Cosmic ray measurement of the ^{54}Mn β^- partial half-life

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In the fully stripped cosmic rays, the electron capture decay of ^{54}Mn ($\tau_{1/2}=312d$) is strongly suppressed. In this situation the β^- decay channel dominates; however, this half-life has never been measured in the laboratory. Some lower limits have been placed on it previously. Using the cosmic-ray data from the Ulysses spacecraft high-energy telescope (HET) and a self-consistent model of the galactic transport of cosmic rays, this partial lifetime can be determined. The best-fit β^- partial decay lifetime is dependent on the interstellar gas density, but is constrained to be between 1–2$\times 10^6$ yr. This is consistent with, but much more restrictive than, earlier limits placed on the lifetime ($>3\times 10^4$ and $>2.95\times 10^5$ yr) from direct and indirect methods, respectively. This determination using the cosmic-ray data requires laboratory verification for which there appears to be interest. [S0556-2813(96)51311-7]

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The cosmic rays can create novel situations for nuclear physics reactions. During the acceleration of the cosmic-ray source material to high energy, the nuclei become fully stripped. In this environment, electron capture decays are strongly suppressed by a lack of electrons. Though some probability exists of capturing an electron out of the interstellar medium, cosmic-ray nuclei are essentially stable to electron capture during their propagation through the galaxy.

The cosmic rays are confined to the galaxy for $\sim$15 million years—the cosmic-ray ''lifetime.'' This lifetime can be measured by β-decay chronometers such as ^{10}Be, ^{26}Al, and ^{36}Cl (e.g., the review paper [1]). There is, however, a great deal of interest in the iron-group (Sc-Ni) cosmic rays since these nuclei carry with them knowledge of the nuclear statistical equilibrium and explosive nuclear burning that created them. It is important to understand the propagation of these cosmic-ray species in addition to the lighter elements. A β-decay chronometer in the iron group would help this propagation study. To this end, cosmic-ray ^{54}Mn has been examined in a number of studies [2,3]. The manganese decay is also important in studies of ^{54}Fe, which is an important measure of the nucleosynthesis of the cosmic-ray source material.

^{54}Mn decays in the laboratory via an allowed electron capture decay to the 835 keV level of ^{54}Cr (Fig. 1). It can also decay by β^+ to the ground state of ^{54}Cr (end-point energy of 355 keV) and by β^- to the ground state of ^{54}Fe (end point at 697 keV). Both are doubly forbidden unique transitions. Due to phase-space (logft) arguments, the β^- decay is expected to dominate with a decay probability of $\sim$500 larger than the β^+.

The experimental measurements and estimates are listed in Table I. Measurements of the β^+ decay mode, and then inferences of the β^- lifetime, are usually made because of the high background of 835 keV photons and their associated internal conversion and shakeoff electrons in the β^- spectrum. So far these (difficult) measurements have yielded only lower limits on the β^- decay of interest for cosmic-ray propagation studies ($>2.95\times 10^5$ yr).

The solid-state charged-particle high-energy telescope (HET) aboard the Ulysses spacecraft was designed to fully resolve the galactic cosmic ray isotopes from H-Ni over the energy range $\sim$40$-$400 MeV nucleon^{-1}. It consists of two sets of three position-sensitive silicon strip detectors (PSD's) and a stack of six thick silicon detectors (see Fig. 2). The PSD's were designed and built at the University of Chicago and have an individual resolution of $\sim$150 μm [4]. Multiple PSD's can make position measurements to within $\sim$60–80 μm. The trajectory information is used to correct for the pathlengths in each detector. Without such information, isotopic separation for heavier elements would be nearly impossible. Both the PSD's and the thick silicon detectors are pulse-height analyzed to obtain energy deposits. The energy losses are analyzed using a dE/dx vs residual E (Bethe-Bloch) technique (e.g., [5]). The scintillator shield and thin bottom silicon ''A'' detector are employed in anticoincidence to eliminate events that are off-geometry or that fully penetrate the telescope. The telescope is more completely detailed elsewhere [6].

Using the HET, high-resolution charge and mass data is available from protons through iron and nickel. Charge resolution is always better than $0.10e$—thus elements are well separated. The manganese galactic cosmic rays are resolved with a $1/e$ mass resolution (assuming Gaussian isotope peaks) of $\sim 0.29u$. The manganese data, along with a fit to three Guassians, is shown in Fig. 3. This isotopic resolution has allowed manganese to be measured in the cosmic rays without serious instrumental restrictions. Older experiments

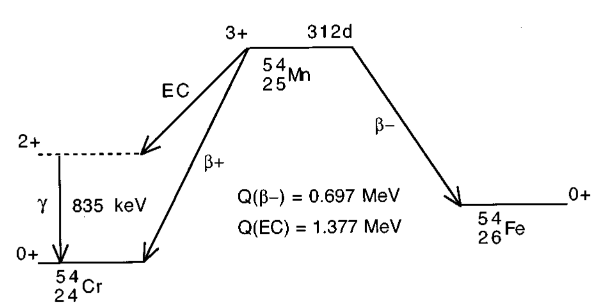

FIG. 1. Nuclear decay diagram for ^{54}Mn.

