ELECTRON CAPTURE DECAY OF COSMIC RAYS: A MODEL OF THE INHOMOGENEOUS INTERSTELLAR MEDIUM

John R. Letaw
Severn Communications Corporation, Severna Park, MD 21146

Rein Silberberg and C.H. Tsao
E.O. Hulburt Center for Space Research
Naval Research Laboratory, Washington, DC 20375

1. Introduction. Traditional analyses of cosmic ray composition seek to identify the sources through a determination of the isotopic abundances of these nuclei prior to acceleration. At the same time, it is both necessary and interesting to understand the nature of the medium through which cosmic rays pass before arriving at our detectors. In fact, only within a model of the interstellar medium (ISM) sampled by cosmic rays can a refined estimate of source composition be made. In this paper we explore an elaboration of the traditional model of the ISM used in studying cosmic ray propagation. Inhomogeneity of the ISM is accomodated in this model. We find within this model that the abundances of some electron capture isotopes, specifically ^{44}Ti, ^{91}Nb, ^{93}Mo, ^{167}Tb, are very sensitive to density inhomogeneities which might be expected in the ISM. These nuclei therefore measure the penetration of heavy cosmic rays into interstellar clouds.

2. Model of the Homogeneous Interstellar Medium. McKee and Ostriker (1977) have characterized the ISM as having three components: (1) a hot component maintained by repeated supernova explosions, having a hydrogen number density of about 0.003 cm^{-3}, and filling about 75% of interstellar space, (2) warm clouds with density of 0.25 cm^{-3} filling most of the remaining space and having (3) cold cores with densities on the order of 40.0 cm^{-3}. If cosmic rays are allowed unrestricted access to interstellar clouds, most of the cosmic ray pathlength is accumulated in clouds. These circumstances are suggested by an examination of gamma ray data from molecular clouds (Issa et al., 1981) showing little cosmic ray enhancement or depletion within. Further support for unrestricted access may be based on the cosmic ray pathlength distribution which rules out trapping and escape from multiple cloud systems after acceleration. Compositional measurements proposed here can test the extent of cosmic ray access to interstellar clouds.

We assume that cosmic rays randomly (in time) encounter density fluctuations in the ISM which may be described by the distribution F(n) of interstellar gas number densities n. This function is normalized so that:

$$\int_0^\infty F(n)dn = 1 \qquad (1)$$

F(n) dn is the fraction of time a cosmic ray spends in regions near density n. Equivalently, it is the (spatial) fraction of accessible ISM with density n. If the entire ISM is accessible then models such as that of McKee and Ostriker (1977) may be invoked to estimate the density distribution.

The model is implemented by replacing the differential pathlength, dx, with xf(n)dn in propagation equations. f(n) is the fraction of cosmic ray pathlength over which the interstellar gas density is n. It is related to F(n) by:

$$f(n) = nF(n)/\langle n \rangle \tag{2}$$

where $\langle n \rangle$ is the mean density of the ISM (i.e., the expectation value of n relative to the distribution F(n)). Central to this model is the random association of density with time and accumulated pathlength. Thus this model differs from the extreme types of inhomogeneity proposed by Wiedenbeck (1983) and two-component ISMs which might be constructed from nested leaky box models.

No effect on the composition of most cosmic rays results from the introduction of inhomogeneities according to this model. Fragmentation of cosmic rays is independent of density, i.e.,

$$dJ \propto J\,dx \implies Jxf(n)dn \tag{3}$$

so that only the zeroth moment of the density distribution is sampled:

$$\ell n\, J \propto x \int_0^\infty n^0 f(n)\, dn = x \tag{4}$$

The abundances of stable secondaries are sensitive only to the total pathlength. They are independent of density.

Since the beta decay mean free path of radionuclides is inversely proportional to density (see, for example, Letaw et al., 1984), their abundance after passage through the ISM is given by

$$\ell n\, J \propto x \int_0^\infty n^{-1} f(n)\, dn = x/\langle n \rangle \tag{5}$$

where $\langle n \rangle$ is the spatial average of the number density. Radionuclides are therefore sensitive to the average density of the ISM and the total pathlength. The pathlength can be determined from stable secondary abundances, hence radionuclides provide a measurement of the mean interstellar gas density as sampled by cosmic rays. We show below how another moment of the ISM density distribution is sampled by electron capture isotopes.

3. Electron Capture Nuclides. Electron capture decay of cosmic rays is inhibited because most of these nuclei are fully ionized. Thus we

say most electron capture nuclides in cosmic rays are "attachment-limited" because they decay rapidly after an electron is attached. Some decays are held up more by the nuclear decay process than the attachment process; these are called "capture-limited." The distinction between capture-limited and attachment-limited nuclides is dependent on density. The effective mean free path for electron capture decay is:

$$\lambda_{eff} = \lambda_a (1 + kn\tau/\lambda_s) \qquad (6)$$

(Letaw et al., 1985). Here λ_a and λ_s are the attachment and stripping mean free paths respectively, τ is the mean decay time (with an electron attached), and k is the constant relating distance and time. When the first term in Eq. 6 dominates the decay is attachment-limited; when the second term dominates it is capture-limited. The two terms are equal at the transition density (n_T). The effective decay mean free path for ^{44}Ti at 100 MeV/N is shown in Fig. 1.

