VARIATIONS IN THE PROPAGATION OF UH-NUCLEI

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Abstract. We have investigated the sensitivity of the predictions of a model of the propagation of UH-nuclei in the interstellar medium on various assumptions.

1. Introduction. At the Paris Conference we reported, Brewster et al. (1981) our initial calculations on the propagation of UH-nuclei, using a leaky box formalism. These results have been discussed in more detail elsewhere, Brewster et al. (1983a). We have since improved this calculation by extending the number of individual nuclides considered, as well as using more recent evaluations of the rigidity dependence of the escape length, the possible source composition, and altered cross sections. We have also considered the effects of using different expressions for the dependence of abundances on first ionization potentials (FIP). In this paper we discuss the sensitivity of the calculated elemental abundances to the various changes made in the propagation assumptions. Details are available in Brewster (1985) and Brewster et al. (1985).

2. Modifications. The number of nuclides considered has been essentially doubled from 580 to 1316 and now includes virtually every one with $26 \leq Z \leq 83$ listed in the "Chart of the Nuclides" (as well as the longest-lived isotopes of Th and U). Those added were all short-lived, and so their production probabilities were included in the cross sections for the production of their final decay products. This has the effect of increasing the partial production cross sections for all the long-lived nuclides, and thus increasing secondary-to-primary abundance ratios.

Another change was in the dependence on rigidity, R, of the mean escape length, λ_{esc}. A recent analysis by Ormes and Protheroe indicates a steeper dependence on rigidity than the $R^{-0.4}$ we used previously. This dependence is expressed as:

$$\lambda_{esc}\,[\mathrm{g/cm^2}] = \begin{cases} (26.9)[1 + (1.88/R)^2]^{-3/2}\, R^{-0.7}, & R < 11.4\ \mathrm{GV} \\ (25.8)\, R^{-0.7} & R > 11.4\ \mathrm{GV} \end{cases}$$

normalized to $\lambda_{esc} = 6.0\ \mathrm{g/cm^2}$ at a kinetic energy of T = 5 GeV/nucleon. The constants in front allow for propagation in a hypothetical interstellar medium (ISM) composed of pure hydrogen. As a consequence of making this change we have also used a different injection spectrum, $dJ/dT \sim R^{-2.0}$ rather than $\sim R^{-2.3}$, as is required for consistency with the observed rigidity spectra of $R^{-2.7}$.

Another modification introduced is a change in the assumed solar system source abundances, which is not a change in the propagation model as such. We now use the Anders and Ebihara (1982) abundances, rather than the earlier Cameron (1982) compilation.

Cosmic ray propagation models generally use the semi-empirical formulas of Silberberg and Tsao (1973, 1977) to calculate the partial, $d\sigma$, and total, σ_T, cross sections needed for the model. These $d\sigma$ and σ_T values have been adjusted by "scaling" from the measured $d\sigma$ values of Au-nuclei observed at the Bevalac, Brewster et al. (1983b).

3. Effects of the Modifications. The effects of making these modifications are demonstrated in the Table for the abundances of various selected elements relative to 10^6 Fe-nuclei and several abundance ratios. Column (1) shows the predicted abundances near earth as calculated by Brewster et al. (1983a), based on the Cameron (1982) solar system abundances at the source. Column (2) shows the effect of increasing the number of nuclides while (3) shows the percentage change due to this modification. As expected, using the larger set of nuclides increases the abundances of almost all the elements relative to iron, since all the partial cross sections were increased. The difference is greatest for the most secondary species like Z = 70. In this table we have also defined various ratios of groups of elements. It should be noted that elements with 44≦Z≦48, 62≦Z≦69, and 70≦Z≦74 are presumed to be predominately, although not purely, secondary in origin, whereas the others are mostly primary, originating in the source.

Table: Abundances and abundance ratios (see text)

