GALACTIC PROPAGATION MODELS CONSISTENT WITH THE COSMIC RAY LIFETIME DERIVED FROM ^{10}Be MEASUREMENTS

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ABSTRACT

Using a propagation calculation with energy dependent parameters, including the depletion of short pathlengths, and incorporating experimental nuclear excitation functions, the variation of the ^{10}Be/^{9}Be ratio with the matter densities in two nested confinement regions is investigated. It is shown that there is no unique correspondence between a ^{10}Be/^{9}Be measurement at low energy and the density of matter in the galaxy. ^{10}Be/^{9}Be measurements at both low and high energy are needed to fully specify the matter densities.

1. **Introduction**   In recent years considerable progress has been made in determining the energy dependence of the pathlength distribution (PLD) for cosmic ray propagation at low energies in the interstellar medium (Garcia-Munoz et al., 1985). However, previous analyses of radioactive cosmic ray isotopes have been done in the context of the simple "leaky box" model, which does not explain, simultaneously, the energy dependence of the measurements of both light and heavy secondary to primary elements (such as B/C and V/Fe or Sc/Fe). In this report, we present results of propagation calculations for ^{10}Be/^{9}Be using experimental nuclear excitation functions and energy dependent parameters in the PLD which give results in agreement with both B/C and sub-Fe/Fe ratios from 100 MeV/n to 30 GeV/n.

2. **The Propagation Calculations**   The propagation code employs the weighted slab technique to calculate the abundances of 96 stable, long-lived or electron capture isotopes from ^{4}He to ^{64}Ni. Radioactive decay (β^{+}, β^{-}, electron capture) is treated explicitly; the effects of ionization energy loss are included; and energy dependent total inelastic cross sections, based upon compiled experimental data, are employed. The partial fragmentation cross sections are based upon semi-empirical formulae of Silberberg and Tsao (1973), modified using available experimental data. Cosmic ray source abundances are from Garcia-Munoz and Simpson (1979), and the ratio of H to He in the interstellar medium is from Cameron (1981). The majority of the cosmic ray data used here were collected during the last period of minimum solar modulation (1974-1979), and the calculations include modulation with an adiabatic deceleration parameter ϕ = 490 MV (Evenson et al., 1984).

The propagation code was run in two modes: single and double runs. In a single run, the abundances of all species were calculated for a series of slabs and then weighted by a single, energy dependent pathlength probability distribution. Such a PLD is illustrated in Fig. 1 where the inset (B) shows the overall

Fig. 1: The energy dependent DE PLD.

shape of the Double Exponential (DE) form, composed of two exponentials with means X_1 and X_2, where X_2 represents the depeletion of short pathlengths (Garcia-Munoz et al., 1984). The energy dependences of X_1 and X_2, shown on part A along with the mean pathlength $<X>$, are determined by fitting the B/C and sub-Fe/Fe data over the energy range 0.1 - 30 GeV/nucleon (Guzik and Wefel, 1984). The DE PLD is qualitatively similar to earlier models (Garcia-Munoz and Simpson, 1970), e.g. the PLD in the "nested leaky-box" model (Cowsik and Wilson, 1975), but is quantitatively different since our DE PLD includes energy dependent parameters.
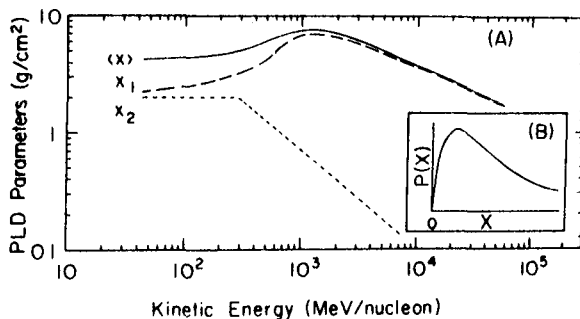
Fig. 2 shows a comparison of the calculated $^{10}Be/^9Be$ ratio for different PLD's, for a constant density of 0.5 atoms/cm^3. The dashed line is for a simple energy independent exponential which is characteristic of the "leaky box" model. Note that when energy dependence of the mean of the PLD is included (lower solid line) the shape of the predicted $^{10}Be/^9Be$ is modified. However, neither of these PLD's fit both the B/C and sub-Fe/Fe ratios. Such a fit requires an energy dependent depletion of short pathlengths (a truncated PLD, see Garcia-Munoz et al., 1984) and results for two types of truncation (yielding essentially identical results) are shown on Fig. 2 (upper solid and dot-dashed curves). Note that above several GeV/nucleon the curves converge, as expected, since at higher energies the truncation becomes negligable (c.f. X_2 on Fig. 1).

In analogy with the "nested leaky box" model, the two components of the energy dependent DE PLD can be associated with confinement in an inner region of density ρ_{IN} (i.e. around the sources) nested within an outer region of density ρ_{OUT} (i.e. the Galaxy) (Guzik and Wefel, 1984).
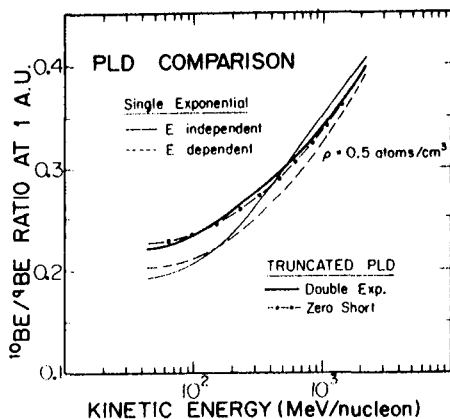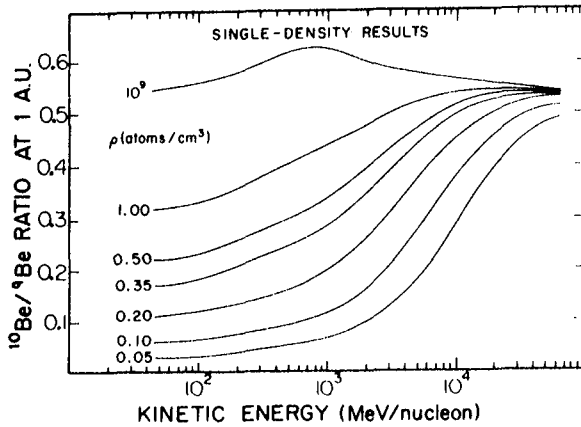

Fig. 2: $^{10}Be/^9Be$ results for different PLD's.

