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Final Technical Report for NASA Grant NAG 5-308 "Cosmic Ray Composition Investigations using ICE/ISEE-3"

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The subject grant has, over the period 1983–1992, supported the analysis of data from the high energy cosmic experiment on ISEE-3 and associated modeling and interpretation activities.

The instrument used for these studies was developed at the University of California Berkeley and the Lawrence Berkeley Laboratory under the direction of Dr. Douglas Greiner and Dr. Harry Heckman. During the period from the launch of ISEE-3 (August 1978) to 1982 data analysis activities were carried out at Berkeley by Dr. Greiner, Dr. Mark Wiedenbeck, and associates. In 1983 Dr. Wiedenbeck joined the faculty of the University of Chicago and responsibility for the ongoing analysis of data from the Berkeley experiment was transferred to Chicago under his direction. NASA grant NAG 5-308 was established at Chicago to support this work.

The ISEE-3 payload included two instruments (the Berkeley instrument and a similar instrument developed independently by the California Institute of Technology) capable of measuring the composition of heavy cosmic rays. The designs of these two instruments incorporated innovations which made it possible, for the first time, to measure *isotopic* as well as the chemical composition for a wide range of elements. These innovations included: 1) the use of a trajectory measuring sensor to allow corrections for particle incidence angles, 2) the development of silicon solid state detectors having a very high degree of thickness uniformity and very thin dead layers, and 3) the development of very stable pulse height analysis circuitry capable of maintaining its calibration to ~ 0.1% over periods of years.

As the result of the demonstration by these two instruments of the capability to resolve individual cosmic ray isotopes, a new generation of detectors has been developed using with very similar designs, but having improved reliability and increased sensitive area. Such instruments have recently been launched on CRRES, Ulysses, SAMPEX, and Geotail, and another is scheduled for launch on Wind. Still larger instruments of this same kind are a key element of the Advanced Composition Explorer mission which is now in its definition phase, with launch scheduled for 1997.

In the Berkeley instrument the mass resolution was found to be limited by the accuracy of the trajectory measurement for all but the lightest elements. In this instrument the trajectory measurements were made using a set of six drift chambers housed in a single gas-filled pressure vessel. In April 1991 these drift chambers suffered a catastrophic loss of gas, eliminating trajectory measurements and with it the possibility of resolving isotopes of elements heavier than helium. Analysis efforts have focused almost exclusively on the data set accumulated during the time the drift chambers were functioning, from August 1978 to April 1991.

The mass resolution of this type of detector system varies greatly with the mass of the nuclei being studied, primarily because the mass difference between adjacent isotopes becomes a smaller fraction of the mass as one goes to heavier nuclei. Because of the

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resolution limitations of the trajectory system it was found that for elements heavier than boron ($Z = 5$) it was not possible to resolve all isotopes if the entire data set was used. Therefore techniques were developed for selecting subsets of the data having improved resolution at the expense of poorer statistics. Thus it was possible to tailor the trade off between resolution and statistics to the needs of each particular study. The most useful cut was based on the particle's angle of incidence θ (measured from the detector normal): the contribution of the trajectory measurement to the mass resolution scales as $\sin 2\theta$ so significant improvements in resolution can be achieved by restricting consideration to particles with small values of θ.

Another important requirement for studies involving measurement of the abundances of rarer nuclides is efficient rejection of background events. It was found that a major source of background was due to particles which entered or exited from the side of the instrument, depositing less than their full energy in the solid state detectors but not penetrating the surrounding plastic scintillator anticoincidence detector. Another background source is due to particles which undergo a nuclear reaction in the detector stack changing the identity of the particle and affecting subsequent energy losses. It was found that backgrounds of these kinds could be rejected with very high efficiency by demanding consistency among all of the measured signals. In principle it only requires measurements of a single energy loss rate, the total energy, and two coordinate pairs (for trajectory) to determine a particle's charge, mass, and energy. However, in the ISEE-3 instrument individual pulse heights are measured from each of the silicon detectors the particle enters (up to 10), and three coordinate pairs are obtained from the trajectory system. These were used to demand that the trajectory coordinates be consistent with a straight line (to within the accuracy of the measurements) and that all energy losses be consistent with those expected from the slowing of a single particle with no change in charge or mass in the instrument.

