1997ICRC....3..357L

STUDY OF ELEMENTAL AND ISOTOPIC COMPOSITION OF COSMIC RAY NUCLEI Ca,Ti, V, Cr, Mn and Fe

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ABSTRACT

We present measurements of the charge and isotopic composition of cosmic ray Ca, Ti, V, Cr, Mn and Fe nuclei made on the Voyager spacecraft. We have analysed 18 yr. of data in the energy range 100 - 300 MeV per nucleon collected by the High Energy Telescope of the cosmic-ray subsystem experiment (CRS) on the Voyager 1 and 2 spacecraft. The average solar modulation level for this measurement is 480 MV. For five isotopes, ^{40}Ca, ^{52}Cr, ^{55}Mn, ^{54}Fe and ^{58}Fe we can determine the cosmic ray source composition which is not significantly different than the solar composition.

INTRODUCTION

Study of the mass composition of cosmic ray elements near the Fe peak is important to test models that have been proposed to explain the compositional differences between the cosmic ray source abundances and solar abundances and to understand the origin of cosmic rays and related nucleosynthesis processes. The Fe isotopes ^{54}Fe and ^{58}Fe are particularly sensitive to conditions at the source and to any differences in the standard picture for the origin of the solar system Fe abundances. The isotopes ^{40}Ca, ^{52}Cr and ^{55}Mn owe their abundances to both alpha particle burning and characteristics of the Fe peak nucleosynthesis. Also of interest are the so called electron capture isotopes, ^{55}Fe, ^{51}Cr and ^{49}V particularly, whose decay by electron capture depends on their energy and the density of the medium being traversed and so provides information on the time of acceleration and the amount of re-acceleration of the cosmic rays. Previous measurements of the overall mass composition of Fe group nuclei include the measurements made by the cosmic ray detector on the ISEE-3 spacecraft (Leske 1993) and new measurements of Mn and Fe nuclei made by the high resolution instrument on Ulysses (Connell and Simpson 1996). A preliminary report of the mass composition of elements from Ca to Fe using the CRS telescopes on the Voyager spacecraft has been given by Lukasiak et al. (1995) and extended version of this study will be published (Lukasiak et al. 1997).

OBSERVATIONS AND DATA ANALYSIS

The data from the High Energy Telescope (HET) of the CRS experiment on both the Voyager 1 and 2 spacecraft from 1977 to 1996 have been used in this analysis. This CRS experiment has been extensively described previously (Stone et al. 1977) and the charge and mass analysis of the telescope events follows closely that described by Lukasiak et al. (1994). Figure 1 shows the mass histograms for the elements Ca through Fe in the combined Voyager 1 and 2 spacecraft measurements from 1977 to 1996. The solid lines in Figure 1 correspond to a fit of a multi-gaussian function to the isotope distribution for each charge. These mass functions are spaced at exactly 1.0 AMU intervals and have resolutions ranging from 0.40 AMU for ^{40}Ca to 0.60 AMU for ^{56}Fe. The results of this study of 18 years correspond to an average level of solar modulation 480MV.

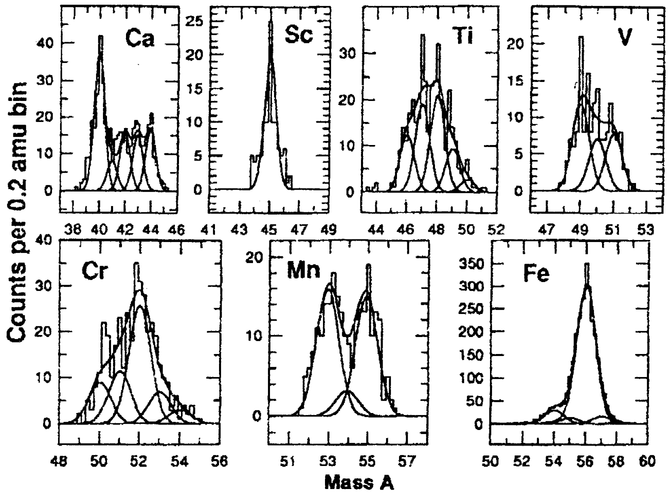

Figure 1. Mass histograms for the elements Ca-Fe showing fitted Gaussian functions.

