually, implanted C and particularly N ions would be expected to have higher retentivity than noble gas ions of comparable atomic mass, since N and C will be readily bound because of the enhanced chemical reactivity which results from the high energy of implantation (cf. Müller, 1972, 1973). A pyrolysis experiment by Chang et al. (1972) shows, in fact, that N\(_2\) is released at considerably higher temperature than are H\(_2\) and He. Thus, the absolute abundances of C and N in lunar fines are not in contradiction with a solar origin of a large fraction of these two elements.

The C\(^{13}/C^{12}\) and N\(^{15}/N^{14}\) ratios in lunar fines deviate from the corresponding terrestrial and – in the case of C – meteoritic ratios by only a few percent, the largest differences being 5%. The average C\(^{13}/C^{12}\) ratio in the solar gas trapped at the lunar surface appears to be 1 to 3% higher than in the reduced carbon of carbonaceous chondrites (Epstein and Taylor, 1972), whereas the average N\(^{15}/N^{14}\) ratio in the trapped gas was found to be a few percent lower than in atmospheric N\(_2\) (Kaplan et al., 1973). Thus, these deviations coincide with the directions in which the C and N isotopic abundances would be changed by thermonuclear reactions. However, there is good reason to suspect that the explanation for these small differences is more trivial. At least in part they are probably due to secondary effects of the type discovered by
Epstein and Taylor (1972) for the $O^{18}/O^{16}$ ratio at the surfaces of lunar dust grains. In the case of nitrogen, an increase of the terrestrial $N^{15}/N^{14}$ ratio by a few percent cannot be excluded. Thus, no positive evidence has been found for isotopic anomalies of solar C and N, and it is our assessment of the data presently available that changes of more than 15% in the isotopic composition of C and N in the material of the outer convective zone relative to terrestrial or meteoritic composition would have been detected in the gases trapped at the lunar surface. Further investigations will very likely allow a reduction of this upper limit.

It is evident from Figure 2 that the presence of Be at the solar surface and the low value of $\text{He}^3/\text{He}^4 = 4.3 \times 10^{-4}$ in the solar wind (Geiss et al., 1972) impose severe limits on solar mixing (Dicke, 1970; Schatzman, 1970). Let us first consider a model in which slow mixing progresses with time towards the interior as a result of the loss of angular

![Graph showing radial profiles of He$^3$/He$^4$ ratio for three solar ages.](image)

Fig. 2. Radial profiles of the He$^3$/He$^4$ ratio in the non-mixing Sun for three solar ages. An initial He$^3$/He$^4$ ratio of $4 \times 10^{-4}$ was assumed.
momentum at the surface (cf. Schatzman, 1962; Dicke, 1970). This model cannot account for the depletion of boron (cf. Cameron et al., 1973), because it would produce a large increase in $\text{He}^3/\text{He}^4$ (see Figure 1), in contradiction to the observed isotopic abundance of helium. On the other hand, a detectable increase of $\text{He}^3/\text{He}^4$ in the outer convective zone would not contradict other observations, if it resulted from an admixture of material from intermediate depth to the outer convective zone. For instance, mixing of 20% of matter from $M_r/M = 0.8$ to 0.9 and 80% from the surface would increase $\text{He}^3/\text{He}^4$ by 20%, decrease Be by 20%, and hardly affect B. The secular increase of $\text{He}^3/\text{He}^4$ implied in the data on solar helium trapped at the lunar surface (Hintenberger et al., 1970; Eberhardt et al., 1972; cf. Geiss, 1972) could have resulted from this type of mixing. If this were the case, the increase of $\text{He}^3/\text{He}^4$ would be accelerating with time because the $\text{He}^3/\text{He}^4$ peak in the solar interior and the mixed region would move towards each other (Figure 2).

The $\text{He}^3/\text{He}^4$-ratio averaged over the whole non-mixing Sun has been steadily increasing towards its present value of $3 \times 10^{-3}$. This shows that it is difficult to

![Diagram](image)

**Fig. 3.** Development with time of the abundances of light nuclei in the pre-main sequence period of the Sun. The adopted solar structure was based on Iben's (1965) model. It was assumed that every $10^6$ yr the whole Sun was instantaneously mixed. A value of $2.5 \times 10^{-4}$ was taken as the original $\text{He}^3/\text{He}^4$ ratio.
decrease He$^3$/He$^4$ in the outer convective zone by mixing. In Figure 1 the He$^3$/He$^4$-ratio falls below its surface value only at $M_t/M = 0.15$, where C$^{13}$/C$^{12}$ is already high and N$^{15}$/N$^{14}$ low. Thus, an admixture of material from this depth is ruled out by the C$^{13}$/C$^{12}$ and N$^{15}$/N$^{14}$ observations. Of course, if the solar interior is mixing, as postulated by Fowler (1972), Dilke and Gough (1972) and Ezer and Cameron (1972) as a remedy for the neutrino malaise, the region of low He$^3$/He$^4$ is enlarged. However, we have calculated that in order to decrease the original average He$^3$/He$^4$-ratio, mixing of a large portion of the Sun every $10^6$ yr is required. In any case, such thorough mixing would change the isotopic abundances of C and N at the surface of the Sun to a degree which is contradicted by observation.