Table 1 through 3 summarize the composition measurements which were obtained from the ISEE-3 experiment. Table 1 lists elemental abundance measurements, Table 2 lists isotope fractions, and Table 3 lists selected isotope ratios. In each case these measurements refer to abundances in interplanetary space in the vicinity of the Earth during the period August 1978 to April 1981. The approximate energies of the measurements are shown in Figure 1. The abundance ratios shown in the tables are the most up-to-date values from the ISEE-3 experiment. In some cases earlier preliminary results were published based on poorer statistics or less refined analysis techniques. Differences between those preliminary values and those listed here are typically within the quoted uncertainties.

These data have been used to investigate a variety of astrophysical problems. Chief among these are: 1) the composition of cosmic ray source material, and its relationship to the nature of the sources and the information they may provide on chemical evolution effects in the Galaxy; 2) the confinement time of cosmic rays in the Galaxy as determined from the surviving fractions of radioactive nuclides produced by nuclear fragmentation reactions during propagation; 3) the time between nucleosynthesis and acceleration of the cosmic ray source material as determined from abundances of primary nuclei which can only decay by electron capture and become stable upon acceleration; 4) matter traversal in the Galaxy by cosmic rays over a wide range of atomic numbers and a wide range of energies, and its bearing on questions of cosmic ray transport; and 5) fractionation of the cosmic ray source material prior to acceleration, as studied using individual isotopes with significant primary content rather than sums over all the isotopes of an element.

The attached bibliography lists the publications which have resulted from the work supported by this grant. It also shows those ISEE-3 paper which were published under the sponsorship of the predecessor to this grant, contract NAS5-20995 at the University of California, Berkeley.

Table 1

Elemental Abundance Ratios Measured with the
High Energy Cosmic Ray Experiment on ISEE-3

Ratio	Measured Value	Ref.
B/C	0.261 ±0.009	*a*
C/O	0.976 ±0.034	*a*
N/O	0.251 ±0.006	*a*
F/Si	0.118 ±0.010	*b*
Ne/Si	0.982 ±0.051	*b*
Na/Si	0.189 ±0.011	*b*
Mg/Si	1.330 ±0.040	*b*
Al/Si	0.211 ±0.009	*b*
P/Si	0.037 ±0.003	*b*
S/Si	0.176 ±0.008	*b*
Cl/Si	0.036 ±0.003	*b*
Ar/Si	0.073 ±0.005	*b*
K/Si	0.064 ±0.005	*b*
Ca/Si	0.154 ±0.009	*b*
Fe/Si	0.719 ±0.054	*b*
Sc/Fe	0.0487 (+0.0044, −0.0037)	*c*
Ti/Fe	0.1630 (+0.0084, −0.0077)	*c*
V/Fe	0.0787 (+0.0053, −0.0047)	*c*
Cr/Fe	0.1527 (+0.0074, −0.0067)	*c*
Mn/Fe	0.0938 (+0.0056, −0.0050)	*c*
Co/Fe	0.0085 (+0.0018, −0.0013)	*c*
Co/Fe	0.0085 (+0.0018, −0.0013)	*c*
Ni/Fe	0.0482 (+0.0039, −0.0033)	*c*
Cu/Fe	< 0.00083	*c*
Zn/Fe	0.00074 (+0.00072, −0.00022)	*c*

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a "The Isotopic Composition of Cosmic Ray Boron and Nitrogen", K. E. Krombel and M. E. Wiedenbeck, *Ap. J.*, **328**, 940 (1988).

b "Composition Measurements from ISEE-3: Fluorine through Calcium", R. A. Leske and M. E. Wiedenbeck, *Proc. 23rd Internat. Cosmic Ray Conf.* (Calgary), submitted 1993.

c "The Elemental and Isotopic Composition of Galactic Cosmic-Ray Nuclei from Scandium through Nickel", R. A. Leske, *Ap. J.*, **405**, 567 (1993).

Table 2
Isotopic Fractions Measured with the
High Energy Cosmic Ray Experiment on ISEE-3

