NASA-CR-192357

GRANT
IN-90-CR
150574
P.14

CALIFORNIA INSTITUTE OF TECHNOLOGY
DIVISION OF PHYSICS, MATHEMATICS, AND ASTRONOMY
SPACE RADIATION LABORATORY
PASADENA, CALIFORNIA 91125

FINAL REPORT

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

RESEARCH RELATIVE TO THE HEAVY ISOTOPE SPECTROMETER TELESCOPE EXPERIMENT

NASA Grant NAG5-722

1 December 1985 - 30 November 1992

Submitted by:

Edward C. Stone
Professor of Physics

Richard A. Mewaldt
Senior Research Associate in Physics

March 12, 1993

(NASA-CR-192357) RESEARCH RELATIVE TO THE HEAVY ISOTOPE SPECTROMETER TELESCOPE EXPERIMENT Final Report, 1 Dec. 1985 - 30 Nov. 1992 (California Inst. of Tech.) 14 p

N93-21196

Unclas

G3/90 0150574

Final Report

on the

Caltech Heavy Isotope Spectrometer Telescope on ISEE-3/ICE

(NASA Grant NAG5-722)

1 December 1985 to 11 November 1992

1. Overview

The Heavy Isotope Spectrometer Telescope (HIST) was launched during August 1978 on ISEE-3 (ICE). HIST was designed to measure the isotopic composition of solar, galactic, and interplanetary cosmic ray nuclei for the elements from H to Ni ($1 \leq Z \leq 28$) in the energy range from ~5 to ~200 MeV/nucleon. The results of these measurements have been used in studies of the composition of solar matter and galactic cosmic ray sources, the study of nucleosynthesis processes, studies of particle acceleration and propagation, and studies of the life-history of cosmic rays in the heliosphere and in the galaxy.

On December 1, 1978, after 110 days in orbit, HIST suffered an electronic failure in its readout system. After that point, only one-half of the telemetry bits associated with the pulse heights measured by HIST were transmitted to Earth. As a result the resolution of HIST was significantly degraded, and it served as an element rather than an isotope spectrometer. Fortunately, HIST was able to measure the isotopic composition of heavy nuclei in the 9/23/78 solar event (the largest solar energetic particle event since 1972) during the brief period that it operated at full resolution.

This grant funded the analysis of data from the HIST instrument over the period from 12/1/85 to 11/30/92. In Section 2 of this final report we summarize the scientific accomplishments that have resulted from HIST measurements during this time period. A bibliography of talks and papers that resulted is attached.

2. Scientific Results

The Isotopic Composition of Solar Flare Nuclei - Although the Sun is the major reservoir of solar system material, most of our present knowledge of the solar system isotopic composition comes from studies of terrestrial, lunar, and meteoritic material. HIST provided the first high-resolution measurements of the individual isotopes of heavy nuclei accelerated in solar flares, thereby demonstrating a new means of sampling directly the isotopic composition of solar material.

In a seminal paper published in Ap. J. Letters in 1985, Breneman and Stone showed that it is the ionic charge to mass ratio (Q/M) that is the principal organizing factor for flare-to-flare variations in composition. By correcting for the Q/M-dependent fractionation that results from acceleration/propagation processes, they were able to derive coronal *elemental* abundances for a wide range of elements. In a paper published in Ap. J. Letters in 1989 (Mewaldt and Stone, 1989), we extended the approach of Breneman and Stone to derive coronal *isotopic* abundances based on HIST data.

Coronal abundances for the elements He, C, N, O, Ne, and Mg were derived by correcting the measured isotopic abundances for acceleration and propagation effects that apparently fractionate the accelerated solar composition. These corrections were based on the measured dependence of the elemental abundances in this flare on the ionic charge to mass ratio (Q/M) of these elements, as measured by the Maryland/MPI instrument on the same spacecraft. Table 1 summarizes these results.

Our studies of solar flare isotopes have concentrated on the large solar event of 9/23/78, one of the largest solar particle events of the last 15 years. Examples of the mass spectra obtained are shown in Figure 1, where the mass resolution is ~0.2 amu. Figure 2 shows a comparison of our solar energetic particle (SEP) isotope results with the "solar system" abundances tabulated by Cameron, with solar wind measurements, and with other SEP measurements. Note that while our results are in all cases consistent with Cameron's tabulation, there is a significant and unexpected difference between the two SEP measurements of $^{22}Ne/^{20}Ne$ and that from the solar wind.