As Cameron et al. (1973) have pointed out, boron could have been depleted early in the life-time of the Sun, when He$^3$ had not yet built up appreciably. On the basis of Iben's (1965) model of a hydrostatically contracting star of $1 M_\odot$, we have estimated the changes in abundances of light nuclei during the pre-main sequence period of the Sun. Iben gives $q$ and $T$ at the solar centre as a function of time. From these data we

![Diagram](image-url)

**Fig. 4.** Same as Figure 3, but with a mixing time of $3 \times 10^5$ yr. In this case, the changes in the C$^{13}$/C$^{12}$ and N$^{15}$/N$^{14}$ ratios are smaller than one percent.
have estimated the dependence of $\rho$ and $T$ on $M_\odot/M$ using a polytropic index $n = 2$ for $t < 10^7$ yr and $n = 3$ for $t > 10^7$ yr. This rather crude approximation seems justified in view of the general uncertainty about the evolution of the early Sun, in particular regarding the question of mixing. We have in fact considered the mixing time $\tau_M$ as a variable parameter and calculated the development of average solar abundances for different $\tau_M$, assuming that every $\tau_M$ yr the whole Sun was mixed instantly. The results are shown in Figures 3 and 4 for $\tau_M = 1 \times 10^6$ yr and $\tau_M = 3 \times 10^5$ yr. Abundances are shown up to the time when $B$ is depleted by the factor of 35 postulated by Cameron et al. (1973). In these calculations it was assumed that after D-burning the initial He$^3$/He$^4$ ratio was $2.5 \times 10^{-4}$. This assumption was made in view of the possibility that the present-day He$^3$/He$^4$ at the solar surface has been slightly increased by deep solar mixing during either its pre-main sequence or main sequence life.

It is seen in Figures 3 and 4 that due to the low Gamov factor of the p-p reaction the ratio He$^3$/He$^4$ is not decreasing but growing. This is also true if an initial He$^3$/He$^4$ = $4 \times 10^{-4}$ is assumed. For $\tau_M \geq 2 \times 10^6$ yr a drastic change in C$^{13}$/C$^{12}$ and N$^{15}$/N$^{14}$ is produced before B is depleted by a factor of 35. This is contradicted by observation. Thus, for B to be depleted in the pre-main sequence Sun by a large factor, mixing times smaller than $2 \times 10^6$ yr are required, in order to avoid significant changes in the isotopic composition of N and C. The obvious difficulty that under any circumstances Be is destroyed faster than B will have to be answered in one of the following ways: (1) Be in the Sun is presently overestimated (cf. Cameron et al., 1973); (2) B is not strongly depleted in the Sun. (3) After Li, Be and B depletion, Be and Li were partly rebuilt by spallation, the Li/Be ratio being adjusted to the present solar surface ratio by some slight mixing.

Geiss and Reeves (1972) argued that the present He$^3$/He$^4$ ratio in the solar wind represents a firm upper limit for (He$^3$ + D)/He$^4$ in the solar nebula and proposed that D retained on Earth and in carbonaceous chondrites must have been isotopically enriched in the cooling solar nebula by a factor of 4 to 10 through reactions between molecular hydrogen and heavier molecules. As suggested by Cameron et al. (1973) this argument would be invalid if He$^3$/He$^4$ in the outer convective zone were somehow grossly lowered by thermonuclear reactions.

We have seen that it is not possible to deplete He$^3$/He$^4$ in the outer convective zone by mixing of the main sequence Sun without drastic changes of the isotopic composition of C and N. Also the pre-main sequence models, which we have explored, gave increases in He$^3$/He$^4$ rather than decreases. In fact, as demonstrated in Tables I and II, the accepted nuclear parameters exclude a decrease of He$^3$/He$^4$ without comparable decrease of N$^{15}$/N$^{14}$ and increase of C$^{13}$/C$^{12}$. The matter of the outer convective zone with an assumed initial He$^3$/He$^4$ ratio of $5.3 \times 10^{-4}$ was subjected to thermonuclear reactions at a fixed temperature until He$^3$/He$^4$ was depleted by 25%, i.e. until He$^3$/He$^4$ = $4 \times 10^{-4}$. The product density $\times$ time required to achieve this depletion and the resulting changes in C$^{13}$/C$^{12}$ and N$^{15}$/N$^{14}$ were calculated. In Table I the results of these calculations are given for several chosen temperatures. In calculating the changes in isotopic composition of C and N given in Table II the He$^3$ content in 30%
TABLE I

$T$ and $\varrho t$ conditions necessary to reduce the $\text{He}^3/\text{He}^4$-ratio from $5.3 \times 10^{-4}$ to $4 \times 10^{-4}$ in the total outer convective zone of the Sun, and the relative changes in the isotopic composition of carbon and nitrogen produced under these conditions ($X = 0.71, Y = 0.27$).

