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THE ISOTOPIC COMPOSITION OF THE ANOMALOUS LOW-ENERGY COSMIC RAYS

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ABSTRACT

We present new observations of the isotopic composition of low-energy He, C, N, O, and Ne nuclei. The observations cover the energy interval from ~5 to 30 MeV per nucleon, the energy range where the "anomalous cosmic ray" fluxes of He, N, O, and Ne have been observed. We compare the isotopic composition of the anomalous cosmic rays with that of higher-energy galactic cosmic rays in an effort to understand the origin of these two components. For three of the elements studied (He, N, and Ne) we find significant variations in the isotopic composition at essentially the same energy where the elemental composition changes (~30–50 MeV per nucleon), in agreement with earlier studies. Thus, fragmentation products such as ^{3}He and ^{15}N that are relatively abundant in galactic cosmic rays appear to be essentially absent from the anomalous cosmic ray component. In addition, we find a difference between the ^{22}Ne/^{20}Ne ratios in the anomalous and galactic cosmic rays, implying that the nucleosynthesis of these two components has differed. Although limited by their statistical accuracy, our low-energy isotope results are generally consistent with the proposed interstellar-neutral origin for the anomalous cosmic rays. If correct, this model suggests that future measurements of anomalous cosmic rays can be used to analyze the isotopic structure and evolution of the local interstellar medium.

Subject headings: cosmic rays: abundances — interstellar: abundances

I. INTRODUCTION

Observations of low-energy cosmic rays during the last solar minimum have revealed that below ~50 MeV per nucleon the energy spectra and elemental composition of quiet-time cosmic rays undergo a change in character. Specifically, anomalous enhancements were discovered in the energy spectra of the elements helium, nitrogen, oxygen, and neon relative to other elements such as hydrogen, boron, and carbon. For example, at ~10 MeV per nucleon the oxygen spectrum is enhanced by a factor of ~30 above that expected from an extrapolation of the spectrum of ~40 to ~100 MeV per nucleon galactic cosmic rays, giving an O/C ratio of ~30:1. Based on a variety of observations of its composition, temporal behavior, and spatial distribution within the heliosphere, it is now established that the so-called anomalous cosmic ray (ACR) component has a nonsolar origin that differs from that of the galactic cosmic ray (GCR) component (see, e.g., the review by Gloeckler 1979).

Previous studies have established that the ACR component includes the elements He, N, O, and Ne, although it is possible that other elements are also enhanced at levels of a few percent of the observed oxygen flux (see, e.g., Webber and Cummings 1983). Isotope measurements of the ACR component show that it consists of relatively pure ^{4}He (Teegarden *et al.* 1975; Mewaldt, Stone, and Vogt 1975, 1976; Garcia-Munoz, Mason, and Simpson 1975), ^{14}N, and ^{16}O (Mewaldt *et al.* 1975, 1976; Webber *et al.* 1975; Mewaldt *et al.* 1981*a*; Smith and McDonald 1983). Thus, in contrast to galactic cosmic rays, there is no evidence for secondary contributions due to fragmentation, and these nuclei therefore represent a relatively pure sample of the source composition.

Several possible origins have been suggested for the ACR component. McDonald *et al.* (1974, 1977) first suggested that it originates in a nearby galactic source of unusual composition. Hoyle and Clayton (1974) suggested that nova outbursts in white dwarfs might produce the observed elemental composition, in which case the isotopes ^{15}N and ^{17}O would be overabundant, or perhaps even the dominant N and O isotopes. The N and O isotope observations of Mewaldt *et al.* (1975, 1976) and Webber *et al.* (1975) ruled out any astrophysical source in which ^{15}N and ^{17}O were more than ~30% of ^{14}N and ^{16}O. Durgaprasad and Biswas (1977) have also discussed a nova origin model for the ACR component, while Biswas, Durgaprasad, and Trivedi (1981) suggested stellar winds from nearby O-type stars, combined with shock acceleration in the interstellar medium (ISM).

It has also been proposed that the ACR component originates from neutral interstellar particles that penetrate the heliosphere, become singly ionized, and are then accelerated to ≥10 MeV per nucleon in the interplanetary medium (Fisk, Kozlovsky, and Ramaty 1974; see also Fisk 1976; Klecker 1977), or at the solar wind termination shock (Pesses, Jokipii, and Eichler 1981; Fisk 1982). In these models the source composition is dominated by those elements which are relatively abundant in the neutral state in the ISM. This results in a selective enhancement of those elements with relatively high first ionization potentials (i.e., He, N, O, Ne, and Ar), consistent with the observed ACR composition. A prediction of all of the local acceleration models, not yet directly tested, is that the ACRs should be singly ionized.

Isotope studies are a key to understanding the origin of the ACR component. If the ACRs originate in a nearby galactic source of unusual elemental composition, isotopic anomalies might also be expected. It is now known that the isotopic composition of GCR source material differs significantly from that of solar system material, at least for the elements Ne, Mg, and Si (see, e.g., the reviews by Mewaldt 1983; Simpson 1983; and references therein). If the ACRs represent interstellar neutral particles that have been ionized and accelerated in the heliosphere, or at its boundary, then isotopic studies, made at 1 AU, can actually analyze the present isotopic structure of the local ISM. In this case, a comparison of the ACR isotopic composition with that of the solar system, which is presumed to represent a sample of the ISM ~5 billion years ago, would provide important information on the evolution of the solar neighborhood, and would provide an important benchmark for the interpretation of GCR isotope measurements.

In this article we report new measurements of the isotopes of low-energy cosmic ray He, C, N, O, and Ne nuclei. These observations, along with other recent measurements, provide further evidence that the isotopic composition of cosmic rays changes as the modulated GCR component merges with the ACR component, and thereby provide new information on the isotopic composition of the ACR component. A preliminary account of this work has been given in Mewaldt *et al.* (1981*a*).

