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WHAT NEW CROSS SECTIONS SAY ABOUT SOURCE COMPOSITION AND COSMIC-RAY PROPAGATION

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Carbon, nitrogen and oxygen comprise $\sim 70\%$ of the heavy particles accelerated at the cosmic-ray sources. Due to their abundance, recent measurements of their partial cross sections have been particularly valuable in permitting improved estimates of the source composition, mean free path, and "age". The major change in the calculated source abundances is a 30% reduction in nitrogen, which is thus notably underabundant in cosmic-ray sources—next only to H and He—relative to solar composition. An interpretation of this observation is offered in an accompanying paper on nucleosynthesis of cosmic-ray nuclei. A revision of the mean path length is also required, downward by 10% to ≈ 4.5 g/cm^2 H-equivalent material, or ≈ 5.5 g/cm^2 in a 10:1 mixture of H:He, at energies of 1 to 10 GeV/u.

1. Introduction. On the basis of earlier data we constructed semiempirical relations for cross sections that were needed in calculating the cosmic-ray source composition and its transformations. The yields of Li, Be, B are particularly important in such calculations, and the measurements of the Orsay group have been vital in permitting more accurate determination of cosmic-ray transformations and of the appropriate parameters for the semiempirical equations.

2. New Experimental Cross Sections. Recently the cross sections of several essential reactions have been measured. Carbon and oxygen constitute about 2/3 of the heavy cosmic-ray nuclei at the sources. Now the breakup cross sections of C and O (with hydrogen as well as heavier nuclei) have been measured by Lindstrom et al. (1975), both for stable and unstable products. These measurements are precise; the errors in collision with hydrogen slightly exceed 10%, about 3 times as accurate as our earlier semiempirical equations (Silberberg and Tsao, 1973). The yields of Li and Be from C had been measured earlier by Yiou et al. (1973); these are in good agreement with those of Lindstrom et al. Only the yield of ^{10}Be from ^{16}O is sufficiently different between the two groups to warrant a remeasurement. The results of Lindstrom et al. show that the yield of B (including its radioactive parents ^{11}C, and ^{10}C) from ^{12}C, is $\approx 20\%$ larger, and that of N (including ^{15}O) from ^{16}O, is 30% larger than the predicted value based on our previous semiempirical equations.

These equations are poorer for heavier targets ($Z > 20$) than for lighter ones. Measurements of the partial cross sections of nuclei near iron have helped improve the calculation of the propagation of cosmic rays, and of their predicted isotopic composition. In our paper on calculation of cross sections (Silberberg and Tsao, 1973) we emphasized that the calculated yields of Li and B from iron-group nuclei are particularly uncertain due to large extrapolations. For the yields of ^{6}Li and ^{7}Li from heavy targets we had to rely on the Monte Carlo calculations of Dostrovsky et al. (1975).

The isotopes of boron fall just between two mass regions in which different parameters are used for calculating the yields of products; we recommended that the mean of the two calculations be adopted. The gap in our knowledge of the yields of Li and B from iron-group nuclei has now been eliminated by the measurements of Raisbeck et al. (1975), who employed a target of Ni. Their yields of ^{6}Li, ^{10}Be and ^{10}B are some 40% less than predicted by the calculations. The measurements of Perron (1975) show that the yield of V from Fe should be reduced ~ 30% relative to the earlier calculation and that of Mn raised about 30%. The data of Lagarde-Simonoff et al. (1975) imply that the yield of K and Sc from Fe is ~ 20% higher, and the yield of Cl from Fe appears to be ~ 20% lower.

Recent measurements of Renberg et al. (1972) suggest that the total inelastic cross sections of p-N reactions used in our papers (e.g., Table 4, Silberberg and Tsao, 1973) should be raised slightly, ~ 2% for heavy nuclei like Pb, and ~ 10% for lighter nuclei like C and O.

3. Calculated Abundances of Cosmic Rays at the Sources. The composition of arriving cosmic rays at energies between 1 and 10 GeV/u is now well known. The arriving composition adopted for the present calculation is identical to that of Shapiro and Silberberg (1975), which differs slightly from the one presented in Denver (Shapiro et al., 1973): the abundance adopted for Li is higher. Using the measured cross sections cited above, as well as appropriately modified semi-empirical ones for those still unmeasured, we derived the source composition shown in Table 1. On the basis of the general abundances of elements, we introduced small contributions of Cl, K and Ti (somewhat arbitrarily ~ 10^{-3} relative to carbon; the secondary component is so dominant for these elements in cosmic rays, that the source component cannot now be directly determined).

