CHARGE AND ENERGY DEPENDENCE OF THE RESIDENCE TIME OF COSMIC RAY NUCLEI BELOW 15 GEV/NUCLEON

A. Soutoul, J.J. Engelmann, Ph. Ferrando, L. Koch-Miramond, P. Masse
Service d'Astrophysique, CENSaclay, F-91191 Gif sur Yvette CEDEX FRANCE

W.R. Webber
Space Science Center, University of New Hamsphire, Durham,NH03824 USA

1 INTRODUCTION.

The relative abundance of nuclear species measured in cosmic rays at earth has often been interpreted with the simple leaky box model. For this model to be consistent an essential requirement is that the escape length does not depend on the nuclear species. The discrepancy between escape length values derived from iron secondaries and from the B/C ratio was identified by Garcia-Munoz and his co-workers using a large amount of experimental data [7-10]. Ormes and Protheroe found a similar trend in the HEAO data although they questioned its significance against uncertainties [9]. They also showed that the change in the B/C ratio values implies a decrease of the residence time of cosmic rays at low energies in conflict with the diffusive convective picture [11-12]. These conclusions crucially depend on the partial cross section values and their uncertainties. Recently new accurate cross sections of key importance for propagation calculations have been measured [6] Their statistical uncertainties are often better than 4% and their values significantly different from those previously accepted [6]. In this paper we use these new cross sections to compare the observed B/C+O and (Sc to Cr)/Fe ratio to those predicted with the simple leaky box model.

2 PROPAGATION CALCULATIONS.

We have used the Comstock computer code previously used by Koch et al,Perron et al.[1-2-3]. The calculation is performed for the simple leaky box model, with an exponential distribution of path lengths in pure hydrogen and takes into account β-decay for long lived species,ionisation energy losses and solar modulation using the force field approximation [4].

The neglect of interstellar helium in propagation calculations is questionable (see OG 7.2-11 this conference).

The input source spectra are identical for all species with a power law in momentum [5].

Nuclear cross sections are based on experimental data wherever possible and are listed in Perron et al. [2]. The cross sections for boron and iron secondaries are those measured by Webber [6]. We otherwise use Silberberg and Tsao's formulae [19].

The computer code uses a stepwise procedure to solve the set of first order differential equations. In the energy and charge range of this paper the energy loss term cannot be neglected and we have checked that it is accurately calculated.

3 RESULTS.

Above 1 GeV/n and at low energies we analyse satellite data which are free from atmospheric effects and have high statistical accuracy [7-8]. At intermediate energies we analyse balloon data as well [13-14-15-16-17-18]. The experimental data for the B/C+O ratio are shown in figure 1. This ratio was chosen because it is relatively insensitive to possible small differences between observed and computed C/O ratio throughout the whole energy range [5]. Also we adjust the source abundances especially those of the main progenitors of boron so that their calculated abundances are close enough to their observed values.

We first compare the calculation to the HEAO B/C+O data. The deceleration parameter appropriate for these data is taken equal to 600MV [5]. We try values of the mean escape length varying with energy according to:

$$(1)\quad \lambda esc=\lambda b*\beta*R^{-\delta} \qquad R > 5.5GV$$
$$\lambda esc=\lambda b*\beta*5.5^{-\delta} \qquad R < 5.5GV$$

where R and β are the interstellar values of the rigidity and the velocity relative to that of light.

We find that λb=24.0 g/cm² and δ=.65 provide a reasonably good agreement in the HEAO energy range (see figure1).

Then we perform a set of propagation calculations with a grid of slightly different values of λb around its nominal value. From this we can derive the values of λesc which precisely yield all the observed B/C+O values and their statistical uncertainties as well (figure 3).

This procedure is repeated for the (Sc to Cr)/Fe ratio with trial functions:

$$(2)\quad \lambda esc=\lambda f*\beta*(1+.4/Ekin)*R^{-\delta} \qquad R > 5.5GV$$
$$\lambda esc=\lambda f*\beta*(1+.4/Ekin)*5.5^{-\delta} \qquad R < 5.5GV$$

where Ekin is the interstellar kinetic energy in GeV/n. The term in parenthesis takes conveniently care of a steepening that is not present in the B/C+O data. Good agreement with the data is found for λf=26.8 g/cm² and δ=.65 (see figure2). From a set of propagation calculations with different λf we derive the λesc values yielding each experimental point (figure 3).

We then compare the B/C+O ratio calculated with (1) to the low energy data.

For this ratio the calculation is dependent on the adopted solar modulation level. Figure 1 shows the calculated curves for 490MV and 350MV [7] (See also OG 4.1-2 this conference). We also wish to check the sensitivity of these results to the adopted β dependence in (1) (constant residence time below 5.5GV). The ratio calculated with a mean escape length independent of energy and equal to 7 g/cm² is plotted on figure 1 for the same levels of modulation as above.

For the (Sc to Cr)/Fe the low energy results of calculations with constant escape length are shown on figure 2. Three distinct values are considered: 7g/cm²,which is appropriate for comparison to the low energy B/C+O data; 11g/cm² consistent with that found around 2GeV/n and finally an infinite escape length correspondind to complete confinement.

4 DISCUSSION.

The abundance ratio calculated with (1) and (2) and a deceleration parameter of 600MV agree reasonably well with the HEAO data (figure 1 and 2).

