THE ASTROPHYSICAL JOURNAL, 377:680–684, 1991 August 20

THE ^{54}Mn CLOCK AND ITS IMPLICATIONS FOR COSMIC-RAY PROPAGATION AND Fe ISOTOPE STUDIES

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Received 1990 August 27; accepted 1991 February 20

ABSTRACT

Radioactive ^{54}Mn, suggested as a "clock" for measuring the lifetime of heavy cosmic rays, has a poorly known β-decay half-life estimated to be in the range from $\sim 10^5$ to 10^7 yr. Some years ago Koch et al. concluded from measurements of the Mn/Fe ratio that a significant fraction of low-energy (<1 GeV/nucleon) ^{54}Mn produced by Fe fragmentation had decayed. Using a propagation code that includes improved fragmentation cross-sections, and recent data from *HEAO 3* and a number of other spacecraft, we have reexamined the evidence for ^{54}Mn decay in cosmic rays. We conclude that present cosmic-ray data cannot establish the degree of ^{54}Mn decay, but point out that this question has important implications for studies of the ^{54}Fe abundance in cosmic-ray source material, as well as for cosmic-ray propagation studies.

Subject headings: cosmic rays: abundances — nuclear reactions

1. INTRODUCTION

Manganese has three isotopes that are either stable or long-lived on cosmic-ray time scales. Of these ^{55}Mn is stable, while ^{53}Mn and ^{54}Mn normally decay by electron-capture with half-lives of 3.7×10^6 yr and 312 days, respectively. In high-energy cosmic rays that are stripped of their electrons ^{53}Mn and ^{54}Mn can be considered stable with respect to electron capture (however, see below), but ^{54}Mn can also decay by either β^+ emission to ^{54}Cr or by β^- emission to ^{54}Fe. The half-lives ($t_{1/2}$) for these decays are poorly known; Casse (1973) estimated $t_{1/2} \sim 2 \times 10^6$ yr for β^- decay and $t_{1/2} \sim 10^9$ yr for β^+ decay, while Wilson (1978) estimated that the β^- half-life might range from 6×10^4 to 10^7 yr. Recently the laboratory measurement of Sur et al. (1989) established a limit of $t_{1/2}(\beta^+) > 2 \times 10^7$ yr for ^{54}Mn, and from this and theoretical arguments they deduced a lower limit of $t_{1/2} > 4 \times 10^4$ yr for the β^- decay mode. Further experimental work on this question is in progress (Norman et al. 1990).

Casse (1973) suggested that ^{54}Mn, a product of Fe fragmentation, might serve as a cosmic-ray clock analogous to ^{10}Be, and thereby test whether Fe-group and CNO nuclei have had a similar propagation history. Some years later Koch et al. (1981) reported that Mn had a significantly flatter energy spectrum than other "secondary" cosmic-ray nuclei such as Sc, Ti, V, and Cr that originate mainly from Fe fragmentation. They concluded that the observed Mn/Fe ratio was best explained by energy-dependent decay of ^{54}Mn, with the product $n_{\rm H}\tau \simeq$ 0.3 to 0.6 Myr cm^{-3}, where $n_{\rm H}$ is the average hydrogen density in the confinement region and τ is the ^{54}Mn β-decay mean life. However, their conclusion was dependent on an assumed source composition for Fe-group nuclei that was identical to that in the solar system (see discussion in Mewaldt 1981). In addition, Ormes & Protheroe (1981), using the same cosmic-ray data but different cross sections, found no evidence for ^{54}Mn decay. Although the question of ^{54}Mn decay is best addressed with Mn isotope studies, there are to date no cosmic-ray isotope observations that resolve ^{54}Mn.

Using available satellite measurements of the elemental composition of cosmic rays and an interstellar propagation/solar modulation code in conjunction with new, more accurate cross sections, we reexamine the question of ^{54}Mn decay in cosmic rays and consider its implications. A preliminary version of this work has been reported by Grove et al. (1990).

