Title

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Author

Wiedenbeck, M.E.

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M.E. Wiedenbeck, D.E. Greiner, F.S. Bieser, H.J. Crawford,
H.H. Heckman and P.J. Lindstrom

University of California Space Sciences Laboratory
and Lawrence Berkeley Laboratory
Berkeley, California, USA 94720

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ABSTRACT

We report the results of an investigation of the isotopic composition of galactic cosmic ray carbon, nitrogen and oxygen (E ~ 80-230 MeV/amu) made using the U.C. Berkeley HKH instrument aboard the ISEE-3 spacecraft. The combination of high mass resolution and a large statistical sample makes possible a precise determination of the relative isotopic abundances for these elements. In local interplanetary space we find: $^{13}C/C = 0.067 \pm 0.008$, $^{15}N/N = 0.54 \pm 0.03$, $^{17}O/O < 0.027$, and $^{18}O/O = 0.019 \pm 0.003$.

INTRODUCTION

A number of different nucleosynthesis processes are capable of producing the isotopes of carbon, nitrogen and oxygen (CNO). Since these elements are by far the dominant component of the "metal" (i.e. $Z > 2$) abundances in common astrophysical sites, information gained about which processes make the dominant contributions to these elements should help in developing models of stellar and galactic evolution. Studies of the isotopic compositions of these elements are particularly useful since various nucleosynthesis processes have distinct isotopic signatures. The CNO isotopes have been studied in the solar system, in stars and in the interstellar medium (a discussion of many of these results can be found in ref. 1). In most sites, ^{12}C, ^{14}N, and ^{16}O are found to be the dominant isotopes.

The cosmic rays form another population about which composition information can be gained. Types of information which may be obtained include the following. First, if, as expected, the local ^{13}C, ^{15}N, ^{17}O, and ^{18}O fluxes consist predominantly of secondary reaction products, these isotopes can be used as probes of cosmic ray propagation in much the same way that Li, Be, and B have been used. Second, if the cosmic ray source is significantly richer than the solar system in these isotopes, it may be possible to obtain information about the nature of the source. Of particular interest in this regard is the $^{13}C/^{12}C$ ratio. In the solar system this ratio is ~ 0.01 whereas radio observations of molecular clouds show a ratio of ~ 0.025. It may ultimately be possible to distinguish such a difference in the cosmic ray source composition. However, such studies are subject to several difficulties. First, in the GCRs the contribution of secondaries produced by the spallation of heavier nuclides on the interstellar gas can significantly enhance the observed abundances of the rarer isotopes and thereby obscure the primary abundances. Second, there is the instrumental difficulty of separating neighboring isotopes which have substantially different abundances.

In this paper we present the results of a measurement of the isotopic composition of CNO in the galactic cosmic rays (E ~ 80 to 230 MeV/amu).

These measurements, made with the U.C. Berkeley HKH instrument on ISEE-3, are consistent with a cosmic ray source composition similar to solar system composition. However, uncertainties in both the observations and in the parameters needed for making the correction for secondary production are large enough to allow other source compositions.

INSTRUMENT AND DATA ANALYSIS

A cross sectional view of the instrument used for these measurements is shown in Figure 1. We combine trajectory information obtained from the six drift chambers (X1-3 and Y1-3) with energy loss information obtained from up to nine of the Si(Li) detectors (D1 through D9) to calculate the charge, mass, and energy of each cosmic ray nucleus which stops in any detector from D3 through D9. This instrument has been described in greater detail in ref. 2. In order to achieve resolution sufficient to resolve adjacent isotopes differing in abundance by more than an order of magnitude, it is necessary to know very precisely the thickness of material penetrated by each particle. This is accomplished by the use of highly uniform Si(Li) detectors (thickness variations ~ 10 μm or less) and by using the angle of incidence (θ) as determined from the drift chambers to calculate the actual thickness traversed by each particle. In addition, we have restricted the isotope analysis to particles incident within 20° of the normal to the detector surfaces since the calculation of the secθ correction to the thickness penetrated is least sensitive to position-measuring errors when θ is small.

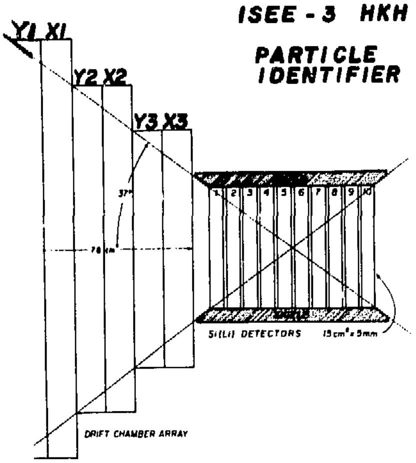

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Fig. 1

Also, particles stopping in the front 0.25 mm of a detector are omitted from the analysis, since at such low energies charge pick-up [3] and Z^3 corrections to the Bethe-Bloche formula cause deviations of the ions' range-energy relation from that obtained by scaling from the proton relation.