Various measurements of solar system neon isotopes are summarized in Figure 3, which includes three lunar/meteoritic components; "neon-A" (thought to be a primordial component); "neon-B" (implanted solar wind); and "neon-C" (thought to be implanted solar flare nuclei). Although the difference between the SEP and solar wind neon measurements is not understood, there is also evidence for it from the lunar/meteoritic data, as evidenced by the difference between neon-B and neon-C. These differences suggest the possibility of mass-dependent fractionation in either the solar flare or solar wind acceleration processes. However, the correction for SEP fractionation effects derived in our analysis actually increases the discrepancy betweenthe solar wind and SEP measurements. In addition, the correspondence of our C, N, O, and Mg results with terrestrial and meteoritic isotopic abundances for these elements places limits on simple fractionation processes in solar flare acceleration and/or propagation. It remains to obtain a quantitative estimate of the fractionation that occurs during solar wind acceleration. Our measurements of ^{21}Ne and ^{3}He also limit the role that nuclear interactions during solar flare acceleration could have played in altering the SEP composition. Thus, while solar system neon remains a puzzle, HIST measurements have succeeded in adding a new dimension to studies of the solar composition and solar flare processes.

Composition and Energy Spectra of the Anomalous Cosmic Rays

At the New Hampshire Symposium on the Outer Heliosphere, held in May of 1989, and again at the 1989 Fall AGU meeting, invited talks were presented that reviewed composition studies of the anomalous cosmic ray component, including isotope studies that we have carried out with the Caltech experiment on ISEE-3(ICE). Such studies are of particular interest because they offer the possibility of measuring directly the isotopic composition of the interstellar medium, which is of significance in galactic evolution studies.

Cosmic Abundances of Matter

During 1989 two review papers were published that were based in large part on our ISEE-3 studies. The papers represent the written versions of two invited talks delivered at the Symposium on "Cosmic Abundances of Matter" held in Minneapolis in August. The first paper (Stone 1989) was an invited review of the abundances of elements and isotopes in solar energetic particles, including the coronal isotopic composition studies discussed above. A second paper (Mewaldt 1989), covering the abundances of isotopes in the galactic and "anomalous cosmic rays" was based in part on the studies of cosmic ray isotopes by the Caltech and Berkeley experiments on ISEE-3. An additional review paper on this topic appears in Mewaldt (1987).

Galactic Cosmic ray Isotopic Composition

A paper entitled "The ^{54}Mn Clock and its Implications for Cosmic Ray Propagation and Fe Isotope Studies" (Grove et al., 1991) was published in the Astrophysical Journal in 1991. An earlier, preliminary version of this work was also presented at the 21st International Cosmic Ray Conference held in Adelaide in January, 1990. This paper investigates the possible use of ^{54}Mn as a cosmic ray clock (beta-decay halflife presently unknown, but estimated to be 10^5 to 10^7 years). Previously, Koch et al. had concluded from studies of the Mn/Fe elemental ratio that a substantial fraction of the ^{54}Mn in low energy cosmic rays had decayed, suggesting a ^{54}Mn half-life of $\sim 10^6$ years. We find that any half-life greater than the laboratory measured experimental limit of $>4 \times 10^4$ years is permitted if allowance is made for the possibility of a non-solar source abundance of ^{55}Mn. We therefore conclude that only Mn isotope studies can exploit the use of ^{54}Mn as a clock. Preliminary measurements by the LBL experiment on ICE do not yet resolve ^{54}Mn, but may with additional analysis.

This paper also points out for the first time the implications of ^{54}Mn decay on Fe isotope studies. Since ^{54}Mn decays to ^{54}Fe, investigations of the ^{54}Fe source abundance should take into account the contributions of ^{54}Mn decay to the observed ^{54}Fe/^{56}Fe ratio. Figure 4 indicates how this contribution would affect the interpretation of our ISEE-3 measurement of this ratio (solid circle), as well as higher energy balloon data (solid diamond).

Helium-3 in Cosmic Rays

In a series of three papers (Mewaldt 1986; Cummings et al. 1986; Webber et al. 1987), we used measurements of ^{3}He from HIST and other instruments to re-examine the use of this rare isotope as a tracer of secondary contributions to Galactic cosmic rays, and as a means to separate the "anomalous" cosmic ray and Galactic cosmic ray contributions to the low energy He-4 spectrum at solar minimum. Even though this was the first cosmic ray isotope to be resolved, it is clear that it still has an important story to tell.