II. INSTRUMENTATION

The bulk of the observations reported here were made with the Caltech Heavy Isotope Spectrometer Telescope (HIST) on *ISEE-3*. The HIST telescope, described in detail by Althouse *et al.* (1978), consists of an array of silicon solid-state detectors of graduated thicknesses which measure the energy loss of nuclei that slow down and stop in the telescope. For nuclei that penetrate three or more detectors, two or more essentially independent determinations of the nuclear charge (Z) and mass can be obtained, as shown in Mewaldt *et al.* (1979). This redundancy minimizes possible background contributions and improves the accuracy of the mass determination.

HIST also includes a pair of two-dimensional position-sensitive detectors that determine the trajectories of individual nuclei. This allows corrections to be made for the path length through each subsequent detector, thereby leading to a significant improvement in isotopic resolution over earlier cosmic ray instruments. Unfortunately, a component failure in the HIST readout logic on 1978 December 1 (which reduced the number of data bits transmitted to Earth) limited the time period during which high-resolution data such as those reported here could be accumulated. For oxygen nuclei the energy range covered by HIST is ~5 to ~150 MeV per nucleon, allowing studies of nuclei with a variety of origins, including solar, galactic, and interplanetary sources.

This report also includes isotope measurements at ~10 MeV per nucleon made with the Caltech Electron/Isotope Spectrometer (EIS) on *IMP-7*. The EIS consists of a stack of 11 fully depleted solid-state detectors surrounded by a plastic scintillator anticoincidence cup. For isotope analysis a standard energy-loss versus residual-energy technique is used for particles that pass through a 50 μm thick detector and stop in a 1 mm thick detector, with all other detectors in anticoincidence. The use of four annular solid-state detectors to form an active collimator for incoming nuclei results in a very clean, low-background response with a geometry factor of 0.07 cm^2 sr. The isotope response of a backup telescope of identical design was calibrated for $1 \leq Z \leq 8$ nuclei at the Lawrence Berkeley Laboratory Bevalac and 88-inch (2.2 m) Cyclotron, and at the Caltech Tandem van de Graaff (Vidor 1975).

A second EIS of similar design but somewhat larger geometry factor (0.23 cm^2 sr), which is carried on *IMP-8*, was used to measure most of the low-energy element abundances reported here. Further details of the EIS design and data analysis procedure can be found in Mewaldt *et al.* (1976).

III. ENERGY SPECTRA AND ELEMENTAL COMPOSITION

Figure 1 shows quiet-time energy spectra for H, He, C, N, and O nuclei obtained during the years 1973–1978 by the Caltech and Chicago experiments on *IMP-7* and *IMP-8*. Of the five elements shown, the fluxes of H and C are both approximately proportional to kinetic energy from ~10 to 100 MeV per nucleon, as expected from the solar modulation of galactic cosmic rays. The elements He, N, and O, on the other hand, clearly show the anomalous enhancements at low energy. Table 1 gives the element composition measured by the *IMP-8* EIS in the energy interval from ~5 to ~15 MeV per nucleon. While this composition is generally consistent with earlier measurements (see, e.g., the review by Gloeckler 1979), our quiet-time C/O ratio is lower than in most previous studies in this energy region (e.g., Klecker *et al.* 1977). The difference is due entirely to the lower absolute flux of C that we measure, possibly the result of a more careful selection of quiet-time periods, or of the reduced level of instrumental background in the EIS instruments. When normalized to galactic cosmic ray abundances at >100 MeV per nucleon, the anomalous fluxes of ~10 MeV per nucleon N, O, and Ne in Table 1 are enhanced with respect to C by factors ranging from ~20 to ~40.

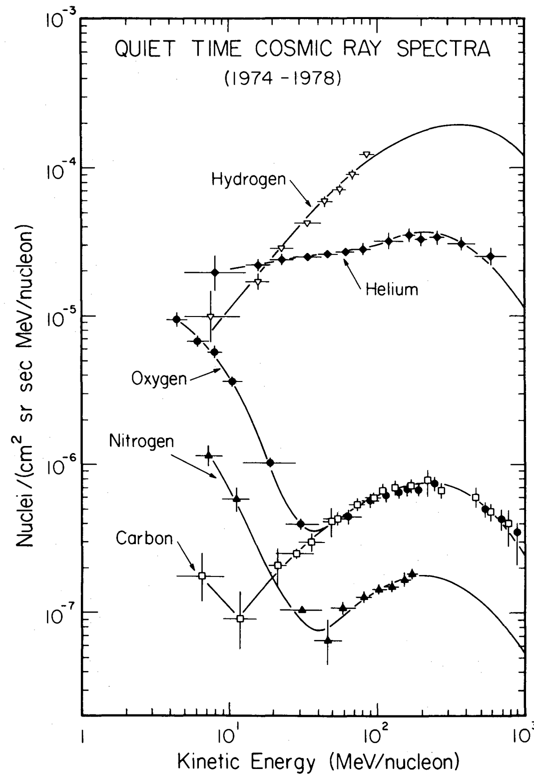

FIG. 1.—Quiet time energy spectra for the elements H, He, C, N, and O measured at 1 AU over the period from 1974 to 1978. Note the "anomalous" enhancements in the low-energy spectra of He, N, and O. The H and He points below 40 MeV per nucleon are 1975 data from the EIS instruments on *IMP-7* and *IMP-8*, while the higher energy points are 1975 data from the University of Chicago experiment on *IMP-7* (Garcia-Munoz, Mason, and Simpson 1977). For C, N, and O the *IMP-8* EIS data were obtained from 1974 to 1976, and extend from ~4 to ~50 MeV per nucleon. Data at ~25 MeV per nucleon and at >50 MeV per nucleon are Chicago *IMP-8* data from 1974 to 1978 (Garcia-Munoz *et al.* 1979). For the GCR component the smooth lines are fits that assume a source spectrum $dJ/dT \propto (T + 400 \text{ MeV per nucleon})^{-2.6}$ (where J is the particle flux and T the kinetic energy per nucleon) and a solar modulation level of $\Phi = 300$ MeV per nucleon. Curves through the low-energy enhancements have been drawn by eye.