Fig. 3: ^{10}Be/^{9}Be ratio as a
        function of density.

Double runs were used to study this
configuration of confinement regions.
In the first step, the propagation code
is run with an exponential PLD whose
mean follows the curve given by X_2 on
Fig. 1. For this step the matter
density has the value ρ_{IN}. Next, the
results of step 1 are used as the
source for a second calcualtion (with
matter density ρ_{OUT}) whose PLD mean
follows the X_1 curve on Fig. 1. This
two step method allows us to treat
separately the densities in the inner
and outer regions, which, physically,
could be quite different.

3. Results   Figure 3 shows results
for different matter densities from
single runs using the DE PLD with
$\rho_{IN} = \rho_{OUT}$. The curves converge at
high energy due to relativistic effects,
and for low energy, the survival of ^{10}Be is directly dependent upon the
matter density. The low energy satellite experiments give a mean value
^{10}Be/^{9}Be = 0.13 ± 0.03 at ~100 MeV/n which implies from Fig. 3, a
matter density of 0.23 ± 0.06 atoms/cm^3, consistent with previous
results which employed single density analysis.

Fig. 4: Results of the two-
        step analysis compared to
        experimental data.

Fig. 4 shows the result of the two-step calculations compared to
experimental data (o, ● – Garcia-Munoz et al., 1977, 1981;
□ – Wiedenbeck and Greiner, 1980; ▽ – Webber et al., 1977; ▼ –Webber and
Kish, 1979; △ – Hagen et al., 1977). The top panel shows the
calculated ^{10}Be/^{9}Be ratio for fixed ρ_{OUT} with ρ_{IN} allowed to vary from
0.05 to 10^9 atom/cm^3. Different values for ρ_{IN} spread the predicted
^{10}Be/^{9}Be ratio at low energy by about a factor of two. The curves
converge above 1 GeV/n since the effect of the inner region decreases
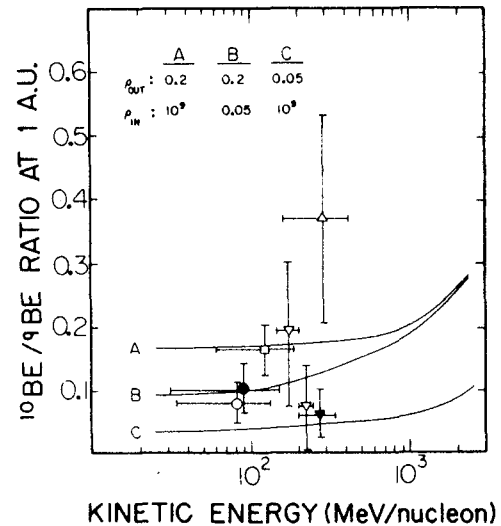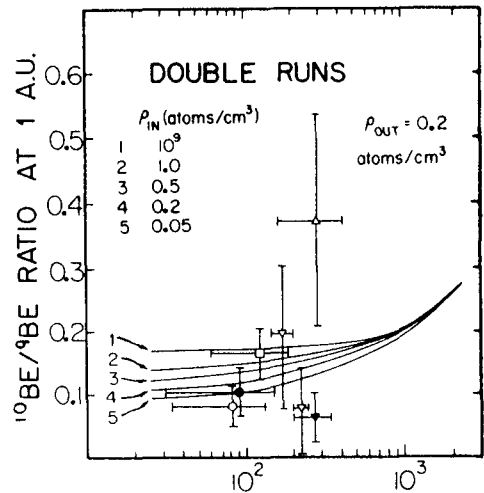with increasing energy. In this model a measurement of the ^{10}Be/^{9}Be

ratio does <u>not</u> uniquely determine the density in the confinement region.

The measured ^{10}Be/^{9}Be ratio at low energy can provide bounds on the density in the outer region. This is illustrated in the lower panel of Fig. 4 where curves A and B show the total spread in the predicted ratio for ρ_{OUT} = 0.2 atoms/cm^3. Assuming a large value for ρ_{IN} allows a smaller value of ρ_{OUT} to be used to reproduce a given value of the ^{10}Be/^{9}Be ratio, as shown by curve C which forms a lower bound to the experimental data. Conversely, assuming a minimum value for ρ_{IN}, a value of ρ_{OUT} = 0.5 atom/cm^3 give an upper limit to the low energy data. Thus, the available measurements constrain ρ_{OUT} to the range 0.05 – 0.50 atoms/cm^3, below the average density of ~1 atom/cm^3 for the galactic disk and above the density of 0.01 atoms/cm^3 of a galactic halo.

<u>4. Conclusions</u>   The cosmic ray PLD, including an energy dependent depletion of short pathlengths, can be represented as two "nested" confinement regions having different matter densities. The available ^{10}Be/^{9}Be measurements do not uniquely determine the density in the outer region, but they do limit the allowed values to a range of 0.05 and 0.50 atoms/cm^3. ^{10}Be/^{9}Be data at high energy (currently unavailable) combined with existing measurements at low energy can determine the matter density in <u>both</u> volumes.

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