TABLE I. ^{54}Mn β^- lifetime estimates.

Technique	Lifetime [yr]	Reference
Estimate	$\sim 2\times 10^6$	[13]
	$9.2\times 10^5 - 6.5\times 10^7$	[14]
β^+ experiment	>2000	[15]
	$>4\times 10^4$	[14]
	$>2.95\times 10^5$	[12]
β^- experiment	$>3.0\times 10^4$	[16]
Cosmic-ray experiment	''a few million''	[2]
	$1-2\times 10^6$	This work

had quoted resolutions around 0.40–0.65u, which have limited their ability to pick out low abundance isotopes in the ''shoulders'' of the more dominant isotope peak. From the Ulysses HET data and galactic cosmic-ray transport calculations, an allowed range for the β^- partial lifetime can be determined.

The galactic cosmic rays observed within the heliosphere are dependent on the details of the transport, or propagation, of the cosmic rays from their source(s), through the interstellar medium (ISM), and into the heliosphere. The standard leaky box model of cosmic-ray galactic propagation is used and solved through the weighted slab technique (e.g., [7]). For each species i, the energy loss, spallation loss and gain, and radioactive decays are tracked through a pathlength of matter (x). Mathematically, this is

$$\frac{dN_i(x,E)}{dx}=\frac{\partial}{\partial E}\left[\left(\frac{dE}{dx}\right)_i N_i\right]-\frac{N_0}{\bar{A}}\sigma_i N_i+\sum_{j\neq i}\frac{N_0}{\bar{A}}\sigma_{ij}N_j-\frac{N_i}{\gamma\beta c n\bar{A}T_i}+\sum_{j\neq i}\frac{N_j}{\gamma\beta c n\bar{A}T_j}. \qquad (1)$$

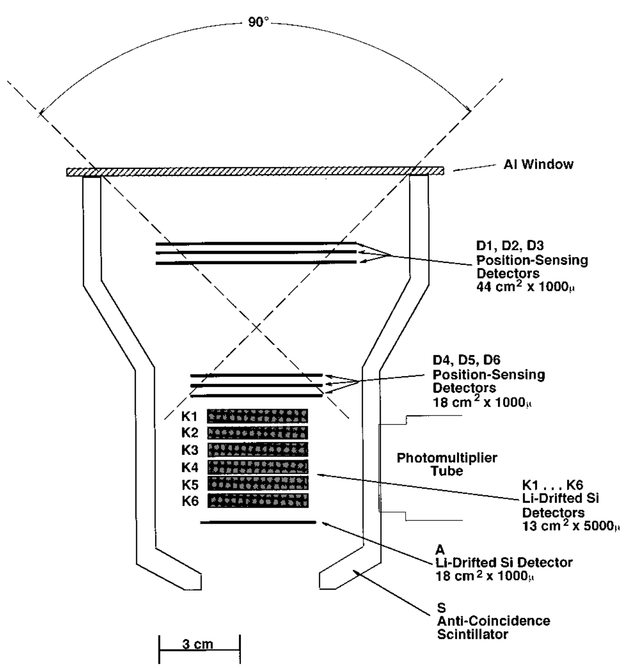

FIG. 2. Ulysses HET instrument cross section.

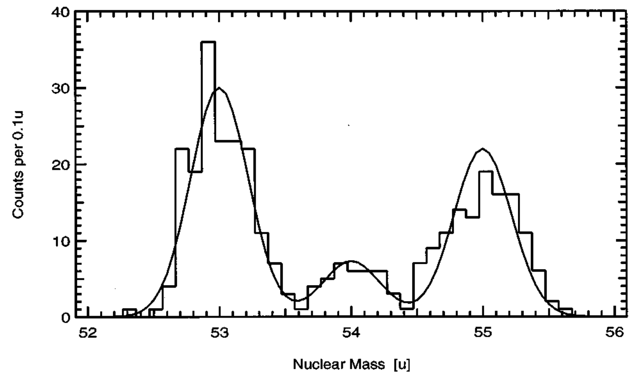

FIG. 3. Ulysses HET galactic cosmic-ray manganese histogram.

$N_i(E,x)$ is the energy and pathlength dependent abundance of the ith species; σ_i is the total nuclear spallation cross section; σ_{ij} is the partial cross section between species i and j; n is the number density of the interstellar material; N_0 is Avogadro's number; and T_i is the half-life of the radioactive species. The radioactive decays are considered for the fully stripped galactic cosmic rays: therefore, electron capture reactions are only possible via electron attachment from the ISM rather than from K-shell capture. Recent measured partial cross sections are used (e.g., [8]).

This number abundance is then integrated over the distribution of pathlengths (the PLD),

$$J_i(E)=\int_0^\infty N_i(x,E)PLD(x,E)dx. \qquad (2)$$

The PLD is the source function in this Green's function solution of the leaky box model. Examples of how this PLD is determined is detailed in a number of places [1,7,9]. More complete discussion of this model of cosmic-ray propagation, its derivation, and its limitations, can be found in [1,7].