Bibliography A complete bibliography of talks and papers since the beginning of this project is attached.

Summary of HIST Accomplishments

Solar Flare Isotopes:

- First instrument to resolve individual solar flare isotopes with $Z > 2$
  - Confirmed that $^{22}Ne/^{20}Ne$ differs in solar flares and solar wind
  - C, N, O, and Mg consistent with terrestrial and meteoritic abundances
- Limits on mass-dependent preferential acceleration in solar flares
- Limits on fragmentation of heavy nuclei during solar flare acceleration
- Derivation of coronal isotopic abundances corrected for mass-dependent acceleration/propagation fractionation effects

Galactic Cosmic Ray Isotopes:

- Evidence for nucleosynthesis effects in the cosmic ray source
  - Confirmed ^{22}Ne enhancement in cosmic rays
  - First evidence that ^{25}Mg and ^{26}Mg also enhanced
  - First direct measure that ^{56}Fe is the dominant Fe isotope
- Evidence from N isotopes that cosmic rays not composed of interstellar matter

Interplanetary Particles:

- Isotopic measurements of "anomalous" N, O, and Ne
- Evidence that "anomalous" and galactic cosmic ray Ne differ

Technical:

- First demonstration of high-resolution cosmic-ray isotope separation in space
- First trajectory measurements with 2-D position-sensitive silicon detectors
- New methods of measuring cross sections with cosmic ray instrumentation

TABLE 1

ISOTOPIC ABUNDANCES OBSERVED IN SEPs AND DEDUCED FOR THE CORONA

Isotope Ratio	Measured Value in SEPs[a]	Value Deduced for the Corona	Anders and Ebihara 1982
$^{13}He/^{4}He$	$\leq 2.6 \times 10^{-3}$	$\leq 1.9 \times 10^{-3}$	4.3×10^{-4}
$^{13}C/^{12}C$	$0.0095^{+0.0042}_{-0.0029}$	$0.0111^{+0.0049}_{-0.0034}$	0.0111
$^{14}C/^{12}C$	<0.0014	<0.0019	0.00
$^{15}N/^{14}N$	$0.008^{+0.010}_{-0.005}$	$0.009^{+0.012}_{-0.006}$	0.0037
$^{17}O/^{16}O$	≤ 0.0021	≤ 0.0024	0.00037
$^{18}O/^{16}O$	$0.0015^{+0.0011}_{-0.0007}$	$0.0019^{+0.0014}_{-0.0009}$	0.00204
$^{21}Ne/^{20}Ne$	≤ 0.014	≤ 0.015	0.0024
$^{22}Ne/^{20}Ne$	$0.109^{+0.026}_{-0.019}$	$0.131^{+0.032}_{-0.024}$	0.073
$^{25}Mg/^{24}Mg$	$0.148^{+0.046}_{-0.026}$	$0.160^{+0.050}_{-0.028}$	0.129
$^{26}Mg/^{24}Mg$	$0.148^{+0.043}_{-0.025}$	$0.173^{+0.050}_{-0.030}$	0.142

[a] Mewaldt, Spalding, and Stone 1984.