Eq. 7 shows the moment sampled by electron capture nuclides.

$$\ln J \propto x \int_0^\infty (1 + n/n_T)^{-1} f(n)\, dn \qquad (7)$$

If the density is always below the transition density, only the zeroth moment of the distribution is sampled as in fragmentation (Eq. 4). If the density is always above the transition density, only the mean density is sampled as in the decay of other radionuclides (Eq. 5). The latter case was explored by Raisbeck et al. (1975). We are interested in the intermediate case where new information about F(n) can be found.

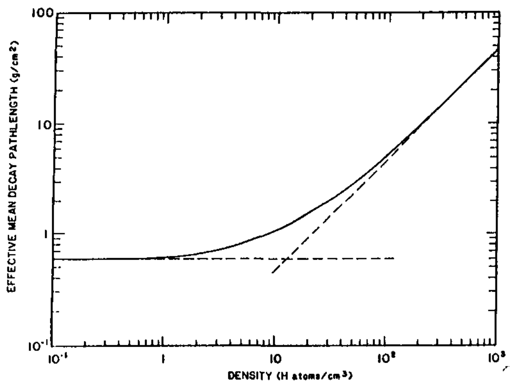


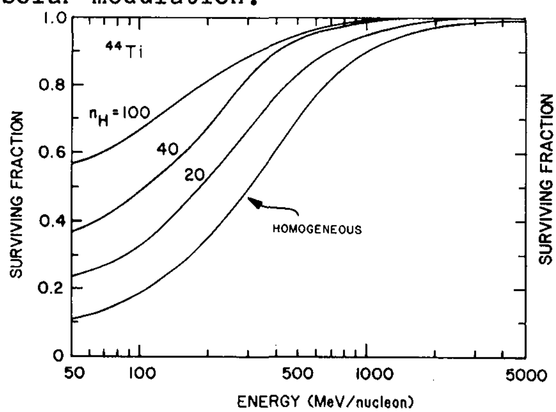
Fig. 1: Effective electron capture decay mean free path of ^{44}Ti at 100 MeV/N versus density.

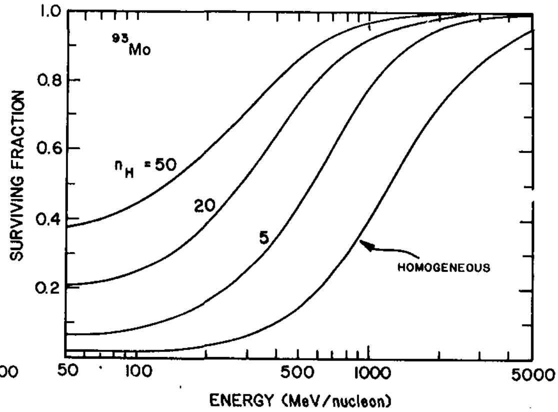
In an ISM with fixed mean density, maximum decay takes place when the medium is homogeneous. This follows from Fig. 1 where it is evident that the decay mean free path increases rapidly with density above n_T. Using a Dirac delta function for the density distribution in this case, we find the upper limit for Eq. 7 to be

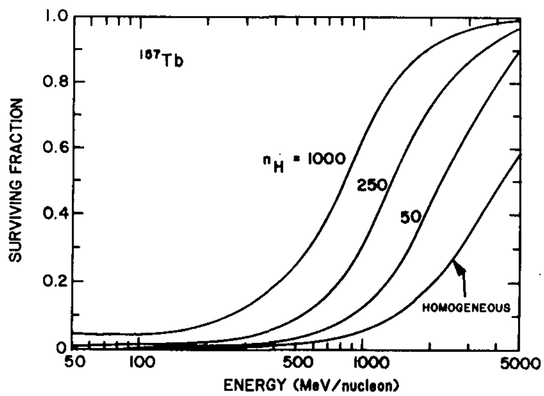
$$x\langle n\rangle/(1 + \langle n\rangle/n_T) \qquad (8)$$

Eq. 7 equals Eq. 8 not only in a homogeneous medium, but also when densities are much greater or much less than the transition density. Only when densities on both sides of the transition density are encountered will slower decay rates and higher surviving fractions be observed.

4. Results and Conclusions. Examples of increased survival fractions are shown in Figs. 2 through 4. The calculations were done for a simple two component medium with a density of 0.003 atoms/cm^3 in rarefied regions. A mean escape time of 10^7 years and rigidity-dependent mean pathlength were used to infer the sizes of clouds of various densities. Electron capture nuclides having interesting transition densities (between 1 and 50 atoms/cm^3) and long effective lifetimes were chosen for study. ^{91}Nb is similar to ^{93}Mo, but is not pictured because its halflife is unknown. We note that ultraheavy nuclides show enhanced survival at median cosmic ray energies. Enhancement of ^{44}Ti at low energies might be obscured by solar modulation.







Figs. 2-4: Survival fractions of ^{44}Ti, ^{93}Mo and ^{157}Tb for several ISM density distributions.

References
Issa, M.R., Riley, P.A., Pei, L.T., and Wolfendale, A.W., 1981,17th Int. Cosmic Ray Conf. (Paris), XG 4.3-4.
Letaw, J.R., et al. 1984 Ap. J. Suppl., 56, 369.
Letaw, J.R., et al. 1985, Ast. Sp. Sci., (November).
McKee, C.F. and Ostriker, J.P. 1977, Ap. J., 218, 148.
Raisbeck, G., Comstock, G.M., Perron, C., and Yiou, F. 1975, Proc. 14th Int. Cosmic Ray Conf., 2, 560.
Wiedenbeck, M.E. 1983, 18th ICRC, (Bangalore),OG 2-8.