INTERPRETATION OF RESULTS

The interpretation of these experimental results requires a model for the propagation of cosmic rays in the galaxy. As a point of reference for earlier calculations we performed these calculations using a standard Leaky-Box model with a simple exponential distribution of path lengths through the interstellar material. The most essential components of this model are: the source composition, the source spectral shape, the composition of the interstellar medium (ISM), the fragmentation cross sections, the interstellar path lengths as a function of energy and the effects of solar modulation. For the source composition we took the solar system abundances (Anders and Ebihara 1982). The source spectral shape was taken to be a power law in rigidity with an index of -2.36. We assumed that the ISM is 90% hydrogen and 10% helium by number with an ionized fraction of 30% (Soutoul, Ferrando and Webber 1990). For the interstellar fragmentation we used the measured and parametric cross sections in hydrogen given by Webber, Kish and Schrier (1990 a,b,c) and the helium cross sections from Ferrando et al. (1988). For the interstellar path length we took $\lambda_{esc} = 40.6\ \beta\ R^{-0.70}$ for rigidities $R > 3.3$GV and $17.6\ \beta$ g/cm^2 for $R < 3.3$ GV which provides a best fit to the ($Z = 21$-23)/Fe ratio measured at both low and high energies. We will now discuss isotope distributions for different charges

Calcium Calcium is dominated by the isotope ^{40}Ca which comprises 0.38±0.02 of all Ca. This fraction, taken with the total measured Ca/Fe charge ratio of 0.210±0.009 and the measured ^{56}Fe fraction of 0.841 of Fe, leads to a ^{40}Ca/^{56}Fe ratio of 0.084±0.007 at the source as compared with a solar abundance ratio of 0.072. Thus the ^{40}Ca/^{56}Fe ratio we deduce at the source is 1.16±0.10% times the solar ratio - slightly enhanced but not significantly so. The heavier isotopes ^{42}Ca, ^{43}Ca and ^{44}Ca are in agreement with the calculations for purely secondary production as shown in Table 1.

Titanium. All isotopes of this charge are dominated by secondary production in the interstellar medium. There is good agreement between the observed and predicted isotope fractions with the possible exception of ^{49}Ti a decay product of the electron capture isotope ^{49}V. All three K-electron capture isotopes ^{49}V, ^{51}Cr and ^{55}Fe will be discussed in a separate paper (Soutoul et al. 1997).

Vanadium. This charge has three isotopes all completely dominated by secondary production. ^{49}V shows a lower mass fraction than predicted from purely secondary production and ^{51}V a considerably larger mass fraction than predicted (Table 1). ^{49}V is an electron capture isotope and ^{51}V is the decay product of the electron capture isotope ^{51}Cr.

Chromium. This charge also shows a complex distribution of isotopes but it is clearly dominated by ^{52}Cr. Only ^{52}Cr is expected to have a significant source abundance. The measured Cr isotopes show some differences with the predicted ones (see Table 1). The measured ^{51}Cr abundance is ~2σ low

Table 1. Cosmic-ray isotopic ratios relative to ^{56}Fe

Element	Measured Ratio [%]	Propagated solar-like abundance	(Exp - Prop.) /del Exp.
^{40}Ca/^{56}Fe	9.46±0.73	8.27	+1.62 σ
^{41}Ca/^{56}Fe	2.15±0.54	1.60	+1.02 σ
^{42}Ca/^{56}Fe	4.17±0.57	4.96	-1.40 σ
^{43}Ca/^{56}Fe	4.39±0.64	5.15	-1.18 σ
^{44}Ca/^{56}Fe	4.82±0.58	5.29	-0.82 σ
^{44}Ti/^{56}Fe	0.19±0.10	0.14	+0.5 σ
^{46}Ti/^{56}Fe	3.93±0.50	4.84	-1.8 σ
^{47}Ti/^{56}Fe	5.78±0.69	5.70	+0.11 σ
^{48}Ti/^{56}Fe	6.37±0.72	6.18	+0.26 σ
^{49}Ti/^{56}Fe	2.67±0.46	1.11	+3.4 σ
^{50}Ti/^{56}Fe	0.73±0.24	0.19	+2.2 σ
^{49}V/^{56}Fe	3.26±0.42	4.56	-3.1 σ
^{50}V/^{56}Fe	2.11±0.39	2.82	-1.8 σ
^{51}V/^{56}Fe	2.34±0.37	0.98	+3.7 σ
^{50}Cr/^{56}Fe	2.70±0.41	2.48	+0.55 σ
^{51}Cr/^{56}Fe	3.58±0.51	4.47	-1.75 σ
^{52}Cr/^{56}Fe	8.42±0.92	7.73	+0.74 σ
^{53}Cr/^{56}Fe	2.29±0.50	1. 58	+1.42 σ
^{54}Cr/^{56}Fe	0.91±0.29	0.46	+1.56 σ
^{53}Mn/^{56}Fe	4.68±0.59	4.21	+0.8 σ
^{54}Mn/^{56}Fe	1.20±0.53	1.25	-0.09 σ
^{55}Mn/^{56}Fe	4.47±0.58	4.04	+0.75 σ
^{54}Fe/^{56}Fe	9.04±0.86	9.44	-0.51 σ
^{55}Fe/^{56}Fe	< 6.0	4.49	
^{57}Fe/^{56}Fe	< 6.3	2.44	
^{58}Fe/^{56}Fe	0.83 ± 0.48	0.44	+0.8 σ