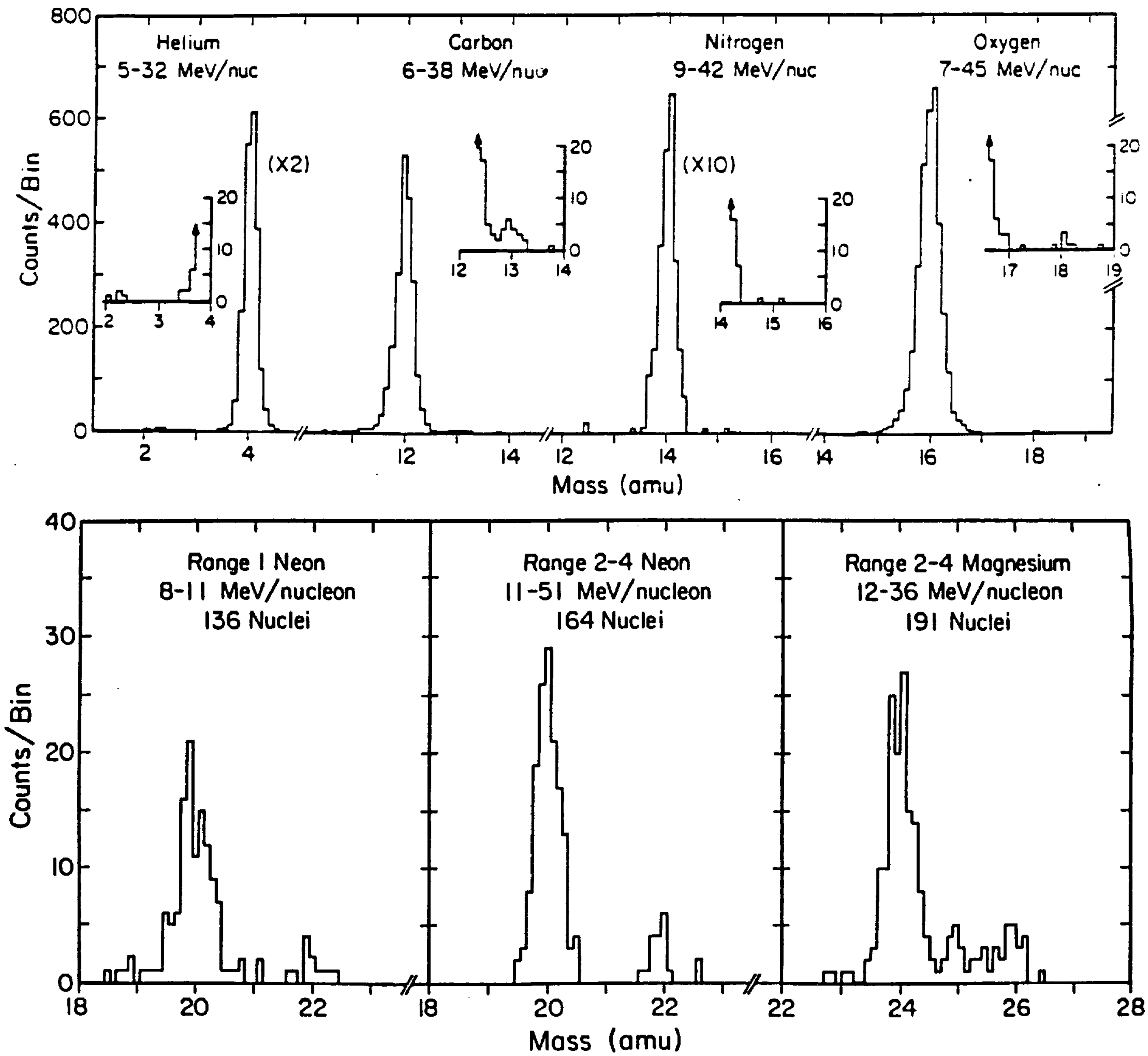
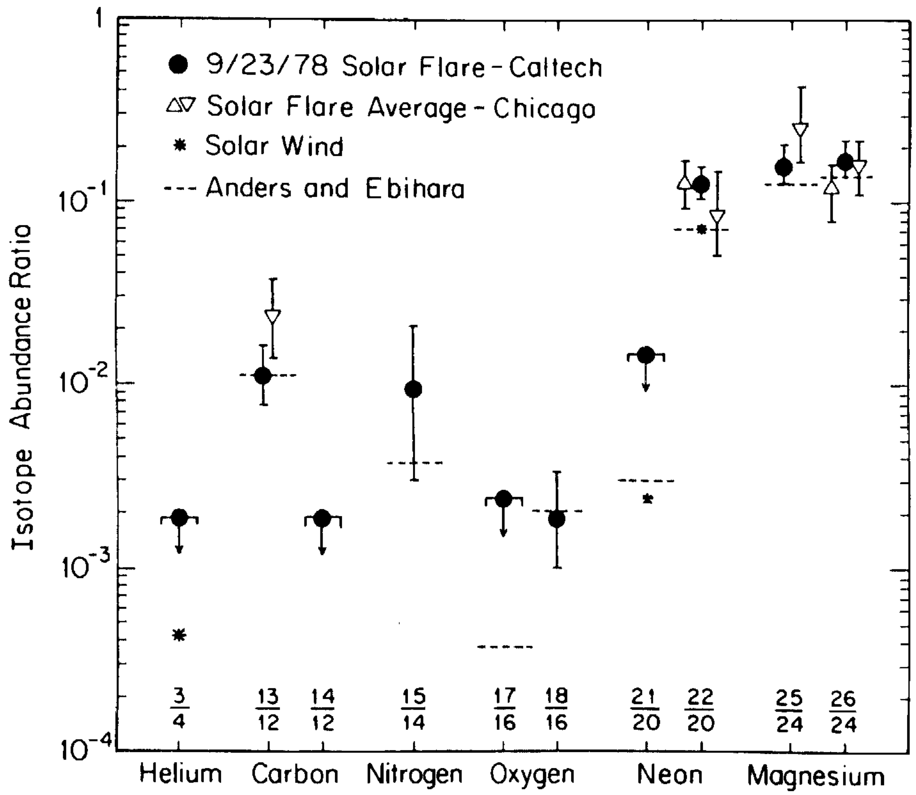