Spectra from a somewhat later time period, obtained by our *ISEE-3* instrument in late 1978, are shown in Figure 2. Also shown schematically in Figure 2 is the O spectrum from Figure

TABLE 1

ELEMENT ABUNDANCE RATIOS

Element	Low Energy[a] Cosmic Rays (~10 MeV/nuc)	Galactic[b] Cosmic Rays (~100 MeV/nuc)	Solar[c] Energetic Particles (~10 MeV/nuc)	ACR Enhancement[d] with respect to GCRs
He.........	~5	54 ± 4	62 ± 11	~4
C..........	0.028 ± 0.008	1.10 ± 0.02	0.47 ± 0.04	≡1.0
N..........	0.18 ± 0.03	0.25 ± 0.01	0.12 ± 0.01	28 ± 9
O..........	≡1.0	≡1.0	≡1.0	39 ± 11
Ne.........	0.07 ± 0.02[e]	0.145 ± 0.006	0.17 ± 0.02	19 ± 8

[a] *IMP-8* data 1974–1978, except for Ne.
[b] Garcia-Munoz and Simpson 1979.
[c] Cook *et al.* 1980.
[d] Evaluated at 10 MeV per nucleon by comparing the abundances in the second column with the GCR abundances in the third column. Note that the energy spectrum of anomalous He differs from that of N, O, and Ne (see, e.g., Fig. 1).
[e] Based on Ne/O from Gloeckler 1979.

1, typical of the 1972 to early 1978 solar minimum period. Note that while the fluxes of anomalous N and O in late 1978 are reduced somewhat from their solar minimum levels due to the effects of solar modulation (see Webber *et al.* 1981; Webber and Cummings 1983), the ACR component still dominates the quiet-time spectra of N and O nuclei between ~5 and ~30 MeV per nucleon. We also observe an enhancement in the ≤30 MeV per nucleon flux of Ne during this time period, consistent with earlier studies.

IV. ISOTOPIC COMPOSITION

In order to address the question of whether the ACR isotopic composition differs from that of galactic cosmic rays, we have divided the HIST data into two energy intervals at ~30 MeV per nucleon, the energy at which the ACR fluxes of N, O, and Ne begin to dominate over the GCR component. In the

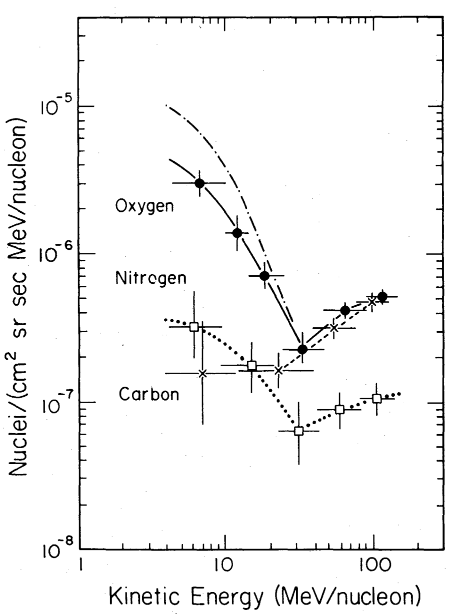

FIG. 2.—Energy spectra of C, N, and O nuclei measured on *ISEE-3* during quiet-time periods between 1978 August 13 and 1978 December 1. Lines connecting the data points have been drawn to aid the eye. The dot-dash line (taken from the O spectrum in Fig. 1) is typical of low-energy O spectra measured during the 1972–1977 solar minimum.

resulting mass histograms, shown in Figure 3, the observed mass resolution ranges from ~0.1 to 0.23 amu. All mass determinations for events with ≥30 MeV per nucleon are based on at least two separate mass determinations, as discussed in Mewaldt *et al.* (1979, 1980). Below 30 MeV per nucleon only a single mass determination was used for a portion of the data (~20%), including, for example, two of the five Ne events. The isotope response of HIST has been calibrated using a combination of accelerator data (Mewaldt *et al.* 1980) and solar flare data (Mewaldt *et al.* 1979; Mewaldt, Spalding, and Stone 1984). As a result, the absolute mass scale is believed to be accurate to ≤0.05 amu.

The *IMP-7* isotope data reported here were accumulated during quiet-time periods from 1972 October to 1978 June. They represent a continuation of the study presented in Mewaldt *et al.* (1976), and are based on the same quiet-time selection criteria. Vidor (1975) concluded that for these criteria less than 1% of the observed N and O nuclei are of solar flare origin during solar minimum conditions. Note that the abundance of 5–15 MeV per nucleon carbon (C/O = 0.028 ± 0.008) is ~20 times lower than is observed in typical solar flare events (C/O ≈ 0.5). Figure 4 shows mass histograms for low-energy N and O nuclei from the *IMP-7* EIS. Also included are Gaussian curves showing the expected response of the instrument to a pure ^{14}N and ^{16}O composition, based on the physical parameters of the detector system (Vidor 1975). The observed resolution agrees well with that expected; we measure an rms mass resolution of $\sigma_m = 0.31 \pm 0.07$ amu for ^{14}N and $\sigma_m = 0.45 \pm 0.04$ amu for ^{16}O, compared to expected values of 0.37 amu and 0.42 amu.