and ^{54}Cr is somewhat high. Again both of these isotopes are K-capture isotopes. For ^{52}Cr the source abundance relative to ^{56}Fe that we deduce is 0.020±0.009% or 1.51±0.68 times the solar fraction of 0.0136.

Manganese. Manganese is dominated by the isotopes ^{53}Mn and ^{55}Mn with only a weak presence of the radioactive decay isotope ^{54}Mn. The observed ^{53}Mn and ^{55}Mn fractions are consistent with calculations for the secondary production assuming a solar abundance of ^{55}Mn at the cosmic ray source. The deduced ^{55}Mn /^{56}Fe ratio at the source is 0.016±0.006 or 1.35±0.48 times the solar ratio of 0.0121 (assuming no decay by K electron capture of ^{55}Fe into ^{55}Mn). The measured ^{54}Mn abundance fraction is 0.34±0.15 of that expected if no decay has occurred. This surviving fraction would imply a ^{54}Mn half-life of (1.0±0.6)x10^6 years assuming interstellar density ρ=0.3 atoms cm^{-3}. The amount of decaying ^{54}Mn amounts to (0.0235±0.0053)x^{56}Fe, a significant fraction which will enhance the ^{54}Fe abundance, thus providing a check on the fraction of ^{54}Mn that has decayed. (The above calculation assumes no K-capture decay of ^{54}Mn to ^{54}Cr, if this decay has occurred the deduced lifetime of ^{54}Mn for β decay will be longer).

Iron. Iron is completely dominated by ^{56}Fe in our data - this isotope comprising 0.84±0.02 of all iron. For the analysis of Fe isotopes we have assumed a tail on the low mass side of the Fe isotope distributions. This tail contains 2.0±0.6% of all ^{56}Fe events and reduces the ^{54}Fe/^{56}Fe ratio by ~20%. For ^{54}Fe the measured ^{54}Fe/^{56}Fe ratio of 0.090±0.009 compares with a calculated ratio of 0.094. This calculated ratio includes a solar source component of 0.063 x ^{56}Fe, the decay of ^{54}Mn = 0.023 x ^{56}Fe, and direct secondary production. The deduced source ratio for ^{54}Fe/^{56}Fe after subtracting the ^{54}Mn decay and secondary production from the measured ratio is thus 0.0585±0.0086 or 0.93±0.14 times the solar ratio of 0.063 - consistent with the solar abundance. For the ^{58}Fe/^{56}Fe ratio our measured value of 0.008±0.005 is dominated by fitting uncertainties. The predicted ratio assuming a solar source ratio is 0.0044 so our value is somewhat higher than but consistent with the solar ratio.

