# ISOTOPE ABUNDANCES OF SOLAR CORONAL MATERIAL DERIVED FROM SOLAR ENERGETIC PARTICLE MEASUREMENTS

R. A. Mewaldt and E. C. Stone

California Institute of Technology, Pasadena, CA 91125 USA

## Abstract

Coronal isotopic abundances for the elements He, C, N, O, Ne, and Mg are derived from previously published measurements of solar energetic particles by first measuring, and then correcting for the charge-to-mass-dependent fractionation due to solar flare acceleration and propagation processes. The resulting coronal composition generally agrees with that of other samples of solar system material, but the previously noted difference between the solar flare and solar wind $^{22}$Ne/$^{20}$Ne ratios remains unresolved.

1. Introduction: Although the Sun contains more than 99% of solar system material, most of our present knowledge of the solar system element and isotope distribution comes from studies of terrestrial, meteoritic, and lunar material. Spectroscopic studies of the solar composition are subject to a number of sources of uncertainty, and in the case of isotopic abundances, are available for only a few elements. Measurements of solar energetic particles (SEPs) accelerated during large solar flares provide a means of sampling directly the composition of solar material, and thereby determining its composition. However, in interpreting such measurements, there has always been a question of the extent to which the observed particle composition might have been fractionated, during either the acceleration process, or the subsequent propagation through interplanetary space.

Recently, a Voyager study [1] by Breneman and Stone (here-in-after B&S) provided an answer to this question. By combining elemental composition measurements from 10 large flares with ionic charge-state measurements [2], B&S showed that the ionic charge-to-mass ratio (Q/M) is the principal organizing factor for the fractionation of SEP elemental abundances by acceleration and propagation processes, and for flare-to-flare composition variations. They found that these variations are a smooth function of Q/M that is well described by a power law. By correcting for these fractionation effects, B&S derived unfractionated coronal abundances for 20 elements. In this paper we report on an extension of the B&S approach to SEP isotope measurements.

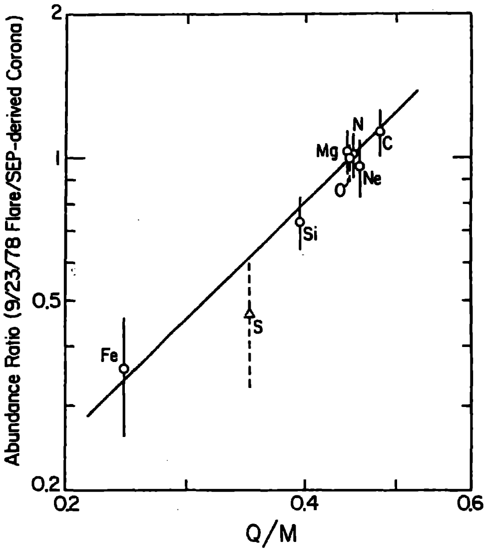


Fig. 1. Ratio of the element abundance for the 9/23/78 flare [3] to that for the SEP-derived corona [1] vs. Q/M. The solid line is a least squares fit to $(Q/M)^{\alpha}$ giving $\alpha = 1.95 \pm 0.44$. The S point is based on ref. [4] and was not included in the fit

2. Approach: Most of the measurements used for this study were obtained by the Caltech Heavy Isotope Spectrometer (HIST) on ISEE-3 during the large solar flare of 9/23/78. When these measurements were originally published ([3] and references therein) the relative isotope abundances were reported essentially as observed, with no corrections for any possible fractionation. To determine the magnitude and Q/M-dependence of the fractionation in the

