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ISOTOPIC ABUNDANCES OF Fe AND Ni IN GALACTIC COSMIC-RAY SOURCES

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ABSTRACT

With a new instrument, designed to determine the isotopic composition of Galactic cosmic-ray nuclei, on board the *Ulysses* spacecraft, we report relative abundance measurements for ^{54}Fe, ^{55}Fe, ^{56}Fe, ^{57}Fe, ^{58}Fe and ^{58}Ni, ^{59}Ni, ^{60}Ni, ^{62}Ni in the overall energy range between ~200 and ~420 MeV nucleon^{-1}. These measurements combine excellent mass resolution ($\sigma \sim 0.28$ amu at ^{56}Fe) with good statistical significance (more than 6000 Fe events). The high mass resolution is achieved by utilizing solid-state, position-sensing detectors to measure—with less than 1° angular error—the trajectory of each nucleus entering the charged-particle telescope. The cosmic-ray source abundances are derived from the measurements using models for propagation from distributed sources in the Galaxy ("leaky-box" model), taking into account solar modulation during penetration of the heliosphere. Overall, except for ^{54}Fe/^{56}Fe and ^{57}Fe/^{56}Fe, we show that the principal Fe and Ni isotopic source ratios have values close to the solar system ratios derived from meteorites. In particular, we note that ^{58}Fe and ^{62}Ni display no evidence of neutron enrichment. We discuss the role of the predominantly electron-capture nuclide ^{54}Mn, which decays mainly by β^- in the cosmic rays, and contributes to the abundance of ^{54}Fe measured in the solar system.

Subject headings: cosmic rays — methods: observational — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

In the search for the origin of the Galactic cosmic rays, one of the principal goals is to determine the elemental and isotopic composition of the nuclei at their sources. For example, is their composition a sample of the interstellar medium, or of explosive nucleosynthesis? It is now established that the cosmic-ray source elemental composition displays a bias that can be correlated with atomic properties—for example, elemental first-ionization potential (Meyer 1985). Thus, the fundamental approach that avoids compositional biases is the measurement of cosmic-ray isotopic composition, which is determined by the nucleosynthetic history of the cosmic-ray source (e.g., Simpson 1983; Mewaldt 1989). Among the critical tests for the origin of the source matter are the source abundances of Fe and Ni isotopes. We report here the measurements of ^{54}Fe, ^{55}Fe, ^{56}Fe, ^{57}Fe, ^{58}Fe and ^{58}Ni, ^{59}Ni, ^{60}Ni, ^{62}Ni, and—by using models for their interstellar and heliospheric propagation—the determination of their source composition. A preliminary report on our results with fewer data has appeared recently (Connell & Simpson 1995). Previous reports include Leske (1993) and Lukasiak et al. (1995).

2. MEASUREMENTS

The measurements in the overall energy range ~30 to ~500 MeV nucleon^{-1} are obtained from the University of Chicago's High Energy Telescope (HET) (Simpson et al. 1992), carried on the *Ulysses* spacecraft, whose trajectory and general mission objectives have been described elsewhere (Wenzel et al. 1992). The data are based on the period from the *Ulysses* launch in 1990 October through the end of 1995.

The high mass resolution measurements reported here were made possible by our technology of position-sensitive, semiconductor detector arrays used to determine the trajectories of the cosmic rays within the HET. For isotopic measurements, the HET has a geometrical acceptance factor of ~4 to ~8 cm^2 sr depending on energy, as described in Simpson et al. (1992). The HET (see Fig. 1) consists of two sets of three position-sensing Si detectors (PSDs) of 1100 μm thickness arranged to determine the trajectory of incident particles. Six 5000 μm Si detectors (labeled K's) provide mass and charge determination by the multiple dE/dx versus residual energy method, used in this work for events stopping in the second through sixth K (K2–K6). A Si detector (A) identifies penetrating events, while a scintillator shield (S) identifies side penetrating events.

Numerous instrumental corrections were derived from the flight data. The PSDs are positioned in sets of three rotated at 60° for redundancy. A set of corrections for each PSD, including its rotational position to within ~0°.02, was obtained using trajectories derived from the other five. Corrections for the slight cants of each K detector relative to the axis of the telescope (less than 1°) were determined. A temperature correction of ~138 ppm °C^{-1} for the K detectors was found. This is dominated by the temperature response of the Si in the detectors. Consistency requirements were made on the energy loss in the PSDs (2.5 σ cut for each charge) and in the mass determinations in the K detectors (2.0 σ cut). There is no cut on the angle of incidence (acceptance angle) of the events. A full description of the HET isotopic analysis will be found in Connell et al. (1997).