In the O distribution shown in Figure 4 there are two events at ^{18}O. We believe that these are real ^{18}O events, since they are both $\sim 4.5\sigma_m$ away from the ^{16}O distribution. In the accelerator calibration data from the backup EIS telescope, using an ^{16}O beam, only two events out of 20,000 fell $4.5\sigma_m$ or more above ^{16}O. In the N distribution there is a single event near mass 15 which is $\sim 3\sigma_m$ away from ^{14}N. This could be either a fluctuation from the ^{14}N distribution (probability ~0.02), or a real ^{15}N. In the ^{16}O calibration there were only ~25 out of 20,000 events $3\sigma_m$ or more above ^{16}O.

Table 2 summarizes the isotope abundance ratios that we obtain from the *IMP* and *ISEE* data. In Figure 5, these results are compared with selected earlier observations, plotted as a function of kinetic energy per nucleon. Also shown in Figure 5 are the results of GCR propagation and solar modulation cal-

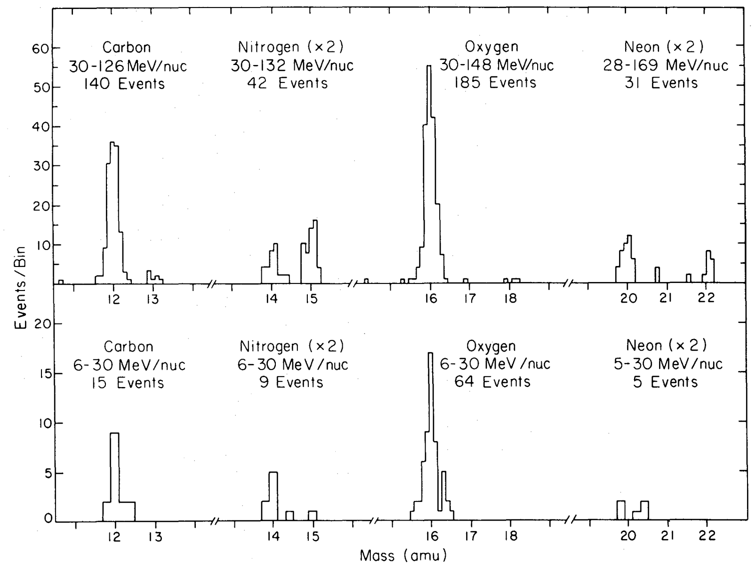

FIG. 3.—Mass distributions of C, N, O, and Ne nuclei measured by HIST in two energy intervals. The top panel shows ≥30 MeV per nucleon galactic cosmic ray data, previously reported by Mewaldt *et al.* (1980, 1981*b*). The bottom panel shows lower-energy nuclei in the energy region dominated by the ACR component.

culations (M. E. Wiedenbeck, private communication). The calculations assume a standard leaky box propagation model with a mean path length $\lambda = 7$ g cm^{-2} of interstellar matter (with He/H = 0.1) and solar modulation with a mean energy loss $\Phi = 300$ MeV per nucleon. Although there is evidence that the interstellar pathlength varies somewhat with energy below 1 GeV per nucleon (see, e.g., Ormes and Protheroe 1983), 7 g cm^{-2} is representative of recent results for ~100 to 200 MeV per nucleon data. The GCR source composition was assumed to have solar system isotopic abundances (Cameron 1982), with the exception of Ne, Mg, and Si, where the abundances of the neutron-rich isotopes ^{22}Ne, ^{25,26}Mg, and ^{29,30}Si were enhanced by the factors summarized in Mewaldt (1983), as indicated by recent measurements. For element abundances, the GCR source composition was taken from Silberberg, Tsao, and Shapiro (1976), except for N, where it was assumed that N/O = 0.03, as required to fit the most recent high-resolution measurements of N isotopes at ≥30 MeV per nucleon (Wiedenbeck *et al.* 1979; Mewaldt *et al.* 1981*b*; Mewaldt 1983; Webber 1982, 1983). Note that these calculations apply only to the GCR component; they do not take into account the ACR component, which has a different composition.

Comparing the isotope ratios of the GCR component with our low-energy measurements in the region of the ACR component, there are three elements, He, N, and Ne, where there are significant differences. The N and Ne differences are also evident in the mass distributions shown in Figure 3. In our earlier study (Mewaldt *et al.* 1976) it was already clear that there was significantly less ^{15}N in the ACR component than in the GCR component. Now, with somewhat better statistical accuracy, we find less than a 0.1% probability that our 6–13 MeV per nucleon *IMP-7* result is consistent with ^{15}N/N > 0.5, as required by the GCR observations. Our *ISEE* data confirm this (^{15}N/N < 0.5 with 99% confidence), as do the recent *Voyager* data (Smith and McDonald 1983). For ^{22}Ne/^{20}Ne we find the 5–28 MeV per nucleon ratio to be less than the ~100 MeV per nucleon value of ~0.6 at the 94% confidence level. This result, and the *Voyager* measurements at somewhat higher energy, support an earlier suggestion by Webber *et al.* (1975), based on *Pioneer 10* data, that ^{22}Ne might be less abundant at low energies. For the C and O isotopes, the statistical accuracy of the data is not sufficient to determine whether there is an energy dependence to the isotopic composition. Our low-energy results do, however, place tighter limits on any possible excess of the rare neutron-rich C and O isotopes at low energies.

TABLE 2

COSMIC RAY ISOTOPE MEASUREMENTS

Isotope Ratio	Low-Energy Cosmic Rays: *IMP 7* Energy (MeV/nuc)	*IMP 7* Observed Ratio	*ISEE 3* Energy (MeV/nuc)	*ISEE 3* Observed Ratio	Galactic Cosmic Rays (~100 MeV/nuc)[a]
^{3}He/^{4}He	5–15	≤0.02	...	...	~0.10
^{13}C/C	...	...	5–30	≤0.11	~0.06
^{15}N/N	6–13	≤0.19	5–30	$0.11^{+0.19}_{-0.11}$	~0.55
^{17}O/^{16}O	7–12	≤0.06	6–30	≤0.03	~0.020
^{18}O/^{16}O	7–11	$0.03^{+0.03}_{-0.01}$	6–30	≤0.03	~0.020
^{22}Ne/^{20}Ne	...	...	5–28	≤0.36	~0.60

[a] See Fig. 5.