Table 1 - Isotopic Abundances Observed in SEPs and Deduced for the Corona

| Isotope Ratio | Measured Value in SEPs [3] | Value Deduced for the Corona | Anders and Ebihara [9] |
|---|---|---|---|
| $^3He/^4He$ | $\leq 2.6 \times 10^{-3}$ | $\leq 1.9 \times 10^{-3}$ | $4.3 \times 10^{-4}$ |
| $^{13}C/^{12}C$ | $0.0095^{+.0042}_{-.0029}$ | $0.0111^{+.0049}_{-.0034}$ | 0.0111 |
| $^{14}C/^{12}C$ | $< 0.0014$ | $< 0.0019$ | 0.00 |
| $^{15}N/^{14}N$ | $0.008^{+.010}_{-.005}$ | $0.009^{+.012}_{-.006}$ | 0.0037 |
| $^{17}O/^{16}O$ | $\leq 0.0021$ | $\leq 0.0024$ | 0.00037 |
| $^{18}O/^{16}O$ | $0.0015^{+.0011}_{-.0007}$ | $0.0019^{+.0014}_{-.0009}$ | 0.00204 |
| $^{21}Ne/^{20}Ne$ | $\leq 0.014$ | $\leq 0.015$ | 0.0024 |
| $^{22}Ne/^{20}Ne$ | $0.109^{+.026}_{-.019}$ | $0.131^{+.032}_{-.024}$ | 0.073 |
| $^{25}Mg/^{24}Mg$ | $0.148^{+.046}_{-.026}$ | $0.160^{+.050}_{-.028}$ | 0.129 |
| $^{26}Mg/^{24}Mg$ | $0.148^{+.043}_{-.025}$ | $0.173^{+.050}_{-.030}$ | 0.142 |

9/23/78 flare event we make use of the charge-state measurements made during this flare on the same spacecraft by the Max-Planck/Maryland group [2], and of the elemental composition measured by our own experiment [3]. Fig. 1 plots the ratio of the abundances measured in this event to the B&S SEP-derived coronal abundances [1] as a function of Q/M. Note that in this flare elements that retain several electrons, such as Fe, Si, and S, are depleted relative to those elements that are nearly fully stripped, such as C. As in the B&S study, this fractionation is well described by the function $(Q/M)^\alpha$, where a least squares fit gives $\alpha = 1.95 \pm 0.44$. From this dependence we would also expect heavy isotopes such as $^{22}Ne$ to be slightly depleted in this flare relative to lighter elements such as $^{20}Ne$.

To correct for the effects of fractionation in this flare and thereby obtain measurements of the coronal isotopic composition we use

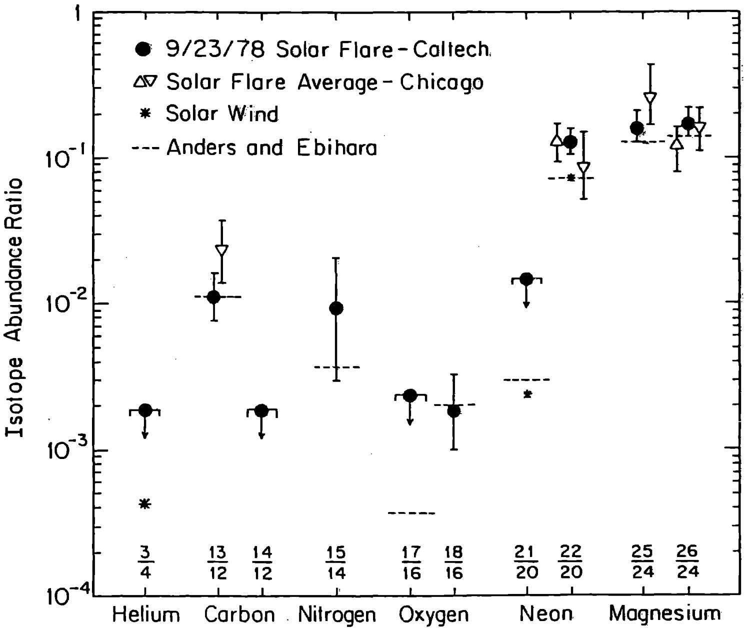
$$\frac{S_i}{S_j} = \left[\frac{M_i}{M_j}\right]^\alpha \left[\frac{N_i}{N_j}\right], \qquad (1)$$

where $S_i$ and $S_j$ are the <u>coronal</u> abundances of isotopes i and j of a given element with masses $M_i$, $M_j$, where $N_i$ and $N_j$ are the <u>observed</u> abundances, as reported in [3], and where $\alpha = 1.95$.