2. THE PROPAGATION MODEL

We model cosmic-ray composition using a standard energy-dependent "leaky-box" model for cosmic-ray propagation, including a rigidity-dependent pathlength for escape from the galaxy of $\lambda_e = 24.9\beta R^{-0.6}$ g cm^{-2} (of pure H) for rigidities >4.0 GV, and $\lambda_e = 10.8\beta$ g cm^{-2} for $R \le 4$ GV, a dependence originally designed to fit observations of the boron to carbon ratio. Here β is the velocity in units of the speed of light. All species are assumed to have identical source spectra that are power laws in rigidity with $dJ/dR \propto R^{-2.3}$. The propagation code is based on that used by the Saclay group (Soutoul et al. 1985), and includes the effects of nuclear fragmentation, radioactive decay, and ionization energy-loss. The cross sections include extensive recent measurements (Webber, Kish, & Schrier 1990a) along with a new semi-empirical program to predict unmeasured cross sections (Webber, Kish, & Schrier 1990b). We also included the effects of electron pickup and subsequent electron-capture decay for nuclei such as ^{51}V, ^{54}Mn, and ^{55}Fe.

Although high-energy cosmic rays are generally considered to be fully stripped, there is actually a significant probability for electron attachment, especially at energies below ~0.5 GeV nucleon^{-1} (see e.g., Raisbeck & Yiou 1975; Letaw et al. 1985).

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In the case of short-lived nuclei such as ^{54}Mn and ^{55}Fe, this can lead to inflight electron-capture decay, since the mean time for stripping the electron is $\sim 10^4$ yr, much longer than the lifetime for electron-capture decay for these (and several other) species. Using cross sections estimated from Crawford (1979), we find that including electron attachment and subsequent decay has a significant effect on interstellar abundance ratios such as Mn/Fe at energies below $\sim$300 MeV nucleon^{-1} and on selected isotope ratios involving ^{54}Mn, ^{55}Fe, or their decay products. Once the energy loss that occurs during solar modulation is taken into account the observable effects of electron capture processes are considerably diminished at 1 AU. At 100 MeV nucleon^{-1}, the lowest energy considered here, electron-capture effects at 1 AU range from $\sim$5% or less for element ratios such as Mn/Fe, to 10%–20% for isotope ratios such as ^{54}Mn/^{53}Mn and ^{55}Fe/^{56}Fe.

These calculations assume a propagation medium that is composed of pure hydrogen, since the fragmentation cross sections for hydrogen are much better known than for He and heavier nuclei which might comprise $\sim$10% of the interstellar medium. Soutoul et al. (1990) have recently emphasized the importance of including He cross sections and of taking into account the increased rate of energy loss of cosmic rays in a medium which is partially ionized. We have examined these effects and believe that they do not have a significant effect on the *relative* abundance of elements (or isotopes) that have similar nuclear charge, such as those considered in this paper.

Corrections for the effects of solar modulation on the relative composition have been evaluated using two separate approaches: the "force-field" approximation (Gleeson & Axford 1968) with a modulation factor $\Phi = 600(Z/A)$ MeV nucleon^{-1}; and the (presumably more accurate) spherically symmetric solution to the Fokker-Planck equation (Fisk 1971), including the effects of diffusion, convection, and adiabatic energy loss. We find that for elemental abundance ratios such as Mn/Fe and (Sc + Ti + V)/Fe the difference between the two approaches amounts to only a few percent at 100 MeV nucleon^{-1}, with negligible differences at more than 200 MeV nucleon^{-1}. However, for certain isotope ratios there are more significant differences (e.g., as much as 10%–15% for ^{54}Mn/^{53}Mn and ^{55}Mn/^{53}Mn). As a result, we have used the numerical Fokker-Planck solutions for the isotope ratios considered in this paper, and the more convenient force-field solutions for abundance ratios of elements.