Table 1. Calculated Source Abundances of Cosmic Rays with $Z \leq 28$

H*	5×10^{4}	Mg	24 ± 2	K	$\sim 0.1^{+0.5}_{-0.1}$
He	2600	Al	2.3 ± 1	Ca	2.4 ± 0.8
C†	100	Si	21 ± 3	Ti	$\sim 0.1^{+0.5}_{-0.1}$
N	8 ± 2	P	$0.2^{+0.4}_{-0.2}$	Cr	0.4 ± 0.3
O	111 ± 2	S	3 ± 0.6	Mn	$\sim 0.1^{+0.5}_{-0.1}$
Ne	15 ± 2	Cl	$\sim 0.1^{+0.5}_{-0.1}$	Fe	22 ± 3
Na	0.9 ± 0.4	Ar	0.8 ± 0.5	Ni	0.8 ± 0.2

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*Would be 2×10^{4}, for a spectrum that depends on rigidity.

†Normalization.

The major change since the conference in Denver is the reduction in source nitrogen, due to larger cross sections for the production of N from O. Implications of this result are discussed in our paper on nucleosynthesis of cosmic-ray nuclei. Due to the increased yield of Mn from Fe, the best-fit value for Mn in the sources is ~ 0.1 relative to carbon. Conditions under which Mn could be nearly absent in cosmic-ray sources are explored in our paper on cosmic-ray chronology from isotopic composition. The elements from O to Fe are somewhat more abundant at the sources than estimated at Denver, as a result of higher values for the total inelastic cross sections.

4. Comparison of Cosmic-Ray Source Abundances with Those of the Solar System.

In order to learn more about the composition of cosmic-ray sources, processes of nucleosynthesis, and injection and acceleration of particles, it is useful to compare the source abundances with those in the solar system. Much of the uncertainty in such a comparison is due to poorly known solar and meteoritic abundances. Table 2 compares cosmic-ray with solar-system abundances, the latter being based on the estimates of Unsöld (1974), Cameron (1973), Withbroe (1971) and Engvold and Hauge (1974). All values are normalized to Mg; the numbers are then much the same as those obtained by using the ensemble of Mg, Si and Fe for normalization. The experts agree within about 20% for most of the abundant elements: H, He, C, N, O, Mg and Si. However, estimates of iron still range widely —over nearly a factor of 2. (The mean values cited in Table 2 vary over some 30%.) There is agreement on sulphur at thermal energies, but measurements of solar flare particles suggest a value that is lower by a factor of ~ 3. Values of solar neon and argon involve discrepancies by a factor of 5. These permit alternative interpretations of the extent and significance of differences between solar and cosmic ray abundances, which are discussed in our accompanying paper on the nucleosynthesis of cosmic-ray nuclei.

Table 2. Ratios of Cosmic-Ray Source Abundances to Solar Ones*

	Unsöld	Cameron	Withbroe	Engvold & Hauge
Fe	0.92	1.18	1.27	1.16
S	0.28	0.27	0.27	0.25
Si	0.97	0.93	0.85	0.70
Mg	1.00	1.00	1.00	1.00
Ne	0.97	0.19	0.76	0.50
O	0.27	0.23	0.24	0.23
N	0.13	0.094	0.10	0.10
C	0.47	0.38	0.39	0.33
He		0.052		0.043
H (vel.)	0.082	0.069	0.072	0.066
H (rig.)	0.033	0.028	0.029	0.027

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*Estimates of solar abundances are those of the respective authors. The cosmic-ray values used are those of Table 1.

Fig. 1 is an updated comparison of cosmic-ray source abundances with those of the solar system, normalized at magnesium. The value for nitrogen is lower by a factor 1.7 (i.e., 1.3 X 1.3) than in our corresponding graph at the Denver Conference. The two factors of 1.3 are due to (a) cross sections of O → N and (b) use of the solar abundances of Table 2, rather than Unsöld's values alone.

Starting with neon, the ratios of cosmic-ray abundances to solar ones agree (i.e., they are consistent with unity), provided that the higher estimates are adopted for neon, sulphur and argon. The pairs of values plotted for Ne, S, and Ar arise from disparate estimates of solar abundances by various authors. Lower solar abundances result in higher values of the CR/solar ratios in Fig. 1. The various labels refer to the following authors: "d," Dupree (1972); "f," flare particles measured by Bertsch et al. (1972) and by Sullivan et al. (1973); "e," Engvold and Hauge (1974); "a," Acton et al.; "g," based on the generally accepted solar abundances at thermal energies (see Table 2); and "u," Unsöld (1974) and Cameron (1973).