Ratio	Measured Value	Ref.
^{7}Be/Be	0.546 ±0.029	*a*
^{9}Be/Be	0.390 ±0.029	*a*
^{10}Be/Be	0.064 ±0.015	*a*
^{10}B/B	0.283 (+0.011, −0.008)	*b*
^{11}B/B	0.717 (+0.008, −0.011)	*b*
^{14}N/N	0.447 (+0.011, −0.010)	*b*
^{15}N/N	0.553 (+0.010, −0.011)	*b*
^{32}S/S	0.65 ±0.04	*c*
^{33}S/S	0.13 ±0.03	*c*
^{34}S/S	0.21 ±0.03	*c*
^{36}S/S	< 0.02	*c*
^{35}Cl/Cl	0.60 ±0.07	*c*
^{36}Cl/Cl	0.13 ±0.07	*c*
^{37}Cl/Cl	0.27 ±0.07	*c*
^{36}Ar/Ar	0.36 ±0.06	*c*
^{37}Ar/Ar	0.23 ±0.06	*c*
^{38}Ar/Ar	0.37 ±0.06	*c*
^{40}Ar/Ar	0.034 (+0.024, −0.017)	*c*
^{39}K/K	0.48 ±0.06	*c*
^{40}K/K	0.25 ±0.07	*c*
^{41}K/K	0.27 ±0.06	*c*
^{40}Ca/Ca	0.27 ±0.04	*c*
^{41}Ca/Ca	0.12 ±0.03	*c*
^{42}Ca/Ca	0.14 ±0.03	*c*
^{43}Ca/Ca	0.23 ±0.04	*c*
^{44}Ca/Ca	0.24 ±0.04	*c*
^{46}Ca/Ca	< 0.012	*c*

Ratio	Measured Value	Ref.
^{44}Ti/Ti	0.015 (+0.013, −0.008)	*d*
^{46}Ti/Ti	0.240 (+0.040, −0.039)	*d*
^{47}Ti/Ti	0.273 (+0.054, −0.057)	*d*
^{48}Ti/Ti	0.376 (+0.061, −0.054)	*d*
^{49}Ti/Ti	< 0.066	*d*
^{50}Ti/Ti	0.063 (+0.026, −0.021)	*d*
^{49}V/V	0.391 (+0.074, −0.073)	*d*
^{50}V/V	0.359 (+0.092, −0.088)	*d*
^{51}V/V	0.250 (+0.073, −0.066)	*d*
^{50}Cr/Cr	0.206 (+0.053, −0.042)	*d*
^{51}Cr/Cr	0.218 (+0.057, −0.056)	*d*
^{52}Cr/Cr	0.458 ±0.055	*d*
^{53}Cr/Cr	0.089 (+0.040, −0.036)	*d*
^{54}Cr/Cr	< 0.052	*d*
^{53}Mn/Mn	0.421 ±0.057	*d*
^{54}Mn/Mn	< 0.095	*d*
^{55}Mn/Mn	0.538 (+0.058, −0.059)	*d*
^{54}Fe/Fe	0.069 (+0.013, −0.012)	*d*
^{55}Fe/Fe	< 0.063	*d*
^{56}Fe/Fe	0.815 (+0.024, −0.025)	*d*
^{57}Fe/Fe	< 0.071	*d*
^{58}Fe/Fe	< 0.029	*d*
^{57}Co/Co	0.32 (+0.25, −0.14)	*d*
^{59}Co/Co	0.68 (+0.14, −0.26)	*d*
^{58}Ni/Ni	0.408 (+0.095, −0.092)	*d*
^{59}Ni/Ni	< 0.20	*d*
^{60}Ni/Ni	0.447 (+0.118, −0.115)	*d*
^{61}Ni/Ni	< 0.073	*d*
^{62}Ni/Ni	< 0.10	*d*

References

a "A Cosmic-Ray Age Based on the Abundance of ^{10}Be", M. E. Wiedenbeck and D. E. Greiner, *Ap. J. (Letters)*, **239**, L139 (1980).

b "The Isotopic Composition of Cosmic Ray Boron and Nitrogen", K. E. Krombel and M. E. Wiedenbeck, *Ap. J.*, **328**, 940 (1988).

c "Composition Measurements from ISEE-3: Fluorine through Calcium", R. A. Leske and M. E. Wiedenbeck, *Proc. 23rd Internat. Cosmic Ray Conf.* (Calgary), submitted 1993.

d "The Elemental and Isotopic Composition of Galactic Cosmic-Ray Nuclei from Scandium through Nickel", R. A. Leske, *Ap. J.*, **405**, 567 (1993).