Figure 1: Mass histograms of He, C, N, O, Ne, and Mg isotopes from the 9/23/78 solar flare.



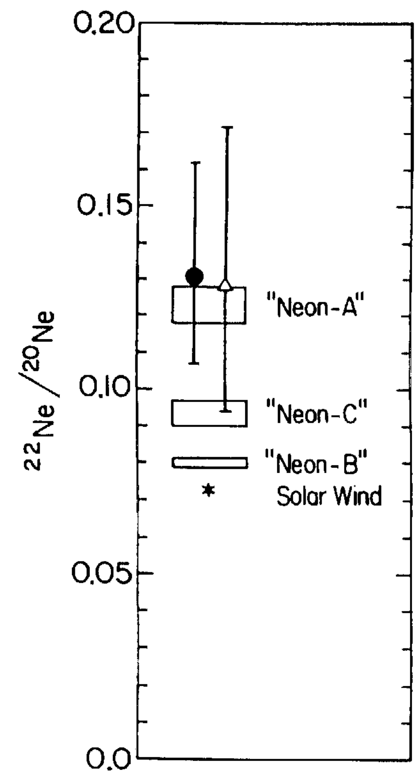


Figure 2: A comparison of isotopic abundances measured for solar flare nuclei and for the solar wind, with solar system abundances tabulated by Cameron.

Figure 3: A comparison of selected solar system $^{22}Ne/^{20}Ne$ ratios. SEP measurements: Caltech; Chicago. Also shown are values for the solar wind and lunar/meteoritic components neon-A, B, and C (see text).