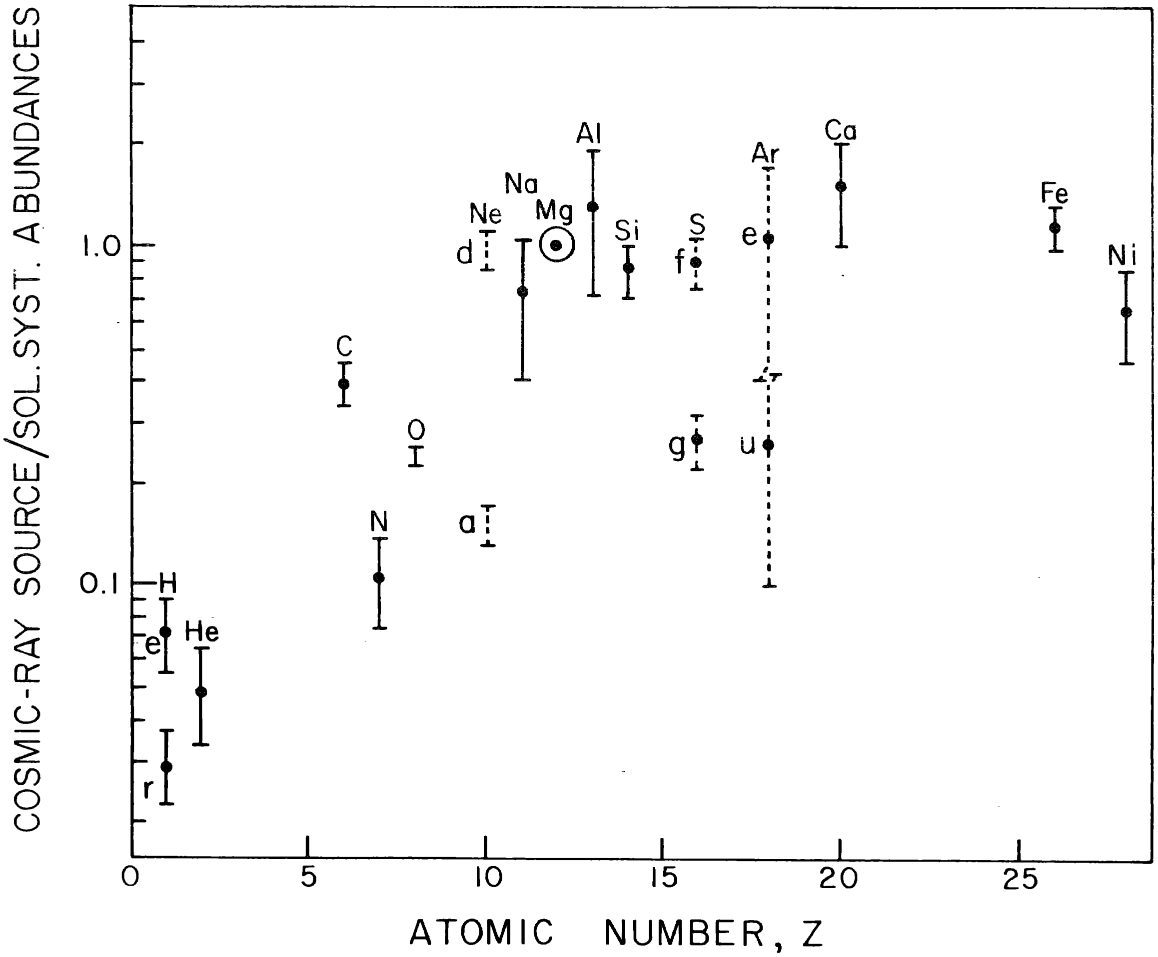

Fig. 1. The ratio of cosmic ray abundances at sources to the elemental abundances in the solar system. The two sets of abundances are normalized at Mg; this is nearly equivalent to using the ensemble of Mg, Si and Fe.

Table 3. Revised Isotopic Composition Calculated for Several Arriving Cosmic-Ray Elements*†

^{6}Li	9	^{10}B	7	^{49}V	0.3
^{7}Li	8	^{11}B	17	^{50}V	0.14
				^{51}V	0.05
^{7}Be	5.5	^{19}F	2.0	^{53}Mn	0.4
^{9}Be	2.9			^{54}Mn	0.3
^{10}Be	1.8	^{39}K	0.4	^{55}Mn	0.2

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*Normalized to (^{12}C + ^{13}C) = 100; †At comparable velocities.