We have also considered the magnitude of fractionation effects on solar flare isotope results reported by others. To do this we note from Fig. 1 (see also Fig. 2 in [1]) that a reasonable estimate of the value of α for a particular flare can be obtained simply from $[(Fe/O)_f]$, the Fe to O ratio of the flare measured in the same experiment. We then use:

$$\alpha_{est} = \frac{\ln[(Fe/O)_f/(Fe/O)_c]}{\ln[(Q/M)_{Fe}/(Q/M)_O]}, \qquad (2)$$

where $(Fe/O)_c$ is the coronal Fe to O ratio from B&S [1]. As an estimate of the charge states of Fe and O we use the average values $Q(Fe) = 14.9 \pm 0.09$ and $Q(O) = 7.00 \pm .02$ from Luhn et al. [2], noting that in large flares the charge states do not appear to vary significantly from flare to flare. We then use Eqn. 1 to obtain an estimate of the coronal abundance [5].



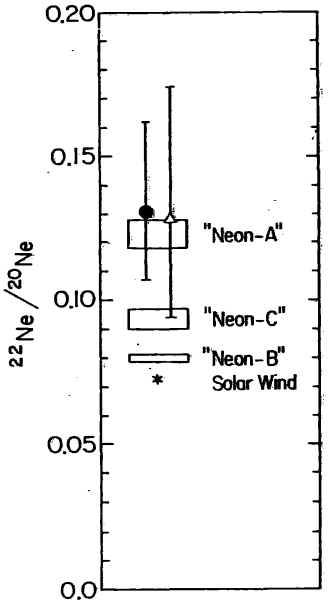


Fig. 2. Comparison of isotopic abundances derived for the corona from SEP measurements (including ● [3]; and Δ, ∇ [6,7,8]) with solar wind measurements [10], and the solar system abundances tabulated by Anders and Ebihara [9]

Fig. 3. Comparison of selected solar system $^{22}$Ne/$^{20}$Ne ratios. Coronal values based on SEP data: ● [3]; Δ [6]; solar wind [10]; neon-A and B from [11]; neon-C from [12]

3. Results: Table 1 includes both our measured isotopic ratios from [3], and the corresponding coronal abundance ratio obtained by correcting for the observed fractionation in the 9/24/78 flare. The uncertainties in the quoted coronal abundance ratios include the uncertainties in the value of $\alpha$. In Fig. 2 we compare our derived coronal composition measurements with the "solar system" abundances of Anders and Ebihara [9] and with the solar wind measurements of Geiss et al. [10]. Also shown in Fig. 2 are various flare-average measurements reported by the Chicago group [6,7,8], corrected for fractionation effects as described above (see also [5]).

4. Discussion: Note in Fig. 2 that the $^{13}$C/$^{12}$C, $^{15}$N/$^{14}$N, $^{18}$O/$^{16}$O, $^{25}$Mg/$^{24}$Mg, and $^{26}$Mg/$^{24}$Mg ratios that we obtain for the corona are consistent with the Anders and Ebihara compilation, in agreement with our earlier conclusions [3] based on the measured ratios, uncorrected for fractionation effects. This is not surprising because the magnitude of the fractionation correction is not large (typically 10-20%).

The isotope $^{22}$Ne is of special interest because of the wide range of $^{22}$Ne/$^{20}$Ne ratios observed in various samples of solar system material [see, e.g., 11]. The isotopic composition of neon in the Sun is controversial, with Anders and Ebihara [9] adopting the solar wind (SW) value as a standard, while Cameron [12] adopts the meteoritic component neon-A for solar system neon. Fig. 3 shows selected solar system $^{22}$Ne/$^{20}$Ne measurements on an expanded scale, including neon-B (directly implanted solar wind). As noted before [6,13,14,3], the spacecraft measurements of $^{22}$Ne/$^{20}$Ne in SEPs are inconsistent with the SW $^{22}$Ne/$^{20}$Ne ratio. Note that the result of correcting our SEP measurements for fractionation effects has increased the magnitude of this difference rather than narrowing it.