Figure 2 shows mass histograms for Fe and Ni. The histograms contain a total of 6035 Fe and 284 Ni events. Gaussian peaks were fitted to the histograms using the maximum likelihood method. The peak positions for ^{56}Fe and ^{58}Ni were free, but the other peak positions were determined by fitting a single center-to-center spacing parameter for each element. A single fractional σ was fitted. A flat background was also fitted, giving 1.04 and 0.09 events per bin for Fe and Ni, respectively. Mass resolution varies from 0.277 ± 0.004 amu for ^{56}Fe to 0.291 ± 0.017 amu for ^{58}Ni. The actual distribution of the data is known to have a low-mass tail, probably due to neutron-changing nuclear interactions within the HET and events stopping in the dead layers of the K detectors. This is under

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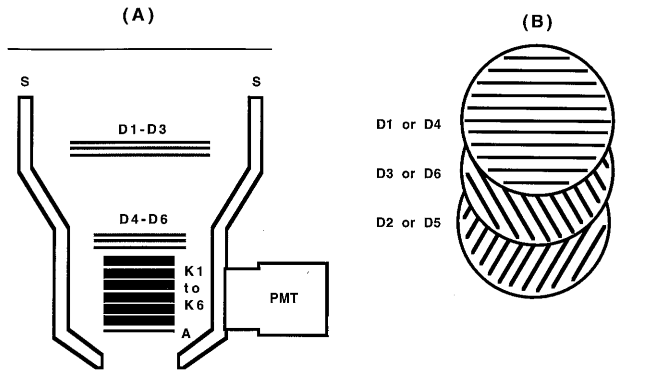

FIG. 1.—(*a*) Cross section view of the *Ulysses* High Energy Telescope (HET) detector elements consisting of six position-sensing silicon detectors, D1–D6, six 5000 μm Si detectors (K1–K6), the Si particle penetration detector (A), and the scintillator shield (S). (*b*) Isometric view of D1–D3 with 222 strips for each detector, or D4–D6 with 143 strips for each detector, oriented 60° in groups of three for redundancy (from Simpson et al. 1992).

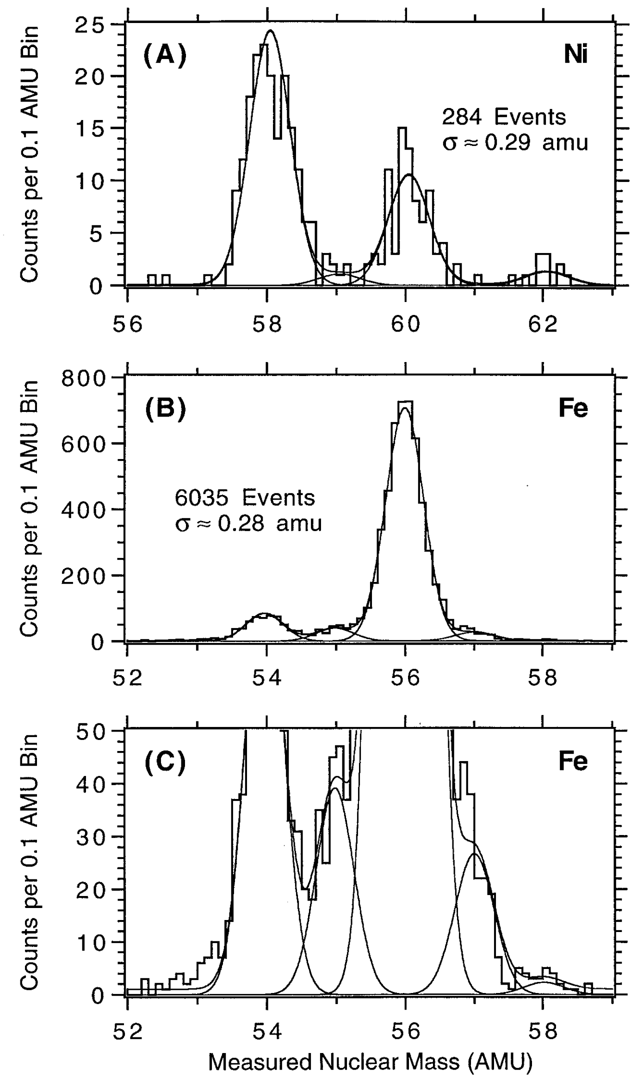

FIG. 2.—Mass histograms of *Ulysses* HET Fe and Ni isotopes. The smooth curves are maximum likelihood fits to the data set. Shown in (*a*) are 279 Ni events with a mass resolution of ~0.29 amu; (*b*) shows 6028 Fe events with a resolution of ~0.28 amu; (*c*) shows the Fe data in (*b*) on an expanded vertical scale to show details of the less abundant isotopes.