3. COMPARISON WITH COSMIC-RAY OBSERVATIONS

We compare our calculations with a compilation of recent spacecraft observations spanning three decades in energy/nucleon, including data from *HEAO 3*, *IMP 8*, *ISEE 3*, and *Voyager 2*. Although the *Voyager* data have been included for completeness, it should be noted that since these measurements were made at an average radial distance of $\sim$22 AU, the level of solar modulation is significantly less than that for the other observations (Ferrando et al. 1990). As a monitor of the production of "secondary" Mn by the breakup of Fe and heavier nuclei we use the ratio (Sc + Ti + V)/Fe, since Sc, Ti, and V should all be essentially absent in cosmic-ray source material [(Sc + Ti + V)/Fe < 0.004 in the solar system]. Figure 1 (see also Mewaldt & Webber 1990), which shows the fit to the "secondary/primary" ratio (Sc + Ti + V)/Fe, illustrates that the model accurately accounts for the production of these Fe-secondaries over a very broad energy range. According to Ferrando et al. (1991) the *Voyager 2* data at $\sim$200 MeV nucleon^{-1} are consistent with the other low-energy measurements when differences in the level of solar modulation are taken into account.

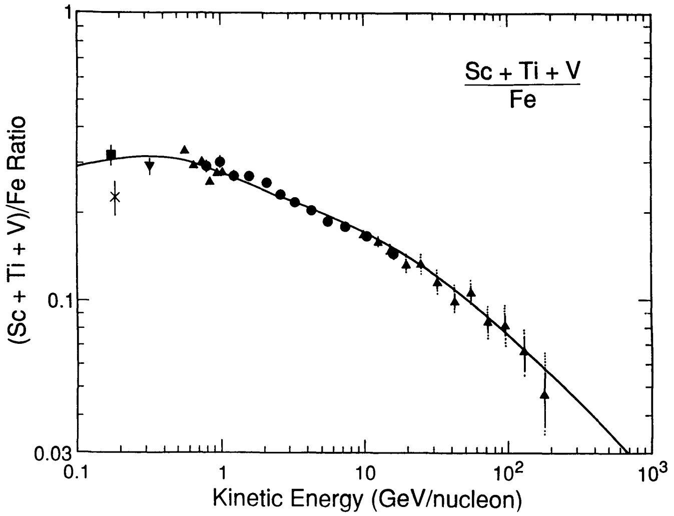

FIG. 1.—Spacecraft observations of the "secondary/primary" abundance ratio (Sc + Ti + V)/Fe are fitted by the leaky-box propagation model with a rigidity-dependent pathlength distribution (see also Mewaldt & Webber 1990). References to the measurements: *upward triangles* (*HEAO 3*; Jones 1985; Vylet et al 1990); *circles* (*HEAO 3*; Engelmann et al. 1989); *square* (*IMP 8*; Simpson 1983); *downward triangle* (*ISEE 3*; Leske & Wiedenbeck 1990); and *cross* (*Voyager 2*; Ferrando et al. 1990). The dotted extensions on the *HEAO 3* points represent possible systematic uncertainties (see Mewaldt & Webber 1990).

Figure 2 shows calculated Mn/Fe ratios for three assumed ^{54}Mn β^- decay lifetimes, based on a "solar system" source abundance of $(\mathrm{Mn/Fe})_s = 0.0106$ (Anders & Grevesse 1989), and an interstellar hydrogen density of $n_\mathrm{H} = 0.3$ cm^{-3} in the cosmic-ray confinement region, as deduced from ^{10}Be and ^{26}Al studies (see summary in Mewaldt 1989). We assume this same density for all the calculations in this paper, noting that equivalent results to those in Figure 2 are achieved for arbitrary