Fig. 3 also includes the component neon-C observed in lunar material, which has been interpreted to represent implanted SEP neon. (see the review by Black [15]). Recent measurements [16] confirm that there is a difference between neon-C and the measured solar wind $^{22}$Ne/ $^{20}$Ne ratio. It should be pointed out that there should presumably also be a fractionation correction applied to the neon-C measurements. While the magnitude of this correction is difficult to estimate, it is probably not large, and the average Fe/O ratio measured in large solar flares at a similar energy (~1 MeV/nucleon, [17]) suggests that the measured neon-C ratio should be multiplied by a correction factor of ~1.1.

In our first report of SEP $^{22}$Ne/$^{20}$Ne ratios [13] we suggested that the difference between the measured SEP and SW isotope ratios could result from fractionation of either the SEP or SW abundances, both of which are presumably derived from coronal material. We have now measured and corrected for the fractionation in SEPs and find that the resulting value for $^{22}$Ne/$^{20}$Ne in the corona differs from the measured SW value to an even greater extent, while we obtain quite reasonable values for the coronal isotopic composition of the other elements studied. Isotope fractionation during solar wind acceleration remains as a possibility for explaining this difference.

5. Acknowledgements: We are grateful to R. E. Vogt and J. D. Spalding for their contributions to the HIST program. This work was supported in part by NASA grants NAG5-722 and NGR 05-001-160.

## References

[1] Breneman H. H. and E. C. Stone Ap. J. (Letters) 299 , L57, 1985.
[2] Luhn A., B. Klecker, D. Hovestadt, G. Gloeckler, F. M. Ipavich, M. Scholer, C. Y. Fan, and L. A. Fisk Adv. Space Res. 4 , No. 2-3, 161, 1984.
[3] Mewaldt R. A., J. D. Spalding, and E. C. Stone Ap. J. 280 , 892, 1984.
[4] McGuire R. E., T. T. von Rosenvinge, and F. B. McDonald Proc. 16th Internat. Cosmic Ray Conf. (Kyoto) 5 , 61, 1979.
[5] The $^{22}$Ne/$^{20}$Ne measurements of Dietrich and Simpson [6] were corrected on a flare by flare basis using their reported Ne event totals and Fe/O ratios. The correction for their Mg result [7] was derived from a weighted average of the Fe/O ratios for flares included. The correction for the results of Simpson et al. [8] was derived from the average Fe/O ratio for their observation period.
[6] Dietrich W. F. and J. A. Simpson Ap. J. (Letters) 231 , L91, 1979.
[7] ———, Ap. J. (Letters) 245 , L41, 1981.
[8] Simpson J. A., J. P. Wefel, and R. Zamow, Proc. 18th Internat. Cosmic Ray Conf. (Bangalore) 10, 332, 1983.
[9] Anders E. and M. Ebihara, Geochim Cosmochim. Acta 46 , 2363, 1982.
[10] Geiss J., F. Buehler, H. Cerutti, P. Eberhardt, and Ch. Filleux, Apollo - 16 Preliminary Science Report, NASA SP-315 , p.14-1.
[11] Podosek F. A. Ann. Rev. Astr. Ap. 16 , 293, 1978.
[12] Cameron A. G. W. in Essays in Nuclear Astrophysics, ed. C. A. Barnes, D. D. Clayton and D. N. Schramm (Cambridge University Press), 1982.
[13] Mewaldt R. A., J. D. Spalding, E. C. Stone, and R. E. Vogt, Ap. J. (Letters) 231, L97, 1979.
[14] Mewaldt R. A. Proc. Conf. on Ancient Sun, ed. R. O. Pepin, J. A. Eddy, and R. B. Merrill (New York: Pergamon), p.81, 1980.
[15] Black D. C. Ap. J. 266, 889, 1983.
[16] Wieler R., H. Baur and P. Signer, Geochim. Cosmochim. Acta 50, 1997, 1986.
[17] Mason G. M., L. A. Fisk, D. Hovestadt, and G. Gloeckler Ap. J. 239, 1070, 1980.