SUMMARY AND CONCLUSIONS

Most of the isotopes of Ca through Fe charges are dominated by interstellar secondary production from cosmic rays traversing the interstellar medium. For these isotopes our measured isotopic ratios with respect to ^{56}Fe are generally consistent to within ±10% with those expected from purely secondary production (except for the K-electron capture isotopes). We observe a ^{54}Mn/^{56}Fe ratio ~0.34 of that expected from interstellar propagation if no decay has occurred. This survival fraction translates into a ^{54}Mn decay lifetime of 1.0±0.6 x 10^6 years assuming interstellar density ρ=0.3 atoms cm^{-3} and not allowing for any additional ^{54}Mn decay to ^{54}Cr by K electron capture. For five isotopes, ^{40}Ca, ^{52}Cr, ^{55}Mn, ^{54}Fe and ^{58}Fe, we can determine the source composition. None of these isotopic ratios with respect to ^{56}Fe measured by Voyager show any significant differences with solar composition. This observation when coupled with the fact that in the Z = 6-16 charge range only ^{14}N and ^{22}Ne (and possibly ^{13}C) out of ten isotopes whose source composition can be reasonably determined using the Voyager data show any significant differences from solar (Webber et al. 1996, 1997) and also new Voyager results on Co and Ni isotopes (Lukasiak et al. 1996) - suggest that the cosmic ray source isotopic composition is remarkably solar like with few very distinctive differences.

Table 2. Cosmic-ray source/solar isotope ratios

Ratio	Voyager Measurements (Webber et al. 1996,1997+this measurement)	Other Recent Measurements	Predictions ^{c}
^{13}C/^{12}C	0.09±0.36		0.6 W-R
^{14}N/^{16}O	0.41±0.04		
^{15}N/^{16}O	2.62±1.65		
^{18}O/^{16}O	1.04±0.72		0.7 W-R
^{22}Ne/^{20}Ne	4.72±0.43		3.5 W-R
^{25}Mg/^{24}Mg	1.06±0.12		1.5 W-R
^{26}Mg/^{24}Mg	1.15±0.11		1.5 W-R
^{29}Si/^{28}Si	0.80±0.18		1.8 SM
^{30}Si/^{28}Si	1.03±0.16		1.8 SM
^{34}S/^{32}S	1.07±0.67	1.41±0.66^a	1.8 SM
^{40}Ca/^{56}Fe	1.16±0.10		
^{52}Cr/^{56}Fe	1.51±0.68		
^{55}Mn/^{56}Fe	1.35±0.48		
^{54}Fe/^{56}Fe	0.93±0.14	1.50±0.10^b	1.5 SM
^{58}Fe/^{56}Fe	1.48±0.75	0.50±0.35^b	1.8 SM
^{59}Co/^{56}Fe	1.23±0.40		
^{58}Ni/^{56}Fe	0.96±0.15	0.95±0.11^b	
^{60}Ne/^{56}Fe	0.99±0.24	1.23±0.18^b	
^{62}Ni/^{56}Fe	0.76±0.40	0.90±0.35^b	

(a) Thayer 1996 (b) Connell and Simpson 1996 (c) from Mewaldt 1989, (W-R=Wolf-Rayet model, SM=Supermetallicity model).

The complete list of cosmic ray source - solar isotope ratios measured by Voyager and other recent experiments is given in Table 2.

REFERENCES

Anders, E. and Ebihara, M. Geochin Cosmochin Acta, 4b, 2363 (1982).

Connell, J. J., and Simpson, J. A. 1996, ApJ. Lett. 475, L61 (1997).

Ferrando, P., et al. Phys. Rev. C., 37, 1490 (1988).

Leske R. A., 1993, ApJ., 405, 567 (1993).

Lukasiak, A., Ferrando, P., McDonald, F. B., and Webber, W. R., ApJ. 426, 366(1994).

Lukasiak et al. , Proc. *24th ICRC*, Roma, 2, 576 (1995).

Lukasiak , A., McDonald, F. B. and W. R. Webber, ApJ, (1997) in press.

Mewaldt, R. A., 1989, in Cosmic Abundances of Matter, ed. C. J. Waddington, A.I.P. Conf. Proc. No 183 (N.Y., AIP Press) 124 (1989).

Soutoul, A., Ferrando, P., and Webber, W. R., Proc. *21st ICRC*, Adelaide, 3, 337(1990).

Soutoul, A., et al. 1997, in preparation.

Stone E. C., et al. Space Sci. Rev. 21, 355 (1977).

Webber, W. R., Kish, J. C., and Schrier, D. A., Phys.Rev., C, 41, 520 (1990 a,b,c).

Webber, W. R., Lukasiak , A., McDonald, F. B., and Ferrando, P., ApJ, 457, 435 (1996).

Webber, W. R., Lukasiak, A., and McDonald, F. B., ApJ, 476, 766 (1997).