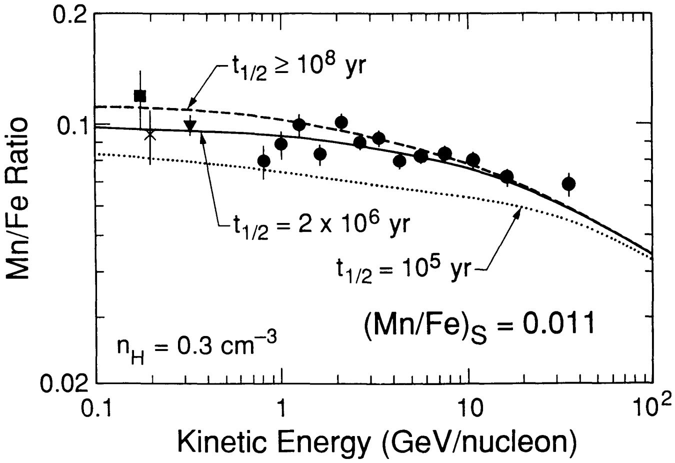

FIG. 2.—A comparison of measured and calculated Mn/Fe ratios for various assumed ^{54}Mn β^--decay half-lives. The calculations assume an interstellar H density of $n_\mathrm{H} = 0.3$ cm^{-3}, but also apply to arbitrary interstellar densities with the same $n_\mathrm{H} t_{1/2}$ product. For references to the measurements, see Fig. 1.

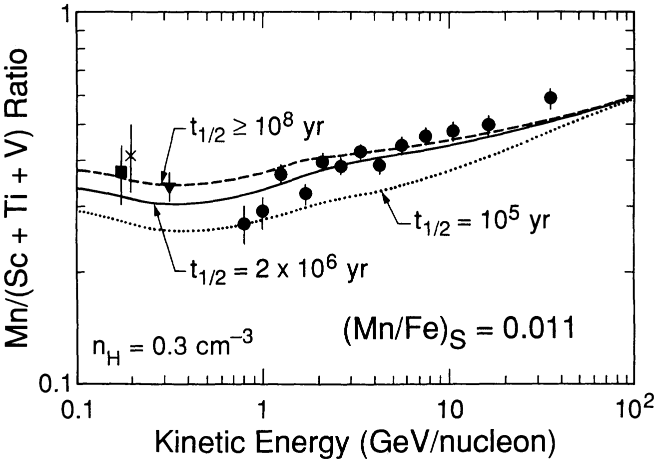

FIG. 3.—Measured and calculated Mn/(Sc + Ti + V) ratios for various assumed ^{54}Mn half-lives. For references to the data see Fig. 1.

values of n_H as long as the product $n_H t_{1/2}$ remains the same (see Koch et al. 1981). In this paper we consider only the β^- decay of ^{54}Mn, ignoring the possibility of β^+ decay which has a measured half-life of larger than 2×10^7 yr (Sur et al. 1989) and an estimated half-life of 10^8–10^9 yr (Casse 1973; Wilson 1978). We have also assumed that all Mn in the source is ^{55}Mn, the only stable isotope of Mn. Note that 80%–90% of observed Mn in cosmic rays is produced by the fragmentation of Fe.

A second approach, shown in Figure 3, uses the ratio of Mn to the Fe-secondaries, Sc + Ti + V (Mewaldt 1981), since such "secondary/secondary" ratios are less sensitive to uncertainties in the energy dependence of the pathlength distribution and to the total interaction cross section of Fe. From Figures 2 and 3 we find that for a Mn source composition equal to that in the solar system, and $n_H = 0.3$ cm^{-3}, the available cosmic-ray data are consistent with a ^{54}Mn half-life of a few million years, in agreement with the results of Koch et al. (1981), but inconsistent with half-lives as short as 10^5 yr.