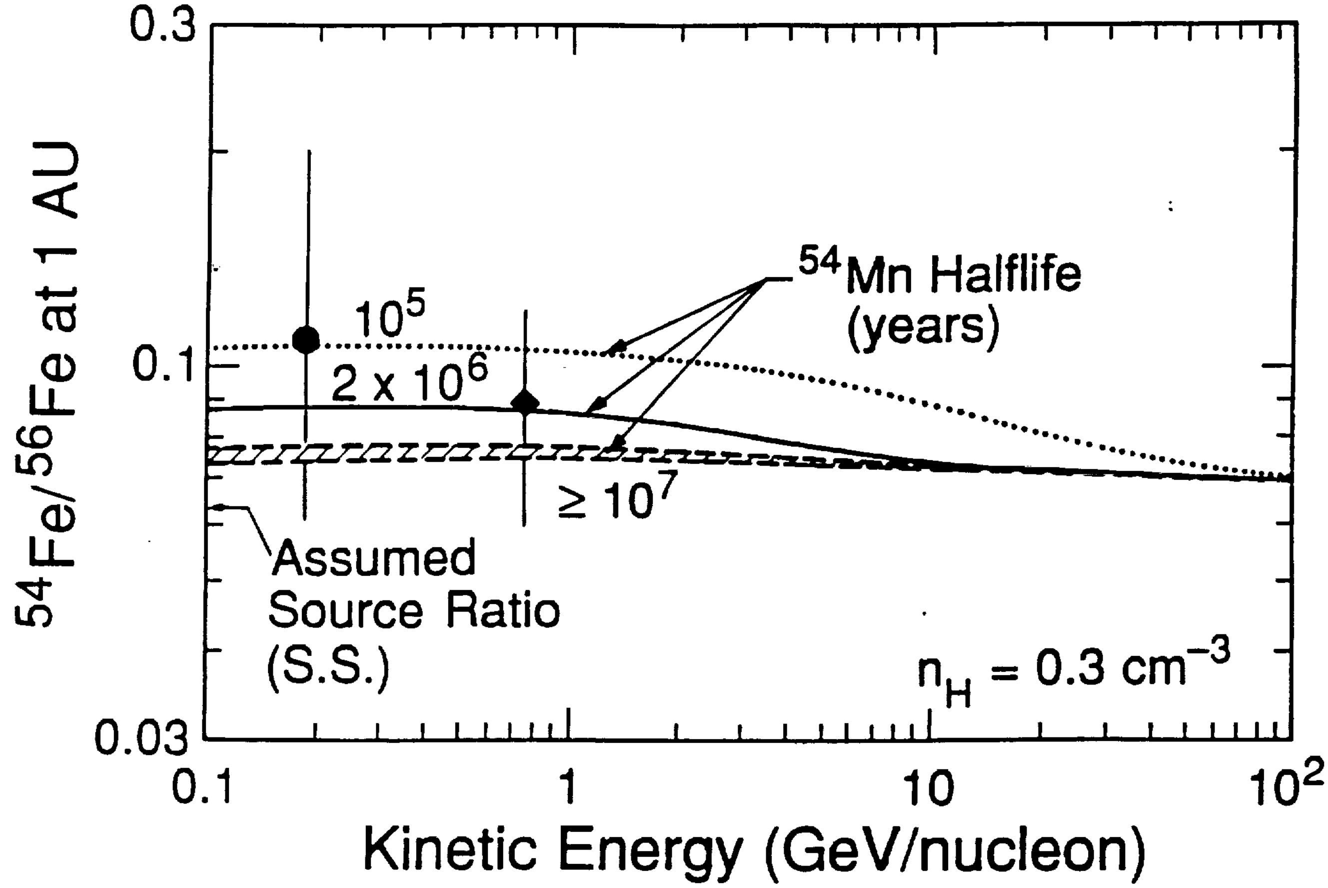


Figure 4: Expected $^{54}Fe/^{56}Fe$ ratios for various assumed ^{54}Mn beta-decay halflives. A solar system (SS) source abundance is assumed. The low-energy measurement is from our ISEE-3 instrument, while the higher energy measurement is based on three balloon intsruments.

Bibliography

Caltech Heavy Isotope Spectrometer Telescope (HIST) on ISEE-3

December 1992

Publications

Althouse, W.E., Cummings, A.C., Garrard, T.L., Mewaldt, R.A., Stone, E.C., and Vogt, R.E., "A Cosmic Ray Isotope Spectrometer", IEEE Trans. on Geosci. Electron. GE-16 , 204 (1978).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "The Isotopic Composition of Solar Flare Accelerated Neon", Ap.J. (Letters) 231 , L97 (1979).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "Satellite Measurements of the Isotopic Composition of Galactic Cosmic Rays", Proc. 16th Int. Cosmic Ray Conf., Kyoto, 12 , 86 (1979).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "High-Resolution Measurements of Galactic Cosmic-Ray Neon, Magnesium, and Silicon Isotopes", Ap.J. (Letters) 235 , L95 (1980).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "The Isotopic Composition of Galactic Cosmic Ray Iron Nuclei", Ap.J. (Letters) 236 , L121 (1980).

Mewaldt, R.A., "Spacecraft Measurements of the Elemental and Isotopic Composition of Solar Energetic Particles", Proc. Conf. Ancient Sun, ed. R.O. Pepin, J.A. Eddy and R.B. Merrill (New York: Pergamon), p. 81 (1980).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "The Isotopic Composition of Solar Flare Accelerated Magnesium", Ap.J. (Letters) 243 , L163 (1981).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "High Resolution Measurements of Solar Flare Isotopes", Proc. 17th Int. Cosmic Ray Conf., Paris, 3 , 131 (1981).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "The Isotopic Composition of Low Energy Cosmic Rays", Proc. 17th Int. Cosmic Ray Conf., Paris, 2 , 68 (1981) and 11 , 431 (1981).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "The Isotopic Composition of Cosmic Ray B, C, N and O Nuclei", Ap.J. (Letters) 251 , L27 (1981).

Mewaldt, R.A., "The Elemental and Isotopic Composition of Galactic Cosmic Rays", Proc. 17th Int. Cosmic Ray Conf., Paris, 13 , 49 (1981).

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

Spalding, J., "The Isotopic Composition of Energetic Particles Emitted from a Large Solar Flare", Ph.D. Thesis, California Institute of Technology (1982).