ISOTOPIC ABUNDANCES OF COSMIC RAYS
(Arriving ^{12}C + ^{13}C Normalized to 100)

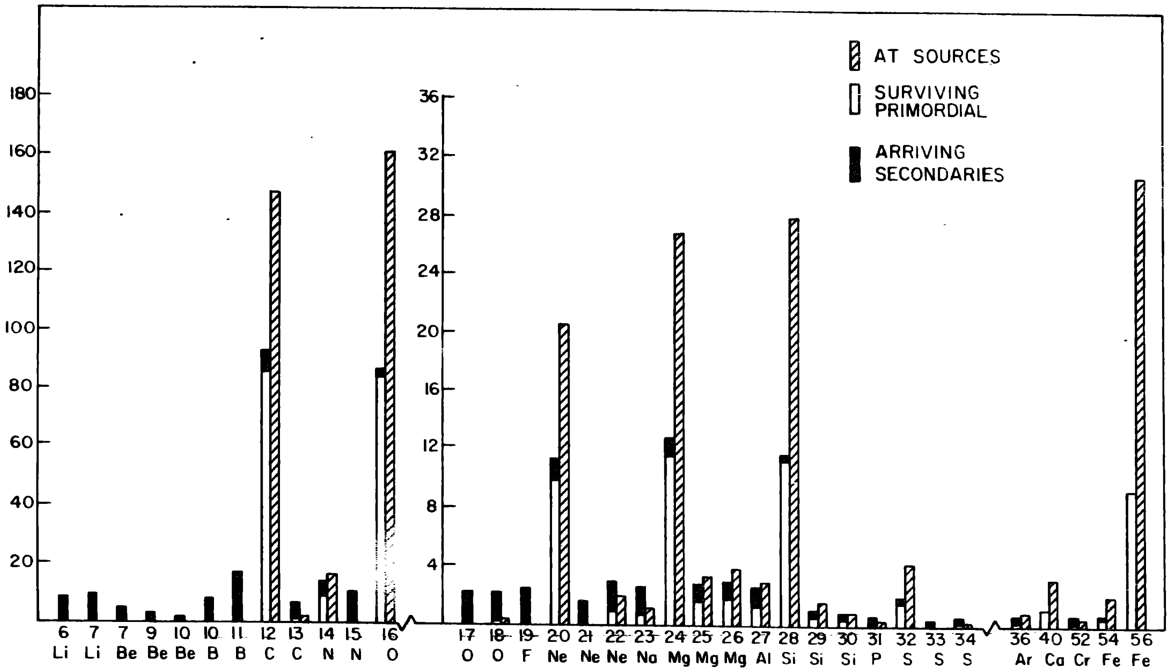

Fig. 2. Relative abundances of nuclides at cosmic ray sources and near the earth. All abundances have been normalized to a value of 100 for the arriving carbon (^{12}C + ^{13}C). In the "arriving" columns, the secondaries and the primordial survivors are shown separately, the values referring to a rigidity cutoff.

5. Mean Path Length Traversed by Cosmic Rays. As discussed above, recent measurements by Yiou (1973) and Lindstrom et al. (1975) have increased the estimated yield of light nuclei from C. Accordingly, the mean path length traversed by cosmic rays is about 10% less than we estimated earlier; it is about 5.5 g/cm^2 in hydrogen with 10% helium (by number), and it would be $\approx$ 4.5 g/cm^2 for pure hydrogen.

6. Isotopic Composition of the Arriving Cosmic Rays. At the Denver Conference, Tsao et al. (1973) presented a table giving the calculated isotopic composition of the arriving cosmic rays using a simple model: the elemental composition at the sources is the one we have calculated, while the isotopic ratios for a given element at the source were taken to be the same as those adopted for ordinary matter by Cameron (1973). Table 3 presents revised estimates for certain elements affected by new cross section values. It is based on high-energy cross sections ($E > 2300$ MeV/u), and the numerical values for ^{10}Be and ^{54}Mn are valid only if these radioisotopes have not decayed en route.

We have also computed the surviving source components and the secondary components for the various arriving nuclides. Fig. 2 displays the isotopic abundances of the cosmic rays. The cross-hatched columns give the abundances at the sources. In the other columns, representing the arriving composition, the dark areas denote the secondary contributions, while the white ones show the surviving source components. Between mass numbers 34 and 56, only the nuclides with significant surviving source components are plotted. Any real differences that may turn up between the composition calculated according to our simple model and isotopic measurements, could reveal special features of source composition and possibly of nucleosynthesis.

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