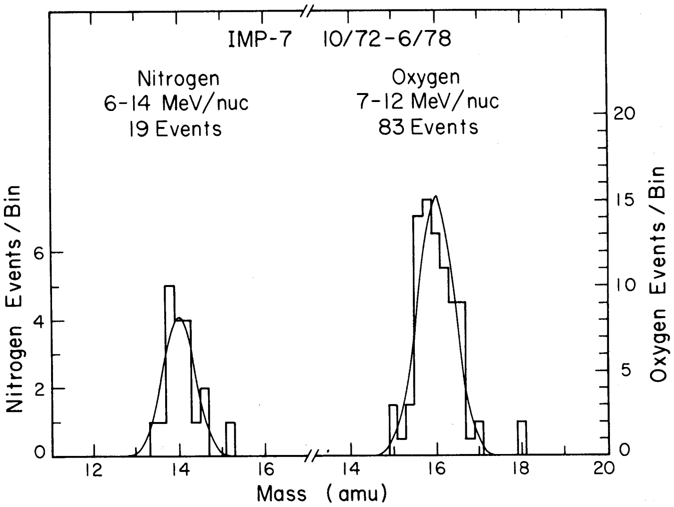

FIG. 4.—Mass distributions of N and O nuclei measured by the *IMP-7* EIS during quiet-time periods from 1972 September to 1978 June. The Gaussian curves show the expected response to a pure ^{14}N and ^{16}O composition.

V. DISCUSSION

For three of the four elements generally agreed to be part of the low-energy ACR component (He, N, and Ne), there is now evidence that the isotopic composition undergoes a transition at the same energy per nucleon where the elemental composition changes. We wish to relate these changes to the composition of the ACR component with the goal of gaining further clues to its origin.

To interpret quantitatively the energy dependence of the isotopic compositions, we consider a two-component description. We assume that the modulated GCR component has a spectral slope $dJ/dE \propto E^{0.7}$, consistent with the 1 AU measurements of Garcia-Munoz *et al.* (1977), and with our ~ 30 to ~ 130 MeV per nucleon C and O data from *ISEE* (Fig. 2). This dependence is extrapolated down to a few MeV per nucleon. For the ACR component, we assume that the elements N, O, and Ne all have the same spectral shape, obtained by subtracting the GCR component from the measured O spectrum in Figure 2. For relative element abundances of the two components we use the values in Table 1, while the GCR isotopic abundances are from Table 2. For the ACR component we consider a range of isotopic compositions in order to deduce the limits imposed by the experimental data, where, for simplicity, we have assumed that solar modulation does not alter the isotopic composition. The curves in Figure 6 show the