However, since the cosmic-ray source abundance of Mn is not independently known, "nonsolar" source abundances of Mn should also be considered. Figures 4 and 5 demonstrate that by adjusting the Mn/Fe ratio at the source excellent fits can be achieved to the observations for ^{54}Mn β^- lifetimes ranging anywhere from $\sim 10^5$ to larger than 10^8 yr. (Note that $t_{1/2} > 10^8$ yr is essentially equivalent to ^{54}Mn stability on cosmic-ray time scales.) Of the possibilities shown in Figures 4 and 5 a half-life of $t_{1/2} \sim 10^5$ yr provides the best fit, but we consider the entire range of half-lives larger than 4×10^4 yr to give an acceptable fit. While these lifetime possibilities might be distinguished by Mn measurements at greater than 50 GeV nucleon^{-1} (see Fig. 5) or by Mn isotope measurements, such data are not now available. We therefore conclude, contrary to Koch et al. (see also Sur et al. 1989), that when consideration is given to a possible nonsolar source composition, presently available cosmic-ray data cannot establish whether any appreciable fraction of ^{54}Mn undergoes β-decay in cosmic rays (see also Mewaldt 1981).

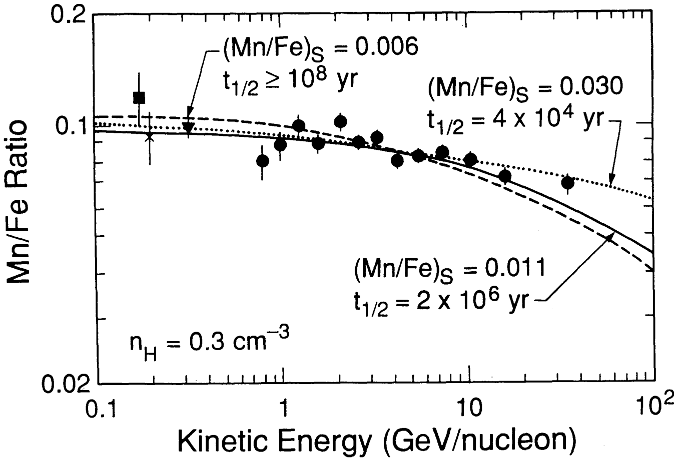

FIG. 4.—Measured and calculated Mn/Fe ratios as in Fig. 2, except that in each case the source abundance of Mn (in the form of ^{55}Mn) has been adjusted as indicated to fit the observations.

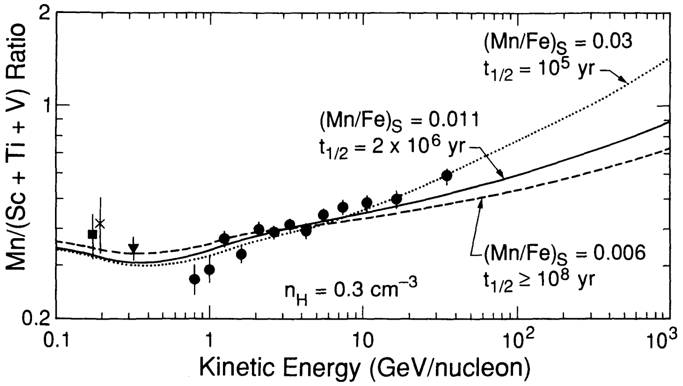

FIG. 5.—Measured and calculated Mn/(Sc + Ti + V) ratios as in Fig. 3, except that in each case the source abundance of Mn has been adjusted as indicated to fit the observations.

4. COSMIC-RAY ISOTOPE STUDIES

To properly interpret the abundance of Mn in cosmic rays will require isotope observations that can individually isolate the contribution of ^{55}Mn from the source and the effect of ^{54}Mn decay. Because the abundance of ^{53}Mn, which is assumed to be entirely of secondary origin, is relatively independent of the abundances of ^{54}Mn and ^{55}Mn, it serves as a useful reference. Figure 6 demonstrates that the ^{54}Mn/^{53}Mn ratio is a sensitive indicator of ^{54}Mn decay, while Figure 7 illustrates the use of the ^{55}Mn/^{53}Mn ratio as a measure of the ^{55}Mn source abundance. Leske & Wiedenbeck (1990) have recently reported preliminary isotope measurements from *ISEE 3* which suggest that some ^{54}Mn has decayed at low energies, but they conclude that their observations are also consistent with the possibility of no decay (see also Wiedenbeck 1990). Upon inspection, their preliminary observations appear to be consistent with roughly equal abundances of ^{53}Mn and ^{55}Mn, which, when compared with Figure 7, would argue against a Mn source abundance as large as Mn/Fe $\simeq 0.03$ such as would be required if the ^{54}Mn half-life is 10^5 yr or less (see Figs. 4 and 5). These issues should be resolved by new isotope observations within the next few years. Note, however, that for ^{54}Mn to serve as a cosmic-ray "clock" analogous to ^{10}Be will require an independent measurement of its β-decay half-life, although precise measurements of the ^{54}Mn/^{53}Mn ratio over a broad energy interval would provide an