The particle's incidence angle is calculated from the measured positions in the X1, X3, Y1, and Y3 drift chambers. The center chambers, X2 and Y2, are used only as consistency checks. The drift chamber transfer functions exhibit an angle-dependent offset. In calculating the components of the incidence direction, $\tan\theta_x$ and $\tan\theta_y$, the use of the outermost chambers permits an approximate cancellation of these offsets, since the drift direction in these chambers is the same. However, the drift direction is reversed in the central chambers and the offsets add. Consequently, when such offsets are neglected the distribution of the consistency parameter, $\Delta X = X2 - 0.5\ (X1 + X3)$, has a total width of approximately one centimeter, although the resolution of the individual chambers is ~ 1 to 1.5 mm. At present we are employing the loose consistency criteria: $|\Delta X| < 5$ mm, $|\Delta Y| < 5$ mm. We expect that by calibrating the offsets we will be able to tighten this consistency requirement.

The calculations of charge and mass which we report in this study are based on the energy deposited in the detector in which the particle stops (E')

and in the immediately preceeding detector (ΔE) using the relation:

$$L \sec\theta = \left[R_p\left(\frac{\Delta E + E'}{M}\right) - R_p\left(\frac{E'}{M}\right)\right]\frac{M}{Z^2}$$

Here, L is the detector thickness, Z and M are the particle's charge and mass in units of the proton charge and mass, respectively, and the function R_p is the tabulated proton range-energy relation.[4] Energy losses in all detectors before those used for charge and mass identification are examined for consistency with this identification and with the observed total energy and stop-detector number. Such consistency checks provide a powerful means of rejecting events involving a nuclear interaction in the detector stack or exhibiting other abnormal behavior.

RESULTS

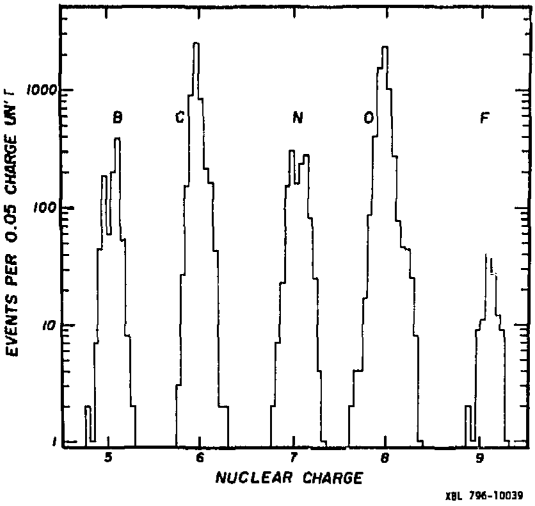


Fig. 2

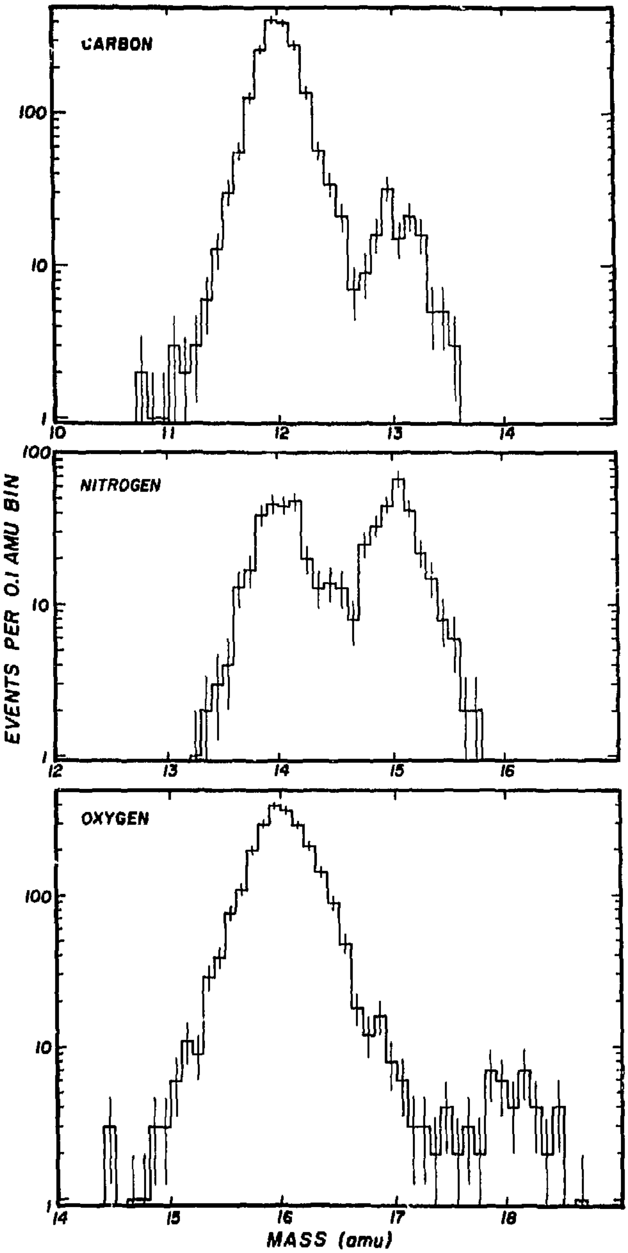
The data used for this study were collected from launch (12 August 1978) through February 1979, omitting the periods when the count rate in D1 indicates an enhanced flux of low energy particles. In Figure 2 we show a charge histogram of events accumulated in the charge range $5 \leq Z \leq 9$ over the entire solid angle viewed by the instrument. These data, analyzed as described above, permit unambiguous charge identification--the charge peaks are widely spaced with no background between the peaks. The shapes of the peaks show clear evidence of the underlying isotope structure. A Gaussian fit to the central 70% of the oxygen events yields a charge resolution ~0.042 charge units.