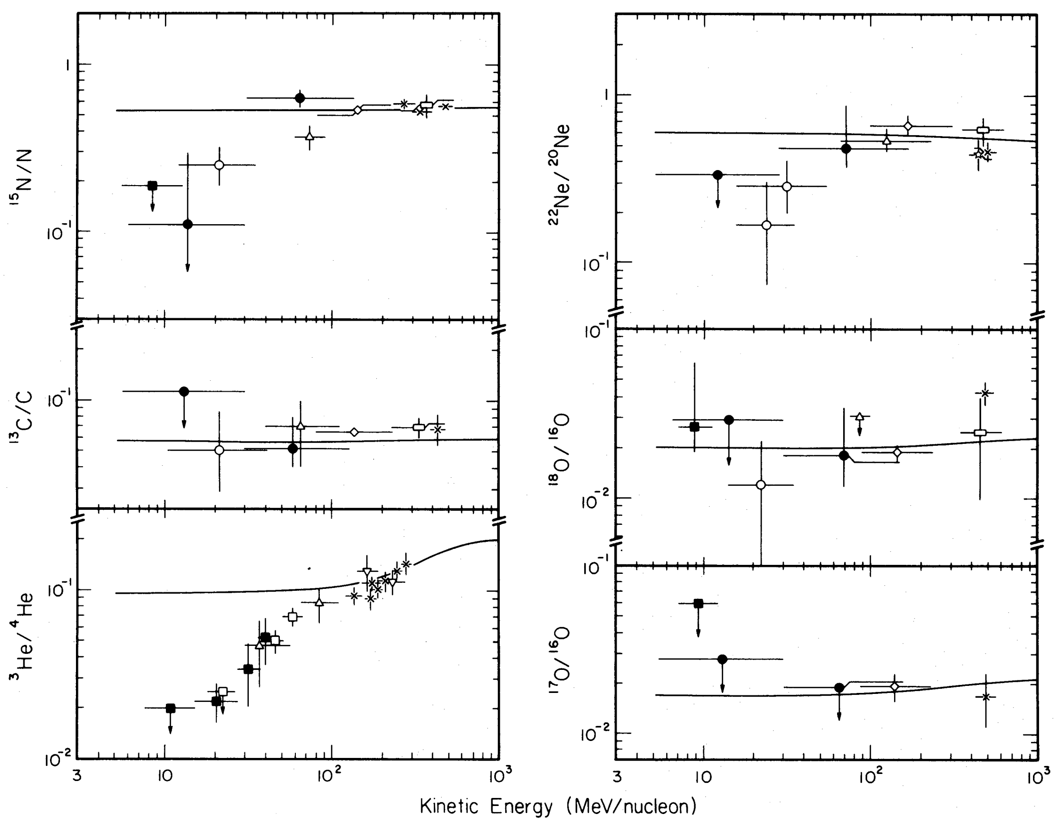

FIG. 5.—Measured and calculated GCR isotope abundance ratios. The calculated ratios (M. E. Wiedenbeck, private communication) apply only to the energy region ≥ 30 MeV per nucleon, but are extrapolated to lower energy. Data points: *filled circle*, this work, *ISEE-3*; *filled square*, this work, *IMP-7*; *diamond*, U. C. Berkeley (Wiedenbeck *et al.* 1979; Wiedenbeck and Greiner 1981*a*, *b*); *triangle*, Chicago (Garcia-Munoz, Mason, and Simpson 1975; Garcia-Munoz, Simpson, and Wefel 1979; Guzik 1981); *rectangle*, Goddard (Fisher *et al.* 1976; Hagen, Fisher, and Ormes 1977); *inverted triangle*, Maryland (Leech and O'Gallagher 1978); *star*, Minnesota (Freier, Young, and Waddington 1980); *cross*, New Hampshire (Webber and Schofield 1975; Webber and Yushak 1979; Webber 1982, 1983); *open square*, *Pioneer 10* (Teegarden *et al.* 1975); *open circle*, *Voyager* (Smith and McDonald 1983). The *Voyager* points (*open circles*) have been averaged and include systematic uncertainties resulting from background subtraction (see Smith and McDonald 1983).

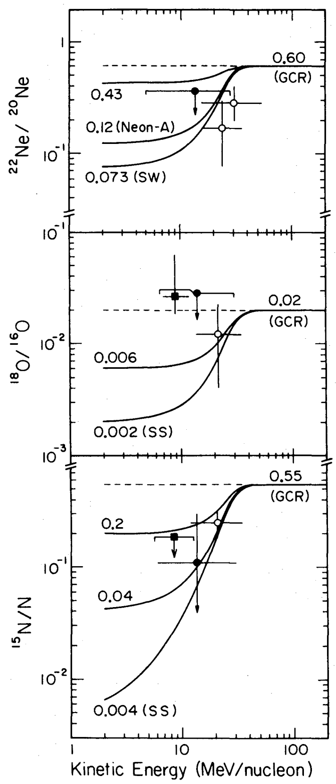

FIG. 6.—Comparisons of the observed ACR composition with calculated curves that assume various ACR compositions (labeled on curves), including the Cameron (1982) solar system (SS) values. Data points: *filled circle*, this work, *ISEE-3*; *filled square*, this work, *IMP-7*; *open circle*, Smith and McDonald (1983), *Voyager 1* and *2*.

expected energy dependence of the isotopic composition that results from adding the contributions from the two components. Comparisons of the observations with the curves indicate the range of allowed ACR isotopic compositions. Assuming more complex spectral forms for the ACR component (see, e.g., Klecker 1977; Webber, Cummings, and Stone 1983) would not alter the conclusions reached here.

The GCR abundances of ^{15}N and ^{18}O are believed to result principally from the fragmentation of heavier cosmic rays as they pass through the ISM (see, e.g., Adams *et al.* 1981). The fact that the ACR ^{15}N/N ratio is much lower than the GCR ratio implies that fragmentation contributions are much less important for this component, as is also evidenced by corresponding low-energy decreases in other abundance ratios sensitive to fragmentation contributions, such as ^{3}He/^{4}He (see Fig. 5) and B/O (McDonald *et al.* 1974; Mewaldt *et al.* 1976; Webber and Cummings 1983). Combining our IMP and ISEE results in the interval 6–13 MeV per nucleon, we find that the ACR component has ^{15}N/N ≤ 0.14.

It can be seen that our IMP ^{18}O/^{16}O ratio (based on two ^{18}O events) is consistent with the GCR ratio, and does not show the low-energy decrease observed for ^{15}N/N, ^{3}He/^{4}He, and B/O. If verified by other measurements (our *ISEE* data show only that ^{17}O/^{16}O and ^{18}O/^{16}O are less than 0.03 for the ACRs) this ^{16}O result would be surprising, since there is little ^{18}O observed in the ISM, and GCR ^{18}O is mainly of secondary origin.

The isotope abundance ratio ^{22}Ne/^{20}Ne is especially interesting because it takes on a range of values in various samples of matter observed in the solar system (see, e.g., Podosek 1978). The two most likely possibilities for the composition of the Sun appear to be solar-wind Ne, with ^{22}Ne/^{20}Ne = 0.073 (Geiss *et al.* 1972), and neon-A, a meteoritic component with ^{22}Ne/^{20}Ne = 0.12. The isotopic composition of GCR Ne is distinctly different from any of the observed solar system components. Our upper limit for the ACR ^{22}Ne/^{20}Ne ratio is lower than both the observed and the source compositions for GCR Ne (see Fig. 6). Integrated over the 5 to 28 MeV per nucleon energy interval, we find only a 10% probability that our measurement could be consistent with an ACR ratio as large as ^{22}Ne/^{20}Ne = 0.43, the best estimate for the GCR-source composition of neon (Mewaldt 1983; see also Fig. 5). This suggests that the nucleosynthesis of the ACR and GCR components has differed.

If the model of Fisk, Kozlovsky, and Ramaty (1974) is correct, then the nuclei comprising the ACR component represent a sample of the local ISM. The inconsistency between ACR and GCR-source Ne is therefore significant in view of recent models which propose that a majority, if not all, of galactic cosmic rays may represent a sample of the interstellar gas (see, e.g., the reviews by Casse 1981; Axford 1981; and references therein). If both of these components do in fact represent samples of ISM material, then these results indicate that the local ISM differs from that of which the galactic cosmic rays are a sample. It is important to get an improved measurement of ACR Ne isotopes to see if the relative abundances are consistent with any of the observed solar system components such as neon-A or solar-wind Ne.