Table 3
Isotopic Abundance Ratios Measured with the High Energy Cosmic Ray Experiment on ISEE-3

Ratio	Measured Value	Ref.
$^{13}\mathrm{C}/^{12}\mathrm{C}$	0.070 ± 0.006	*a*
$^{17}\mathrm{O}/^{16}\mathrm{O}$	0.019 (+0.004, −0.003)	*b*
$^{18}\mathrm{O}/^{16}\mathrm{O}$	0.019 ± 0.002	*b*
$^{21}\mathrm{Ne}/^{20}\mathrm{Ne}$	0.25 (+0.05, −0.04)	*b*
$^{22}\mathrm{Ne}/^{20}\mathrm{Ne}$	0.67 (+0.10, −0.07)	*b*
$^{25}\mathrm{Mg}/^{24}\mathrm{Mg}$	0.28 (+0.04, −0.03)	*b*
$^{26}\mathrm{Mg}/^{24}\mathrm{Mg}$	0.30 (+0.04, −0.03)	*b*
$^{26}\mathrm{Al}/^{27}\mathrm{Al}$	0.036 (+0.037, −0.022)	*c*
$^{29}\mathrm{Si}/^{28}\mathrm{Si}$	0.109 (+0.024, −0.014)	*a*
$^{30}\mathrm{Si}/^{28}\mathrm{Si}$	0.084 (+0.020, −0.014)	*a*
$^{44}\mathrm{Ti}/^{48}\mathrm{Ti}$	0.041 (+0.036, −0.023)	*d*
$^{46}\mathrm{Ti}/^{48}\mathrm{Ti}$	0.64 (+0.17, −0.16)	*d*
$^{47}\mathrm{Ti}/^{48}\mathrm{Ti}$	0.73 (+0.26, −0.23)	*d*
$^{49}\mathrm{Ti}/^{48}\mathrm{Ti}$	< 0.19	*d*
$^{50}\mathrm{Ti}/^{48}\mathrm{Ti}$	0.168 (+0.076, −0.059)	*d*
$^{49}\mathrm{V}/^{50}\mathrm{V}$	1.09 (+0.48, −0.34)	*d*
$^{51}\mathrm{V}/^{50}\mathrm{V}$	0.70 (+0.42, −0.27)	*d*
$^{50}\mathrm{Cr}/^{52}\mathrm{Cr}$	0.45 (+0.14, −0.11)	*d*
$^{51}\mathrm{Cr}/^{52}\mathrm{Cr}$	0.48 (+0.18, −0.15)	*d*
$^{53}\mathrm{Cr}/^{52}\mathrm{Cr}$	0.194 (+0.108, −0.084)	*d*
$^{54}\mathrm{Cr}/^{52}\mathrm{Cr}$	< 0.12	*d*
$^{54}\mathrm{Mn}/^{53}\mathrm{Mn}$	< 0.25	*d*
$^{55}\mathrm{Mn}/^{53}\mathrm{Mn}$	1.28 (+0.32, −0.25)	*d*
$^{54}\mathrm{Fe}/^{56}\mathrm{Fe}$	0.084 (+0.017, −0.015)	*d*
$^{55}\mathrm{Fe}/^{56}\mathrm{Fe}$	< 0.078	*d*
$^{57}\mathrm{Fe}/^{56}\mathrm{Fe}$	< 0.089	*d*
$^{58}\mathrm{Fe}/^{56}\mathrm{Fe}$	< 0.036	*d*
$^{59}\mathrm{Co}/^{57}\mathrm{Co}$	2.2 (+2.1, −1.4)	*d*
$^{59}\mathrm{Ni}/^{58}\mathrm{Ni}$	< 0.58	*d*
$^{60}\mathrm{Ni}/^{58}\mathrm{Ni}$	1.10 (+0.50, −0.35)	*d*
$^{61}\mathrm{Ni}/^{58}\mathrm{Ni}$	< 0.19	*d*
$^{62}\mathrm{Ni}/^{58}\mathrm{Ni}$	< 0.28	*d*

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a "High Resolution Observations of the Isotopic Composition of Carbon and Silicon in the Galactic Cosmic Rays", M. E. Wiedenbeck and D. E. Greiner, *Ap. J. (Letters)*, **247**, L119 (1981).

b "Isotopic Anomalies in the Galactic Cosmic-Ray Source", M. E. Wiedenbeck and D. E. Greiner, *Phys. Rev. Letters*, **46**, 682 (1981).