Mewaldt, R.A., "The Elemental and Isotopic Composition of Galactic Cosmic Ray Nuclei", Reviews of Geophys. and Space Phys. 21 , 295 (1983).

Mewaldt, R.A., Spalding, J.D., and Stone, E.C., "Further Isotopic Studies of Heavy Nuclei in the 9/23/78 Solar Flare", Proc. 18th Int. Cosmic Ray Conf., Bangalore, 4 , 42 (1983).

Lau, K.H., Mewaldt, R.A., and Wiedenbeck, M.E., "An Accelerator Test of Semi-Empirical Cross-Sections", Proc. 18th Int. Cosmic Ray Conf., Bangalore, 9 , 255 (1983).

Mewaldt, R.A., Spalding, J.D., and Stone, E.C., "A High Resolution Study of the Isotopes of Solar Flare Nuclei", Ap.J. 280 , 892 (1984).

Mewaldt, R.A., Spalding, J.D., and Stone, E.C., "The Isotopic Composition of the Anomalous Low-Energy Cosmic Rays", Ap.J. 283 , 450 (1984).

Mewaldt, R.A., "Cosmic Ray ^{3}He Measurements", Proc. 19th Int. Cosmic Ray Conf., La Jolla, 2 , 64 (1985).

Lau, K.H., Mewaldt, R.A., and Stone, E.C., "Measurements of Fe and Ar Fragmentation Cross Sections", Proc. 19th Int. Cosmic Ray Conf., La Jolla, 3 , 91 (1985).

Lau, K.H., "A Cerenkov-ΔE-Cerenkov Detector for High Energy Cosmic Ray Isotopes and an Accelerator Study of ^{40}Ar & ^{56}Fe Fragmentation", Ph.D. Thesis, California Institute of Technology (1985).

Mewaldt, R.A., "^{3}He in Galactic Cosmic Rays", Ap.J. 311 , 979 (1986).

Webber, W.R., Golden, R.L., and Mewaldt, R.A., "A Re-Examination of the Cosmic Ray Helium Spectrum and the ^{3}He/^{4}He Ratio at High Energies", Ap.J. 312 , 178 (1987).

Cummings, A.C., Mewaldt, R.A., and Stone, E.C., "Solar Cycle Variations of Anomalous ^{4}He as Deduced by Studies of Cosmic Ray ^{3}He", Geophys. Res. Letters, 13 , 1043 (1986).

Mewaldt, R.A., "Galactic Cosmic Ray Isotope Spectroscopy: Status and Future Prospects", *13th Texas Symposium on Relativistic Astrophysics* (World Scientific, Singapore), M. Ulmer, ed., 1987, p. 573.

Mewaldt, R. A. and Stone, E. C., "Isotope Abundances of Solar Coronal Material Derived from Solar Energetic Particle Measurements", *Proc. 20th Int. Cosmic Ray Conf.*, Moscow, 3 , 255 (1987).

Mewaldt, R.A., Stone, E.C., "Isotope Abundances of Solar Coronal Material Derived from Solar Energetic Particle Measurements", *Ap.J.*, 337 , 959 (1989).

Mewaldt, R. A., "The Abundances of Isotopes in the Cosmic Radiation", in *Cosmic Abundances of Matter* C. J. Waddington, editor, AIP Conference Proceedings #183, (American Institute of Physics, New York) p. 125, 1989.

Stone, E.C., "Solar Abundances as Derived from Solar Energetic Particles", in *Cosmic Abundances of Matter* C. J. Waddington, editor, AIP Conference Proceedings #183, (American Institute of Physics, New York) p. 72, 1989.

Grove, J. E., Hayes, B. T., Mewaldt, R.A., and Webber, W. R. "The ^{54}Mn Clock and its Implications for Cosmic Ray Propagation and Fe Isotope Studies", *Proc. 21th Int. Cosmic Ray Conf.*, Adelaide, 3 , 397, 1990.

Grove, J. E., Hayes, B. T., Mewaldt, R.A., and Webber, W. R. "The ^{54}Mn Clock and its Implications for Cosmic Ray Propagation and Fe Isotope Studies", *Ap. J.*, 377 , 680, 1991.

Abstracts/Talks

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "First Results from the Heavy Isotope Spectrometer Telescope on ISEE-C", EOS Trans. AGU 59 , 1152 (1978).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "Isotopic Measurements of Energetic Heavy Nuclei in Solar Flares", Bull. Am. Phys. Soc. 24 , 694 (1979).