Figure 3 shows mass histograms for carbon, nitrogen, and oxygen including only those events with $\theta < 20°$ (these comprise ~40% of the data shown in Fig. 2). Peaks corresponding to ^{12}C, ^{13}C, ^{14}N, ^{15}N, ^{16}O, and ^{18}O are evident. The ^{17}O events have not been resolved from ^{16}O. Mass resolutions obtained from Gaussian fits to the central 70% of the peaks vary from $\sigma_M = 0.17$ amu for ^{12}C to $\sigma_M = 0.25$ amu for ^{18}O. Note, however, that the observed mass distributions deviate considerably from a Gaussian shape in their tails. We believe that these tails result from errors in the calculated incidence angles due to uncalibrated non-linearities of the drift chambers.

In Table 1 we show the observed abundance ratios. Since the various nuclides are collected over equal intervals of particle range (defined by detector thickness and the 0.25 mm cutoff imposed at the front of each detector), a correction must be applied in order to compare abundances over constant energy-per-nucleon intervals. Assuming that the spectra of both isotopes involved in the ratio have the form $J \propto E^{-\gamma}$ over the energy interval of the observation and that the proton range-energy relation is of the form $R \propto E^{\alpha}$, the measured ratios must be corrected by:

$$\left(\frac{N_1}{N_2}\right)_{E/M} = \left(\frac{N_1}{N_2}\right)_R \left(\frac{M_1}{M_2}\right)^{\frac{1-\gamma}{\alpha}}$$

In the energy interval covered by our measurements the spectral index should lie between -1 (J = AT spectrum) and 0 (flat spectrum). The former value is probably more appropriate for the present near-solar-maximum period. The uncertainties shown in Table 1 reflect the combination of statistical errors and the uncertainty in estimating the contribution of the tail of one isotope peak to an adjacent peak. Uncertainties in the correction to equal energy-per-nucleon are not included.



XBL 795-9862

Fig. 3

DISCUSSION

Table 2 is a comparison of our results with other electronic detector measurements[5-8] of the CNO composition and with a theoretical calculation.[9] All of the measurements shown here are in reasonable agreement except for the University of New Hampshire measurement of $^{15}N/N$. This disagreement may simply be the result of an underestimate of the uncertainty in that work (which was described as preliminary by the authors).

The final row in Table 2 shows the local abundance ratios expected from the propagation of a source with solar-like composition through interstellar matter.[9] From the close agreement between the measurements and the calculation we draw some general conclusions. First, the cosmic ray source abundances do not contain a large (i.e. order of magnitude or greater) overabundance of the rare isotopes ^{13}C, ^{17}O, and ^{18}O. The measured ^{15}N abundance is also not inconsistent with solar-like source composition, although a $^{15}N/N$ ratio substantially greater that the solar system value (0.004)[10] is also permitted. Second, standard propagation models (which are primarily from Li, Be, and B abundance data) can adequately describe the observed CNO isotopes.

The cosmic ray isotopic composition measurements are now achieving sufficiently high precision so that more detailed tests of propagation models is possible. In order to make such comparisons it will be necessary to perform the calculations taking into account a full range of parameters describing parent composition, nuclear interaction processes, pathlength distribution, ionization energy loss (and possibly continuous acceleration) and solar modulation. In such calculations emphasis must be on a realistic evaluation of the uncertainties involved.

Table 1

Isotope Ratio	Measured*	Corrected to Equal Energy per Nucleon†
$^{13}C/C$	0.061 ± 0.007	0.067 ± 0.008
$^{15}N/N$	0.52 ± 0.03	0.54 ± 0.03
$^{17}O/O$	< 0.025	< 0.027
$^{18}O/O$	0.017 ± 0.003	0.019 ± 0.003

*Constant intervals of particle range.
†Assumes a J = AT spectrum.

Table 2

Energy (MeV/amu)	Isotope Ratio				Reference
	$^{13}C/C$	$^{15}N/N$	$^{17}O/O$	$^{18}O/O$	
130	0.067 ± 0.008	0.54 ± 0.03	< 0.027	0.019 ± 0.003	this work
100	$0.07^{+0.02}_{-0.03}$	0.47 ± 0.06		< 0.028	8
260		0.60 ± 0.03			5
450	< 0.09	0.4 ± 0.2	< 0.065	0.025 ± 0.015	6
1200		0.45 ± 0.07			7
theory ($\gtrsim$ 2000)	0.06 ± 0.01	0.45 ± 0.05	0.02 ± 0.01	0.02 ± 0.01	9

ACKNOWLEDGEMENTS

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