Z	Original (1)	All Nuclides (2)	% (1)-(2) (3)	A&E (4)	% (2)-(4) (5)	Exp FIP (6)	$R^{-0.7}$ (7)	% (4)-(7) (8)	Step FIP (9)	% (4)-(9) (10)	Scaling (11)	% (7)-(11) (12)
38	27	26	-4%	26	0%	46	46	77%	26	0%	48	4%
46	3.2	4.2	31%	4.0	-5%	4.2	4.1	3%	3.2	-20%	4.9	20%
50	5.5	6.7	22%	6.3	6%	7.1	7.1	13%	5.1	-19%	8.4	18%
52	6.0	6.6	10%	5.2	-21%	4.6	4.6	-12%	2.3	-56%	5.4	17%
56	3.9	4.3	10%	4.0	-7%	7.9	8.0	100%	4.0	0%	9.4	18%
70	.27	.51	89%	.57	12%	.64	.64	12%	.54	5%	1.1	72%
78	.90	.95	6%	.95	0%	.74	.75	-21%	.95	0%	1.0	33%
82	1.5	1.5	0%	1.8	20%	2.0	2.1	17%	1.8	0%	2.4	14%
N_1/N_2												
N (44≤Z≤48) / N (50≤Z≤58)	.56	.59	5%	.61	3%	.57	.56	-8%	.75	23%	.56	0%
N (62≤Z≤69) / N (75≤Z≤83)	.52	.73	40%	.67	-8%	.86	.84	25%	.68	1%	1.1	31%
N (70≤Z≤74) / N (75≤Z≤83)	.24	.35	46%	.31	-11%	.34	.33	6%	.31	0%	.45	36%
N (80≤Z≤83) / N (75≤Z≤79)	.85	.80	-6%	.99	24%	1.3	1.3	31%	.97	-2%	1.1	-15%

The effect of using the Anders and Ebihara (1982) abundances is shown in Column (4) with the resulting percentage changes shown in (5). These changes are entirely due to the differences between the two abundance compilations and while significant are relatively minor.

The application of corrections for the apparent dependence of source abundances on FIP are shown in the next few columns. Column (6) shows the effect of an exponential FIP dependence of the form f = 9.32 exp (-0.288I), so f = 1.0 for a potential, I, of I = 7.75 eV, while (9)

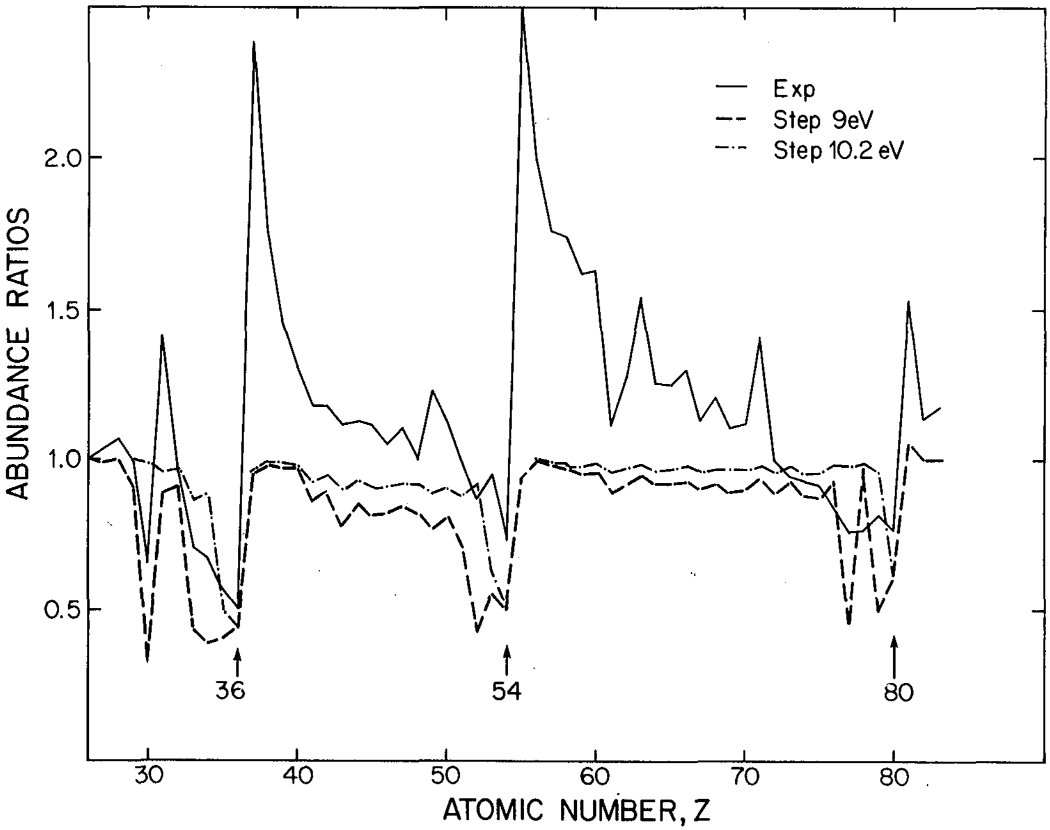

Fig. 1. The ratio of the abundances of a solar system source after propagation, with and without the application of a FIP correction, as a function of the atomic number Z.