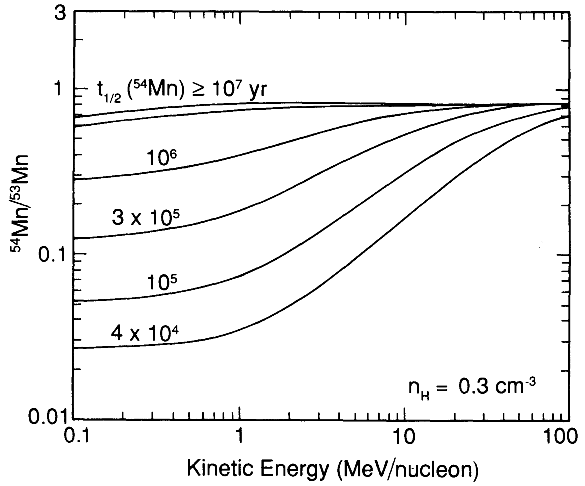

FIG. 6.—^{54}Mn/^{53}Mn ratio vs. kinetic energy/nucleon for various possible values of the ^{54}Mn half-life. In each case the ^{55}Mn source abundance has been adjusted to fit the observed Mn elemental abundance (see Figs. 4 and 5), although these curves are relatively independent of the ^{55}Mn source abundance. The calculations assume an interstellar H density of 0.3 cm^{-3}.

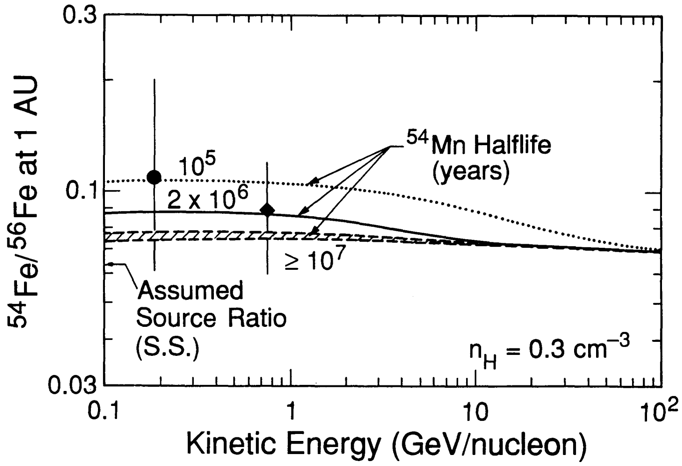

FIG. 8.—Expected ^{54}Fe/^{56}Fe ratio for various assumed ^{54}Mn β-decay half-lives. The calculations assume a solar system (SS) source ratio as indicated. The low-energy measurement is from Mewaldt et al. (1980), while the high-energy point is based on the results of Webber (1981), Young et al. (1981), and Tarle, Ahlen, & Cartwright (1979).

important test of many of the aspects of cosmic-ray propagation models.