An additional element of interest is argon, which, because of its relatively large first ionization potential, would also be expected to be a member of the ACR component if the essence of the interstellar neutral origin proposed by Fisk, Kozlovsky, and Ramaty (1974) is correct. There is the suggestion of an Ar enhancement in the *Voyager* data of Webber and Cummings (1983), at a level of ~ 0.002 of that of O. Assuming Cameron (1982) abundances for the ISM, one might expect Ar/O ≈ 0.005 or greater for the model of Fisk, Kozlovsky, and Ramaty. If an Ar enhancement is verified, isotopic studies of ACR Ar would be interesting, since several distinct isotopic components of Ar have been detected in solar system material (see, e.g., Podosek 1978).

There remains the possibility that other elements may also be members of the ACR component. Various experiments have observed possible evidence for a C enhancement below ~ 10 MeV per nucleon (Klecker *et al.* 1977; Webber, Stone, and Vogt 1979; Webber and Cummings 1983; see also the lowest energy C point in Fig. 1). In addition, Webber and Cummings (1983) observe similar enhancements in Mg and Si at the level of $\sim 10^{-2}$ of that of O. They were unable to decide if the C, Mg, and Si enhancements represented an ACR contribution, or were possibly due to a residual solar or interplanetary component. A recent model by Fisk (1982) predicts that "anomalous" hydrogen might also have been observable at 1 AU during the 1976–1977 solar maximum period, and possible evidence for anomalous H has been presented by Stone and Mewaldt (1983). As a further test of the interstellar-neutral model for ACR origin it would be useful to have calculations of the spectra expected for Ar, C, H, and other elements that exist in the neutral state in the ISM with any appreciable abundance.

In summary, we have found further evidence for an energy-dependent isotopic composition at low energies, thereby placing new restrictions on the composition and origin of the ACR component. We find no strong evidence for an exotic isotopic composition; indeed, with the possible exception of $^{18}O/^{16}O$, our ACR results are entirely consistent with tabulated solar-system abundances, and with the interstellar-neutral origin proposed by Fisk, Kozlovsky, and Ramaty (1974), in which the ACRs represent a sample of the local ISM. Galactic evolution models predict that the isotopic composition of the ISM should evolve with time as a result of the cumulative effect of nucleosynthesis in successive generations of stars. Although the isotopic composition of Ne in the local ISM is unknown, the isotopic composition of C, N, O, and other elements has been measured in the ISM by radio astronomy studies of interstellar molecules (see the reviews by Wannier 1980 and Penzias 1980). While these measurements indicate important differences between the interstellar gas and the solar system isotopic abundances (such as those compiled by Cameron 1982 or Anders and Ebihara 1982), these differences are of the order of a factor of 2 or 3, and would not be detectable with the present ACR isotope measurements. However, if measurements with mass resolution comparable to that from our *ISEE* experiment could be obtained over a several-year period, isotopic variations of the magnitude observed for N and O isotopes in the ISM should be detectable in the ACR component at energies below ~ 10 MeV per nucleon. Thus, future measurements of this kind, possibly during the next solar minimum period, may provide a unique opportunity to study the evolution of the ISM in the solar neighborhood.