study and has not been included in the fits (see details in Connell et al. 1997).

It is possible to improve the mass resolution slightly, to ~0.27 amu at ^{56}Fe, by requiring the trajectory of each particle, when projected beyond the apparent stopping detector, end its range in an active detector region. This eliminates events stopping in the detector support structure, but also cuts perfectly valid events. The slight improvement in resolution does not justify the reduction in the total number of events (~7%). This cut does not influence the relative abundances.

Table 1 lists in column (2) the principal measured isotopic ratios for Fe and Ni. The average energies were 290 MeV nucleon^{-1} for Fe and 309 MeV nucleon^{-1} for Ni. The measured ratios were corrected for energy intervals (less than 1.5% correction) under the valid assumption that the spectra for all these species were the same. The stated uncertainties reflect the propagated uncertainties in the fits to the data and do not include uncertainties in the propagation calculation.

3. SOURCE ABUNDANCES

The cosmic rays propagate from their sources in the Galaxy to the observer via the interstellar medium and the heliosphere. For the propagation of the Fe and Ni isotopes we used a weighted-slab model of interstellar propagation (e.g., Garcia-Munoz et al. 1987) using a single exponential path-length distribution ("leaky-box" model) in which the nuclei are mainly confined to the Galaxy. The maximum of the energy-dependent average path length is ~9.2 g cm^{-2}. This propagation model satisfied the observed B/C and sub-Fe/Fe element ratios, as shown by DuVernois, Simpson, & Thayer (1995, 1996b), and employs the most recent nuclear cross sections and estimates of interstellar ionization losses (e.g., Thayer 1995), including ionized H II. We note that Fe is a factor of more than 10^3, and Ni more than a factor of 10, more abundant than the elements beyond Ni. This ensures that, aside from ^{56}Fe spallating into ^{54}Fe and ^{55}Fe, secondary nuclear species produced during interstellar propagation are not major contributors to the observed Fe and Ni isotopes.

The source calculations also employed a spherically symmetric model of the heliosphere for solar modulation. This assumption is justified by the fact that, simultaneously, *Ulysses* found that the latitude dependence accounted for an increase in the flux by less than 50% from 0° to 80° and—throughout the period of measurements—that the spectral shape of the cosmic rays reflected the effects of solar modulation, including adiabatic deceleration (Simpson et al. 1995). During the measurement period, the flux of Galactic cosmic rays increased from the lowest level ever recorded by neutron monitors in 1991 to within ~10%–20% of previous levels of solar minima. An event-weighted average modulation parameter of $\phi = 840$ MV was used. In a recent study DuVernois et al. (1996a) analyzed the effect of this large-scale change in modulation on the measured fluxes of the isotopes of the elements from C to Si. An extrapolation of their analysis to Fe and Ni shows that the effect of changing modulation is not significant for the measurements we report here.

The cosmic-ray source abundance ratios derived from these calculations are listed in column (3) of Table 1. The current accepted values for the corresponding solar system isotopic abundance ratios are shown in column (4). Based on the