The ^{54}Fe/^{56}Fe ratio in cosmic rays is of interest because of its significance for understanding the nucleosynthesis of cosmic-ray material (see, e.g., Woosley 1976; Mewaldt 1989). Because the β^-decay of ^{54}Mn produces ^{54}Fe, interpretations of the ^{54}Fe abundance in cosmic rays are subject to the uncertainties in ^{54}Mn decay discussed above. Figure 8 shows the calculated dependence of the ^{54}Fe/^{56}Fe ratio on the assumed ^{54}Mn β^- decay half-life, along with a summary of the status of cosmic-ray isotope observations. Note that for an assumed solar system source composition (^{54}Fe/^{56}Fe = 0.063) the expected ^{54}Fe/^{56}Fe ratio at 1 AU can range from less than 0.08 to more than 0.10, depending on the ^{54}Mn lifetime. At present this entire range is consistent with existing cosmic-ray data. To our knowledge, this complication to the interpretation of Fe isotope observations has not been pointed out previously. It is clear that future studies of Fe isotopes should at the same time measure the isotopic composition of Mn.

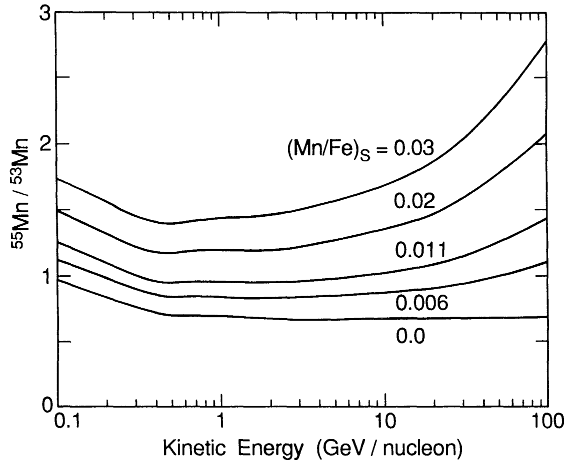

FIG. 7.—^{55}Mn/^{53}Mn ratio vs. kinetic energy/nucleon, labeled with the assumed ^{55}Mn source abundance relative to Fe. In the solar system, Mn/Fe = 0.011. The increase in the ratio below 500 MeV nucleon^{-1} is due to the decay of ^{55}Fe following electron pickup, while the increase at high energies results from the reduced production of secondary Mn as the rigidity-dependent pathlength decreases. These curves depend only weakly on the degree of ^{54}Mn decay.

The possible decay of ^{54}Mn in cosmic rays also has implications for cosmic-ray propagation that are not always appreciated. Such studies often use the ratio of the abundance of "Fe-secondaries" (for example, nuclei with $Z = 21$–23) to the abundance of Fe (e.g., Fig. 1) as a measure of the average pathlength of heavy cosmic-ray nuclei such as Fe, to be compared with the pathlength of lighter nuclei such as C, N, and O, as measured by the B/C ratio. For an assumed ^{54}Mn half-life that ranges from $t_{1/2} = 10^5$ yr to $t_{1/2} = \infty$ the ratio of Fe-secondaries to Fe differs by $\sim 3\%$ as a result of the decay of ^{54}Mn to ^{54}Fe. It is therefore important that studies of cosmic ray propagation consider these possibilities and document whatever assumptions have been made about the ^{54}Mn half-life.

5. SUMMARY

In summary, we conclude that the role of ^{54}Mn decay in cosmic rays is unlikely to be understood by elemental composition measurements such as those considered here; rather, precise measurements of the isotopic composition of cosmic-ray Mn will be required. Even then, it appears unlikely that ^{54}Mn can achieve its potential as a cosmic-ray clock until either its β-decay lifetime is established independently or its isotopic composition in cosmic rays is measured over a broad energy interval. The latter objective is possible with a combination of low-energy isotope measurements planned for the 1990s on missions that include Ulysses, CRRES, SAMPEX, WIND, Geotail, and ACE, along with high-energy measurements proposed for NASA's Astromag Particle Astrophysics mission.

This work was supported in part by NASA under grants NAG8-678, NAG5-722, and NAGW-1919. We appreciate the assistance of T. L. Garrard with the propagation calculations. Some of this work was performed while B. T. Hayes was the recipient of a Caltech Summer Undergraduate Research Fellowship (SURF).

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