shows that of a step dependence with f = 1 for I $\leq$ 9 eV and f = 0.3 for I $>$ 9 eV. Column (7) shows the very minor effect of changing the rigidity dependence. The differences between no FIP correction and exponential or step FIP dependence are shown in Columns (8) and (10) respectively. There is clearly a strong effect, both on FIP and on which FIP dependence is assumed. This can be more clearly seen in Fig. 1, which shows the Z dependence of the abundance changes and illustrates the fact that a step FIP dependence, unlike the exponential dependence, never increases the abundances significantly, but only depletes them. Figure 1 also shows the effects of a FIP dependence with a step at 10.2 eV, the Lymann H_α, which while not a good fit to the abundance ratios if standard solar abundances are assumed, is reasonable if C2 chondritic meteorite abundances are assumed, Binns et al. (1984). This higher energy step can be seen to still further reduce the effect of applying a FIP correction.

The differences between these various FIP dependencies are large enough that it should be possible to test them by examining data in the $32 \leq Z \leq 42$ and $50 \leq Z \leq 60$ charge ranges. For example, the large relative abundances of $_{38}$Sr and $_{56}$Ba reported from the HEAO C3 experiment, Binns et al. (1981, 1983), both appear to imply that the exponential FIP dependence is a better representation than the step dependencies unless the source abundances are quite anomalous.

The effects on the exponential FIP abundances of adjusting the σ_T and dσ values, by scaling the predicted values on the basis of those observed for Au-nuclei, Brewster et al. (1983b), are shown in Column (11). The scaling factors used for dσ are shown in Fig. 2 as a function

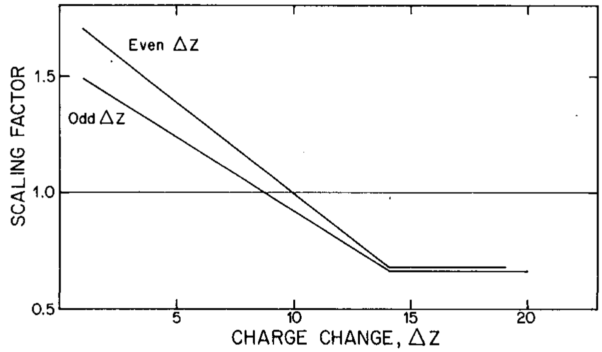

Fig. 2. The scaling factor applied to the predicted cross-sections as a function of ΔZ.

of the charge change, ΔZ, and can be seen to increase dσ values for small ΔZ and decrease them for large ΔZ. Column (12) shows the percentage changes between (7) and (11) and can be seen to be always positive, reflecting the greater importance of small charge changes in the propagation process. The recent observations reported elsewhere at this conference, Kertzman et al. (1985; OG 7.2-21), on the interactions of other heavy nuclei show that these scaling factors are strongly Z dependent and hence that the application of the Au-results to other primary nuclei is probably not justified, see e.g. the recent Pb/Pt results also reported at this conference, Waddington et al. (1985; OG 4.4-7).

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References

Anders, E., and Ebihara, M. (1982), Geochimica et Cosmochimica Acta, **46**, 2363.
Binns, W. R., et al. (1981), Ap. J. **247**, L115.
Binns, W. R., et al. (1983), Ap. J. **267**, L93.
Binns, W. R., et al. (1984), COSPAR Symposium.
Brewster, N. R. (1985), Ph.D. Thesis, Univ. of Minn.
Brewster, N. R., Freier, P. S., and Waddington, C. J. (1981), 17th ICRC, **Vol. 9**, 126.
________. (1983a), Ap.J. **264**, 324.
________. (1985), to be published in Ap.J., July 1.
Brewster, N. R., et. al. (1983b), Proc. 18th ICRC, **9**, 259.
Cameron, A. G. W. (1982), Essays in Nuclear Astrophy., ed. C. A. Barnes, Cambridge U. Press.
Kertzman, M. P., et al. (1985), this conf., Paper OG 7.2-21.
Ormes, J. F., and Protheroe, R. J. (1983), Ap.J. **264**, 324.
Silberberg, R., and Tsao, C. H. (1973), Ap. J. Suppl. **25**, 335.
_________. (1977), Proc. 15th ICRC, **2**, 84.
Waddington, C. J., et al. (1985), this conf., Paper OG 4.4-7.