<table>
<thead>
<tr>
<th>Temperature (10^4 K)</th>
<th>$\varrho t$ required (g cm^{-3} s)</th>
<th>$(C^{13}/C^{12})/(C^{18}/C^{12})_0$</th>
<th>$(N^{15}/N^{14})/(N^{15}/N^{14})_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>a</td>
<td>1.7</td>
<td>0.50</td>
</tr>
<tr>
<td>14</td>
<td>$1.5 \times 10^{14}$</td>
<td>1.7</td>
<td>0.50</td>
</tr>
<tr>
<td>16</td>
<td>$1.4 \times 10^{14}$</td>
<td>1.8</td>
<td>0.39</td>
</tr>
<tr>
<td>18</td>
<td>$2.3 \times 10^{14}$</td>
<td>1.9</td>
<td>0.22</td>
</tr>
<tr>
<td>20</td>
<td>$4.9 \times 10^{11}$</td>
<td>2.2</td>
<td>0.11</td>
</tr>
</tbody>
</table>

* $\text{He}^3/\text{He}^4$ cannot be decreased by the assumed percentage.

TABLE II

Reduction of the $\text{He}^3/\text{He}^4$-ratio from $5.5 \times 10^{-4}$ to $5.5 \times 10^{-5}$ in 30% of the convective zone and mixing with 70% of unchanged material. The required $T$ and $\varrho t$ conditions produce large relative changes in the isotopic composition of carbon and nitrogen ($X = 0.71, Y = 0.27$).

<table>
<thead>
<tr>
<th>Temperature (10^4 K)</th>
<th>$\varrho t$ required (g cm^{-3} s)</th>
<th>$(C^{13}/C^{12})/(C^{18}/C^{12})_0$</th>
<th>$(N^{15}/N^{14})/(C^{15}/N^{14})_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>a</td>
<td>5.8</td>
<td>0.70</td>
</tr>
<tr>
<td>18</td>
<td>$7.8 \times 10^{13}$</td>
<td>5.8</td>
<td>0.70</td>
</tr>
<tr>
<td>20</td>
<td>$1.3 \times 10^{13}$</td>
<td>5.7</td>
<td>0.70</td>
</tr>
</tbody>
</table>

* $\text{He}^3/\text{He}^4$ cannot be decreased by the assumed percentage.

of the outer convective zone was reduced by 90% through thermonuclear reactions at a fixed temperature and then this material was mixed with 70% of matter which had remained cold, giving $\text{He}^3/\text{He}^4 = 4 \times 10^{-4}$. It is seen that in these two limiting cases and for all temperatures the assumed modest decrease of $\text{He}^3/\text{He}^4$ by 25% is accompanied by large changes in the $C^{13}/C^{12}$ and $N^{15}/N^{14}$ ratios which should have been found in the solar gas trapped at the lunar surface, or in the case of $C^{13}/C^{12}$, in the observation of sunspots by Hall et al. (1972).

Only a large error in at least one of the involved cross sections would change this basic conclusion. Fowler (1972) has mentioned the possibility that a $\text{He}^3 + \text{He}^3$ resonance at exactly the right energy could sufficiently lower the $\text{He}^3$ abundance in the solar core as to explain the deficient neutrino flux from the Sun (Davis, 1972). The recent search for this resonance by Parker et al. (1973) has had a negative result. As the authors mention, any resonance escaping detection by their method should have a width of several hundred keV and would already be included in the adopted $\text{He}^3 (\tau, 2p) \text{He}^4$ reaction rate.

We conclude that the presently available evidence on solar isotopic abundances and on nuclear reaction rates and very general theoretical considerations confirm that the $\text{He}^3/\text{He}^4$ ratio in the solar wind is a firm upper limit for $(\text{He}^3 + D)/\text{He}^4$ in the protosolar material.
Acknowledgements

The authors have greatly benefited from several conversations with H. Reeves. They thank S. Vega and A. Reuveni for help in performing the calculations and S. Lewis for reading the manuscript. Discussions with P. Eberhardt and O. Müller are gratefully acknowledged.

This work was supported by the Swiss National Science Foundation Grants No. 2.405.70 and No. 2.592.71. It was completed while one of us (P. B.) held a fellowship of this Foundation.

References