TABLE 1

Ulysses HET ISOTOPIC ABUNDANCE RATIOS

Isotopic Ratio (1)	Measured (%) (2)	Source (%) (3)	Solar[a] (%) (4)	GCRS/SS Ratio (5)
$^{54}Fe/^{56}Fe$	11.4 ± 0.6	9.3 ± 0.6	6.3	1.5 ± 0.1
$^{55}Fe/^{56}Fe$	5.4 ± 0.4	1.6 ± 0.5	0	...
$^{57}Fe/^{56}Fe$	$3.9^{+0.35}_{-0.38}$	$3.7^{+0.33}_{-0.36}$	2.3	$1.6^{+0.14}_{-0.16}$
$^{58}Fe/^{56}Fe$	$0.34^{+0.10}_{-0.14}$	$0.18^{+0.10}_{-0.14}$	0.32	$0.6^{+0.3}_{-0.4}$
$^{59}Ni/^{58}Ni$	$4.6^{+2.6}_{-2.1}$	$2.6^{+2.1}_{-1.7}$	0	...
$^{60}Ni/^{58}Ni$	$45.0^{+6.8}_{-6.5}$	$43.2^{+6.7}_{-6.4}$	38.2	1.1 ± 0.2
$^{61}Ni/^{58}Ni$	<1.6	<1.2	1.7	<0.7
$^{62}Ni/^{58}Ni$	$5.8^{+2.3}_{-1.9}$	$5.4^{+2.2}_{-1.8}$	5.3	$1.0^{+0.4}_{-0.3}$

[a] Anders & Grevesse 1989; Cameron 1982.

reviews by Anders & Grevesse (1989) and Cameron (1982), we conclude that, for the Fe and Ni, the solar system ratios, derived mainly from meteorites, probably have fractional errors of the order of less than 2%, far smaller than the statistical uncertainties in our Galactic source determination.

4. DISCUSSION

The principal isotopic ratio $^{60}Ni/^{58}Ni$ clearly shows no significant neutron-rich enhancement that would be predicted by nucleosynthesis models requiring neutron enrichment in Ni (e.g., Arnett 1996) but is close to its solar system value. The upper limit on the $^{61}Ni/^{58}Ni$ ratio appears to be inconclusive, or perhaps too low, for source models enriched by Wolf-Rayet nucleosynthesis products (e.g., Prantzos, Arnould, & Arcoragi 1987). The $^{59}Ni/^{58}Ni$ source ratio, where ^{59}Ni is an electron-capture nucleus ($\tau_{1/2} = 7.6 \times 10^4$ yr), is 1.5 σ from zero, which does not rule out a source component of ^{59}Ni. The absence of ^{59}Ni in the cosmic-ray source would indicate a significant time delay between ^{59}Ni synthesis and cosmic-ray acceleration. Since contributions to ^{62}Ni from spallation of the rare, heavier nuclei are negligible, the principal error in the $^{62}Ni/^{58}Ni$ ratio in Table 1 is the low statistical weight. However, this $^{62}Ni/^{58}Ni$ source ratio is close to its solar system value and inconsistent with nucleosynthesis models requiring a substantial neutron enhancement of ^{62}Ni.

Beyond ^{62}Ni (not shown in Fig. 2*a*) are two events near the position of ^{64}Ni. That would be consistent with the solar system ratio of 0.9% of $^{64}Ni/Ni$.

The cosmic-ray source ratio $^{54}Fe/^{56}Fe$ is approximately 50% higher than the solar system ratio. Part of the excess ^{54}Fe may be the result of our propagation model slightly underestimating the production of secondary nuclides from ^{56}Fe; the 3 σ source abundance of ^{55}Fe indicated in Table 1 would support this conclusion. ^{55}Fe, which does not exist in the solar system, is a short-lived electron-capture nuclide ($\tau_{1/2} = 2.68$ yr) that would not be present in the cosmic-ray source if there were a significant time delay between nucleosynthesis and particle acceleration. If the secondary production in our model were increased to eliminate the source abundance of ^{55}Fe shown in Table 1, the Galactic cosmic-ray source to solar system ratio (GCRS/SS) of $^{54}Fe/^{56}Fe$ would only be reduced to $\sim 1.3 \pm 0.1$.

^{54}Mn is also a secondary product of ^{56}Fe spallation. As pointed out by Grove et al. (1991), ^{54}Mn decays via electron capture and β^+ to ^{54}Cr, and by β^- to ^{54}Fe. While normally the electron-capture channel dominates ($\tau_{1/2} = 312$ days), for cosmic rays (which are full stripped) the β^- channel to ^{54}Fe is believed to dominate. There is no laboratory measurement of the non–electron-capture decay lifetime of ^{54}Mn. The HET has excellent mass resolution at Mn, and clear peaks for ^{53}Mn, ^{54}Mn, and ^{55}Mn are observed. From these *Ulysses* data, DuVernois (1996) in our laboratory has restricted the partial lifetime of ^{54}Mn to between 1 and 2 Myr to be consistent with the observed ^{10}Be and ^{26}Al abundances, assuming the same Galactic propagation history for Fe group cosmic rays. In Table 2 we show that this range of lifetime does not appreciably change the $^{54}Fe/^{56}Fe$ ratio—thus only a small part of the $^{54}Fe/^{56}Fe$ excess appears to arise from spallation of ^{56}Fe and ^{54}Mn decay by β^-.