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REFERENCES

Adams, J. H., Shapiro, M. M., Silberberg, R., and Tsao, C. H. 1981, *Proc. 17th Internat. Cosmic Ray Conf.* (Paris), **2**, 256.
Althouse, W. E., Cummings, A. C., Garrard, T. L., Mewaldt, R. A., Stone, E. C., and Vogt, R. E. 1978, *Geoscience Electronics*, **16**, 204.
Anders, E., and Ebihara, M. 1982, *Geochim. Cosmochim. Acta*, **46**, 2363.
Axford, W. I. 1981, *Proc. 17th Internat. Cosmic Ray Conf.* (Paris), **12**, 155.
Biswas, S., Durgaprasad, N., and Trivedi, Sushma S. 1981, *Proc. Earth Planet. Sci.*, **90**, 337.
Cameron, A. G. W. 1982, in *Essays in Nuclear Astrophysics*, ed. C. A. Barnes, D. D. Clayton, and D. N. Schramm (Cambridge: Cambridge University Press).
Casse, Michel. 1981, *Proc. 17th Internat. Cosmic Ray Conf.* (Paris), **13**, 111.
Cook, W. R., Stone, E. C., and Vogt, R. E. 1980, *Ap. J.* (*Letters*), **238**, L97.
Durgaprasad, N., and Biswas, S. 1977, *Proc. 15th Internat. Cosmic Ray Conf.* (Plovdiv), **2**, 103.
Fisher, A. J., Hagen, F. A., Maehl, R. C., Ormes, J. F., and Arens, J. F. 1976, *Ap. J.*, **205**, 938.
Fisk, L. A. 1976, *J. Geophys. Res.*, **81**, 4633.
———. 1982, presented at the Solar Wind V Conference, Woodstock, Vermont.
Fisk, L. A., Kozlovsky, B., and Ramaty, R. 1974, *Ap. J.* (*Letters*), **190**, L35.
Freier, P. S., Young, J. S., and Waddington, C. J. 1980, *Ap. J.* (*Letters*), **240**, L53.
Garcia-Munoz, M., Margolis, S. H., Simpson, J. A., and Wefel, J. P. 1979, *Proc. 16th Internat. Cosmic Ray Conf.* (Kyoto), **1**, 310; and **13**, 401.
Garcia-Munoz, M., Mason, G. M., and Simpson, J. A. 1975, *Proc. 14th Internat. Cosmic Ray Conf.* (Munich), **1**, 319.
———. 1977, *Ap. J.*, **213**, 263.
Garcia-Munoz, M., Mason, G. M., Simpson, J. A., and Wefel, J. P. 1977, *Proc. 15th Internat. Cosmic Ray Conf.* (Plovdiv), **1**, 230.
Garcia-Munoz, M., and Simpson, J. A. 1979, *Proc. 15th Internat. Cosmic Ray Conf.* (Kyoto), **1**, 270.
Garcia-Munoz, M., Simpson, J. A., and Wefel, J. P. 1979, *Ap. J.* (*Letters*), **232**, L95.
Geiss, J., Buehler, F., Cerutti, H., Eberhardt, P., and Filleux, Ch. 1972, *Apollo 16 Preliminary Science Report* (NASA SP-315, p. 14-1).
Gloeckler, G. 1979, *Rev. Geophys. Space Phys.*, **17**, 569.
Guzik, T. G. 1981, *Ap. J.*, **244**, 695.
Hagen, F. A., Fisher, A. J., and Ormes, J. F. 1977, *Ap. J.*, **212**, 262.
Hoyle, F., and Clayton, D. D. 1974, *Ap. J.*, **191**, 705.
Klecker, B. 1977, *J. Geophys. Res.*, **82**, 5287.
Klecker, B., Hovestadt, D., Gloeckler, G., and Fan, C. Y. 1977, *Ap. J.*, **212**, 290.
Leech, H. W., and O'Gallagher, J. J. 1978, *Ap. J.*, **221**, 1110.
McDonald, F. B., Lal, N., Trainor, J. H., Van Hollebeke, M. A. I., and Webber, W. R. 1977, *Ap. J.*, **216**, 930.
McDonald, F. B., Teegarden, B. J., Trainor, J. H., and Webber, W. R. 1974, *Ap. J.* (*Letters*), **187**, L105.
Mewaldt, R. A. 1983, *Rev. Geophys. Space Phys.*, **21**, 295.
Mewaldt, R. A., Spalding, J. D., and Stone, E. C. 1984, *Ap. J.*, **280**, 892.
Mewaldt, R. A., Spalding, J. D., Stone, E. C., and Vogt, R. E. 1979, *Ap. J.* (*Letters*), **231**, L97.
———. 1980, *Ap. J.* (*Letters*), **235**, L95.
———. 1981*a*, *Proc. 17th Internat. Cosmic Ray Conf.* (Paris), **2**, 68.
———. 1981*b*, *Ap. J.* (*Letters*), **251**, L27.
Mewaldt, R. A., Stone, E. C., Vidor, S. B., and Vogt, R. E. 1975, *Proc. 14th Internat. Cosmic Ray Conf.* (Munich), **1**, 349.
———. 1976, *Ap. J.*, **205**, 931.
Mewaldt, R. A., Stone, E. C., and Vogt, R. E. 1975, *Proc. 14th Internat. Cosmic Ray Conf.* (Munich), **1**, 306.
———. 1976, *Ap. J.*, **206**, 616.
Ormes, J. F., and Protheroe, R. J. 1983, *Ap. J.*, **272**, 756.
Penzias, A. A. 1980, *Science*, **208**, 663.
Pesses, M. E., Jokipii, J. R., and Eichler, D. 1981, *Ap. J.* (*Letters*), **246**, L85.
Podosek, F. A. 1978, *Ann. Rev. Astr. Ap.*, **16**, 293.
Silberberg, R., Tsao, C. H., and Shapiro, M. M. 1976, in *Spallation Nuclear Reactions and Their Applications*, ed. B. S. P. Shen and M. Merker (Dordrecht: Reidel), p. 49.
Simpson, J. A. 1983, *Ann. Rev. Astr. Ap.*, in press.
Smith, B., and McDonald, F. B. 1983, to appear in the late paper volumes of the *18th Internat. Cosmic Ray Conf.* (Bangalore), Paper OG2-2.
Stone, E. C., and Mewaldt, R. A. 1983, *Bull. Am. Phys. Soc.*, **28**, 742.
Teegarden, B. J., von Rosenvinge, T. T., McDonald, F. B., Trainor, J. H., and Webber, W. R. 1975, *Ap. J.*, **202**, 815.
Vidor, S. B. 1975, Ph.D. thesis, California Institute of Technology.
Wannier, P. G. 1980, *Ann. Rev. Astr. Ap.*, **18**, 399.
Webber, W. R. 1982, *Ap. J.*, **255**, 329.
———. 1983, submitted to *Proc. 18th Internat. Cosmic Ray Conf.* (Bangalore), paper OG2-9.
Webber, W. R., and Cummings, A. C. 1983, in *Solar Wind Five*, ed. M. Neugebauer, (NASA Conf. Pub. 2280, p. 427).
Webber, W. R., Cummings, A. C., and Stone, E. C. 1983, submitted to *Proc. 18th Internat. Cosmic Ray Conf.* (Bangalore), paper OG1-1.
Webber, W. R., McDonald, F. B., Trainor, J. H., Teegarden, B. J., and von Rosenvinge, T. T. 1975, *Proc. 14th Internat. Cosmic Ray Conf.* (Munich), **12**, 4233.
Webber, W. R., McDonald, F. B., von Rosenvinge, T. T., and Mewaldt, R. A. 1981, *Proc. 17th Internat. Cosmic Ray Conf.* (Paris), **10**, 92.
Webber, W. R., and Schofield, N. J. 1975, *Proc. 14th Internat. Cosmic Ray Conf.* (Munich), **1**, 312.
Webber, W. R., Stone, E. C., and Vogt, R. E. 1979, *Proc. 16th Internat. Cosmic Ray Conf.* (Kyoto), **5**, 357.
Webber, W. R., and Yushak, S. M. 1979, *Proc. 16th Internat. Cosmic Ray Conf.* (Kyoto), **1**, 383.
Wiedenbeck, M. E., and Greiner, D. E. 1981*a*, *Phys. Rev. Letters*, **46**, 682.
———. 1981*b*, *Ap. J.* (*Letters*), **247**, L119.
Wiedenbeck, M. E., Greiner, D. E., Bieser, F. S., Crawford, H. J., Heckman, H., and Lindstrom, P. J. 1979, *Proc. 16th Internat. Cosmic Ray Conf.* (Kyoto), **1**, 412.

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