Transport into the heliosphere is treated in a standard spherically symmetric model of the solar-wind modulation of the cosmic rays. The solar modulation has a slight, but measurable, effect on the ratios of the manganese isotopes. Solar modulation is parameterized by the force field value ϕ, but calculated through a more physical, and complicated, model. In terms of V, the solar-wind velocity, and κ, the diffusion coefficient,

$$\phi=\frac{1}{3}\int\frac{V(r)}{\kappa(r)}dr. \qquad (3)$$

The form $\kappa=\beta R$ is chosen, where β is the particle velocity in natural units, and R is the particle's rigidity. So ϕ is expressed in rigidity (MV). For the data set under consideration, an averaged value of ϕ=840 MV is used. This value is determined from the low energy α-particle flux in Earth orbit on the IMP-8 satellite. This tracks well with the Earth-based neutron monitoring stations. More detail can also be found, for example, in [1,7,9].

The stable cosmic-ray isotopes are insensitive to the density of the ISM in Eq. (1). However, for the radioisotopes the density becomes related to the confinement time of the

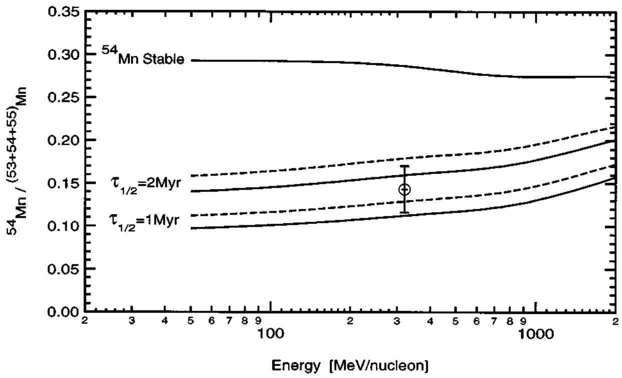

FIG. 4. ^{54}Mn/Mn data and transport model results: circle, Ulysses HET data; solid lines, 0.24 atom cm^{-3}; dashed lines, 0.33 atom cm^{-3}. Stable, 1 million, and 2 million year β^- partial half-lives.

cosmic rays in the galaxy. The density determines the physical length of the flight because the total amount of material passed through in the ISM is fixed by the PLD. The cosmic-ray velocity is known from its energy, hence

$$\lambda_{\text{escape}} = \rho \beta c T_{\text{escape}}. \tag{4}$$

Here, β is the velocity in natural units; ρ is the ISM density to the cosmic rays; λ_{escape} is the pathlength for galactic escape at the measured energy (from the PLD); and T_{escape} is the escape, or confinement, time.

The cosmic-ray confinement time is determined by running the propagation calculations for varying densities, matching the model output to the data, and converting that density into an escape time by Eq. (4). The resulting densities from experiments looking at ^{10}Be, ^{26}Al, and ^{36}Cl are reviewed in [9]. The densities scatter in the region of 0.24–0.33 atom cm^{-3}. This range should tighten considerably in the next year or so, when HET measurements of the above three chronometers are analyzed.

In this work, that range of densities is assumed, and then the β^- partial half-life of ^{54}Mn is varied. For the range of half-lives of 1–2 million years, the data agrees with the density range of 0.24–0.33 atom cm^{-3}. If the iron-group cosmic rays have a similar propagation history to the lighter cosmic rays, this is the allowed lifetime. This is summarized in Fig. 4. The errors on the ^{54}Mn isotopic fraction include both statistical and a conservative estimate of the systematics from the cosmic-ray transport model. The systematics are determined by varying the transport code's parameters and recording the sensitivity of the results to the uncertainties in the inputs.

The ^{54}Mn partial β^- half-life is restricted to the range of 1–2 million years in order for the iron-group cosmic rays to have the same propagation history as the lighter cosmic rays. This determination is robust to uncertainties in the propagation parameters and the statistical uncertainties of the measurement. A β^- partial half-life outside of the 1–2 million year range would alter our understanding of the iron-group cosmic rays.

In either case, a laboratory measurement of the β partial lifetimes would enable ^{54}Mn to be used as a cosmic-ray chronometer for the iron-group nuclei. Several investigators are considering searches for these β decays [10,11] since the estimate of the β^- lifetime from this work is only a factor of ~3.4 times longer than the indirect limit [12].

The Ulysses HET has allowed a measurement of the manganese cosmic rays with good isotopic resolution. This measurement has been analyzed using conventional models for the galactic and heliospheric transport of the cosmic rays. Examining the manganese data in light of the density of the ISM to the cosmic rays, a range of allowed β^- partial half-lives is obtained. This range is 1–2 million years, including statistical and systematic uncertainties in the measurement and the transport models. A lifetime in this range corresponds to a β^+ partial decay lifetime of ~0.5–2 billion years, depending on the relative phase spaces available between the two decays.

Hopefully within the next year or so there will be measurements of the β^+ or β^- partial decay lifetimes of ^{54}Mn. In addition to being a high-precision nuclear physics determination, this result is of considerable value to the understanding of the cosmic rays.

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