TABLE 2

$^{54}Fe/^{56}Fe$ RATIO DEPENDENCE ON ^{54}Mn LIFETIME

^{54}Mn $\tau_{1/2}$(yr)	Measured (%)	Source (%)	Solar (%)	GCRS/SS Ratio
10^5	...	8.0 ± 0.6	...	1.3 ± 0.1
2×10^6.........	11.4 ± 0.6	9.3 ± 0.6	6.3	1.5 ± 0.1
10^7	...	10.4 ± 0.6	...	1.6 ± 0.1

None of the above arguments, however, apply to ^{57}Fe where there is no significant secondary contribution but our source ratio of $^{57}Fe/^{56}Fe$ is significantly enhanced. We note that observations of SN 1987A have been interpreted as indicating a ratio of ^{57}Ni to ^{56}Ni (which decay to ^{57}Fe and ^{56}Fe, respectively) of ~ 2 times solar, which is also consistent with some models of Type II supernova nucleosynthesis (Clayton et al. 1992 and references therein).

5. CONCLUSIONS

We know of no propagation models, including reacceleration models, wherein source abundances could be assumed to be enhanced significantly with heavier isotopes of Fe and Ni, but, after propagation, could be reduced to our observed abundance ratios of $^{58}Fe/^{56}Fe$, $^{60}Ni/^{58}Ni$, or $^{62}Ni/^{58}Ni$. From the principal source isotopic ratios of Fe and Ni isotopes in Table 1 we conclude that—with the exception of $^{54}Fe/^{56}Fe$ and $^{57}Fe/^{56}Fe$—their source matter is close to solar system values.

Except for a few isotopic anomalies, such as Ne, the trend in recent investigations from C to Si is toward isotopic abundance ratios that are close to solar system values (e.g., Webber et al. 1996; DuVernois et al. 1995; Connell & Simpson 1993a, 1993b; but see also Wiedenbeck & Greiner 1981a, 1981b) which do not support supermetallicity models (Woosley & Weaver 1981). Thayer (1996), in our laboratory, has shown from *Ulysses* HET measurements that the source ratio of $^{34}S/^{32}S$ also is not enhanced significantly above its solar system ratios.

For Type I supernovae (helium-burning white dwarfs) Thielemann et al. (1995) find that the Fe group nuclides do not have a composition close to solar: ^{57}Fe, ^{58}Ni, and ^{62}Ni are overproduced by more than a factor of 2.

Recently, Woosley & Weaver (1995) have investigated the evolution of Type II supernovae and point out that at present it is impossible to predict with accuracy the abundances of certain isotopes whose production is sensitive to the still controversial explosion mechanism. Current developments in the experimental determination of the cross sections of short-lived radioisotopes will undoubtedly change the relative production abundances in future model calculations of explosive nucleosynthesis.

Since the interstellar medium isotopic composition appears from present investigations to be more solar system–like than the composition from explosive nucleosynthesis (e.g., Arnett 1996), present evidence suggests that cosmic-ray particle acceleration occurs mainly in the interstellar medium.

The isotopic abundance ratios, especially for Fe and Ni in the solar system, are derived from meteorites and are believed to be measurements of the primordial solar system isotopic abundances some ~4.6 Gyr ago (Anders & Grevesse 1989; Cameron 1982). On the other hand, since the source composition we report here for cosmic-ray matter is modern (i.e., $\sim 10^7$ years old), this work suggests that the Galactic sources for cosmic rays—at least for Fe and Ni—have not changed dramatically despite over 4.6 Gyr of Galactic chemical evolution.

Note added in manuscript.—In a recent Letter ("The Isotopic Composition of Iron in the Solar Wind: First Measurements with the MASS Sensor on the *Wind* Spacecraft"), Oetlicker et al. (1997) point out that their values for ^{54}Fe/^{56}Fe and ^{57}Fe/^{56}Fe are in agreement with our Galactic cosmic-ray source composition. The high value of ^{54}Fe/^{56}Fe (35%–50% above "solar system") may raise new questions concerning the nucleosynthesis of Fe.

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