Spalding, J.D., Mewaldt, R.A., Stone, E.C., and Vogt, R.E., "Satellite Measurements of the Isotopic Composition of Galactic Cosmic Rays", Bull. Am. Phys. Soc. 24 , 692 (1979).

Mewaldt, R.A., "Studies of Elemental and Isotopic Composition of Solar Flare Nuclei", Bull. Am. Phys. Soc. 24 , 618 (1979).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "The Isotopic Composition of Energetic Solar Flare Nuclei from Carbon Through Iron", Proc. 16th Int. Cosmic Ray Conf., Kyoto, 5 , 74 (1979).

Mewaldt, R.A., "Isotopic measurements of Solar and Galactic Cosmic Rays", EOS Trans. AGU 60 , 907 (1979).

Spalding, J.D., Mewaldt, R.A., Stone, E.C., and Vogt, R.E., "The Isotopic Composition of Heavy Nuclei Accelerated in Solar Flares", EOS Trans. AGU 60 , 907 (1979).

Mewaldt, R.A., Spalding, J.D., Stone, E.C., and Vogt, R.E., "The Isotopic Composition of Cosmic Ray Carbon, Nitrogen, and Oxygen Nuclei", Bull. Am. Phys. Soc. 25 , 546 (1980).

Spalding, J.D., Mewaldt, R.A., Stone, E.C., and Vogt, R.E., "High Resolution Measurements of Solar Flare Mg and Si Isotopes", Bull. Am. Phys. Soc. 25 , 596 (1980).

Stone, E.C., "Isotopic Composition of Low Energy Galactic Cosmic Rays", Bull. Am. Phys. Soc. 25 , 571 (1980).

Stone, E.C., "The Isotopic and Elemental Composition of Solar Energetic Particles", EOS Trans. AGU 62 , 350 (1981).

Mewaldt, R.A., Spalding, J.D., and Stone, E.C., "Isotopic Studies of Heavy Nuclei in the 9/23/78 Solar Flare Event", Bull. Am. Phys. Soc. 27 , 571 (1982).

Mewaldt, R.A., "Isotopic Anomalies in Galactic Cosmic Rays", Bull. Am. Astron. Soc. 14 , 645 (1982).

Mewaldt, R.A. and Stone, E.C., "Solar-Cycle Variations of the Anomalous Cosmic Ray Component", Proc. 19th Int. Cosmic Ray Conf., La Jolla, 5 , 167 (1985).

Cummings, A.C., Mewaldt, R.A., and Stone, E.C., "Solar Cycle Variations of Anomalous ^{4}He as Revealed by Studies of Cosmic Ray ^{3}He", Bull. Am. Phys. Soc. 31 , 872 (1986).

Mewaldt, R.A. and Stone, E.C., "Solar Coronal Isotopic Abundances Derived from Solar Energetic Particle Measurements", EOS Trans. AGU 67 , 1142 (1986).

Mewaldt, R.A. and Stone, E.C., "Isotopic Abundances of Solar Coronal Material Derived from Solar Energetic Particle Measurements", Bull. of Amer. Astron. Soc. 18 , 1042 (1986).

Mewaldt, R.A. and Stone, E.C., "Solar Coronal Isotopic Abundances Derived from Solar Energetic Particle Measurements", Bull. Am. Phys. Soc. 32, 1037 (1987).

Mewaldt, R. A., "The Isotopic Composition of Energetic Nuclei from Solar and Galactic Sources", EOS Trans. Am. Geo. Union 68, 1406 (1987).

Mewaldt, R. A., "Composition and Energy Spectra of the Anomalous Cosmic Rays", invited talk presented at the Symposium on the Outer Heliosphere, Durham, New Hampshire, May 21-24, 1989.

Stone, E.C., "Solar Energetic Particles as a Measure of Solar Coronal Abundances", EOS Trans. AGU 70, 1255 (1989).

Mewaldt, R.A., "Further Evidence for Anomalous Cosmic Ray Hydrogen", EOS Trans, AGU 70, 1255 (1989).

Adams, J.H., Badhwar, G.D., Mewaldt, R.A., Mitra, B., O'Neal, P.M., Ormes, J.F., and Streitmatter, R.E., "The Cosmic Ray Fe Spectrum at Solar Minimum", Bulletin of the American Physical Society, APS 36, 1394 (1991).