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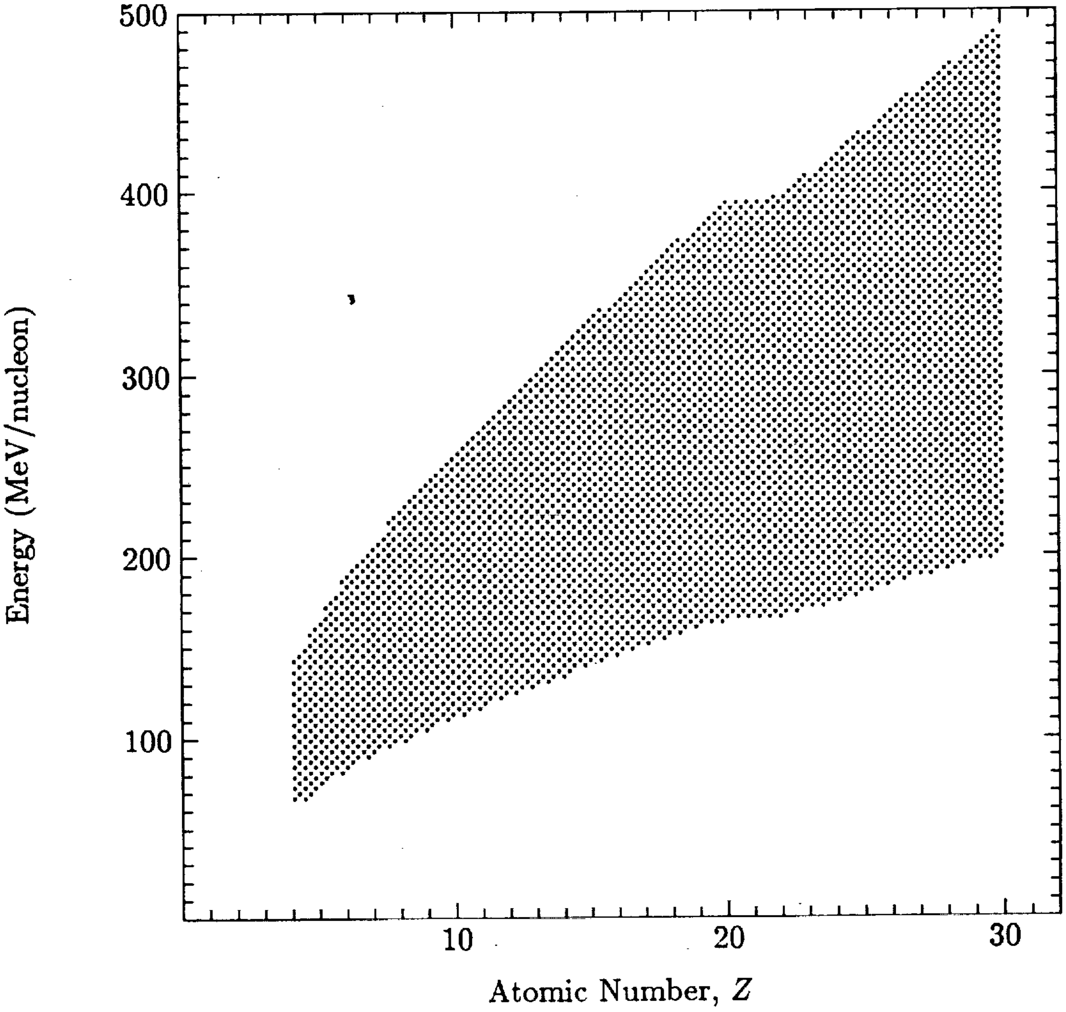

Figure 1
Shaded area shows the approximate energy intervals used for composition measurements as a function of the atomic number of the measured element.

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2. "The Isotopic Composition of Neon in the Galactic Cosmic Rays—A High Resolution Measurement", D. E. Greiner, M. E. Wiedenbeck, F. S. Bieser, H. J. Crawford, H. H. Heckman, and P. J. Lindstrom, *Proc. 16th Internat. Cosmic Ray Conf.* (Kyoto), **1**, 418 (1979).

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5. "A Study of Galactic Cosmic Ray Propagation Models Based on the Isotopic Composition of the Elements Lithium, Beryllium and Boron", G. F. Hinshaw, M. E. Wiedenbeck, and D. E. Greiner, *Proc. 17th Internat. Cosmic Ray Conf.* (Paris), **9**, 191 (1981).

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8. "Samples of the Milky Way", R. A. Mewaldt, E. C. Stone, and M. E. Wiedenbeck, *Scientific American*, **247**, 100 (1982).

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10. "The Effect of Cross-Section Uncertainties on the Derivation of Source Abundances from Cosmic-Ray Composition Observations", M. E.Wiedenbeck, in *Composition and Origin of Cosmic Rays*, (M. M. Shapiro, ed.), D. Reidel Publ. Co., Dordrecht, Holland (1983), p. 343.

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17. "Nitrogen Isotopes in Cosmic Ray Source Material", K. E. Krombel and M. E Wiedenbeck, *Proc. 20th Internat. Cosmic Ray Conf.* (Moscow), **1**, 360 (1987).

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