Perron et al. have suggested that these data are consistent with larger values of δ than previously calculated from balloon data [2]. Further calculations showed that even larger values of δ would provide a better fit [3-9]. Our adopted value of δ is in agrement with these results. The flattening in λesc for boron is not observed for iron secondaries, in the HEAO data (see figure 3).This difference could be even more marked below 1GeV/n although large statistical uncertainties of the (Sc to Cr)/Fe ratio in balloon data do not allow to draw firm conclusions. Interestingly enough the low energy satellite data and the HEAO data around 1 GeV/n are consistent with the same value of λesc within uncertainties for iron secondaries (see figure 2).

At low energies the dependence of the escape length with energy from the B/C+O ratio is less than previously reported [7-9-10]. Indeed if a modulation level as low as 350MV is adopted a constant grammage(7 g/cm²) would keep agreement with the B/C+O data,whereas for a larger modulation level a constant residence time would agree better.

The values of λesc yielding the experimental HEAO ratio are shown in figure 3 together with those calculated from (1) and (2). The differences between the escape length values derived from iron secondaries and from boron are statistically significant especially below 4 GeV/n. They are larger than those reported by Koch et al. and similar to those from Ormes and Protheroe [3-9]. At low energies, calculations with the escape length from B/C+O ratio underestimate iron secondaries by a large factor (see figure 2). Above 1GeV the (Sc to Cr)/Fe ratio predicted from (1) is also plotted on figure2. The underestimate of this ratio resulting from the use of (1) could be accounted for by a 5% overestimate of partial cross sections for boron and an underestimate of similar amount for those of subiron secondaries. Systematic errors can be generated by the calculation of cross sections. Partial cross sections from iron have been accurately measured at several energies below 2GeV/n and show a rather steep and quite consistent energy dependence [6]. Starting from this grid the program calculates the cross sections at all other energies.We estimate that for reasonably smooth interpolation , possible systematic errors on the calculated ratio below 2 GeV/n are less than 4% for iron secondaries and even smaller for boron where partial cross sections are nearly independent of energy.

5 CONCLUSION.

We have compared the observed B/C+O and (Sc to Cr)/Fe ratio between 100 MeV/n and 15 GeV/n to those calculated with the simple leaky box model. This calculation incorporates several important cross sections recently measured with high accuracy [6]. The large energy range considered here allows a detailed study of their energy dependence. At high energies our adopted rigidity dependence agrees well with previous studies [3-9].

For the B/C+O ratio the data from 2 GeV/n down to 100 MeV/n can be accounted for with a constant escape length if the modulation is moderately strong(350MV). If the modulation is as strong as 500MV a turn over may be present around 2.GeV/n and a constant residence time consistent with diffusion convection theory would agree better with the data [12].

The (Sc to Cr)/Fe ratio is less sensitive than the B/C+O ratio to the precise shape of the escape length energy dependence below 2Gev/n. The IMP data at low energy and the HEAO data below 2Gev/n can be accounted for with similar values of the escape length within uncertainties,whereas at intermediate energies larger values would provide a better agreement with the ballon data.

However, our calculations fails to reproduce the observed ratios with the same escape length for boron and iron secondaries. This effect is quite marked at low energies and it is still present in the HEAO data at least up to 4GeV/n. Part of this discrepancy may be due to our interpolation of partial cross sections. Some truncation of pathlength may be indicated by the low and high energy data as well [7-10].

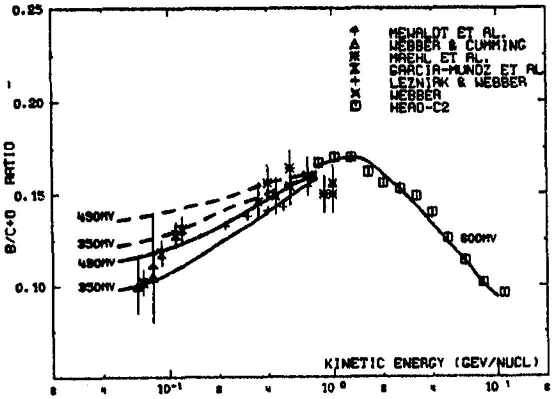

FIG 1- B/C+O RATIO
Full lines: calculated with formula (1). See text.
Dashed lines:calculated with escape length 7 g/cm2. Modulation level as indicated.

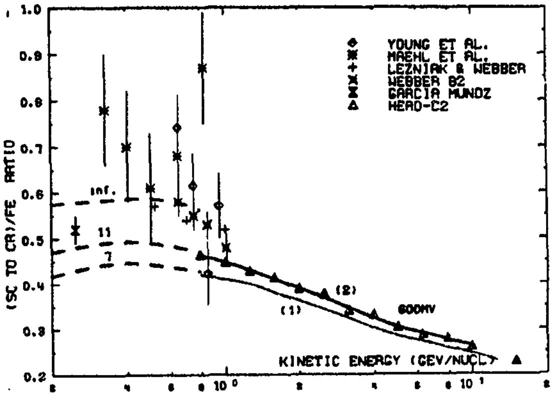

FIG 2- (Sc to Cr)/Fe RATIO
Full lines: calculated with formula (1) or (2). See text.
Dashed lines:calculated with constant escape length. From top to bottom: infinite (complete confinement), λesc=11 g/cm2 , λesc=7 g/cm2

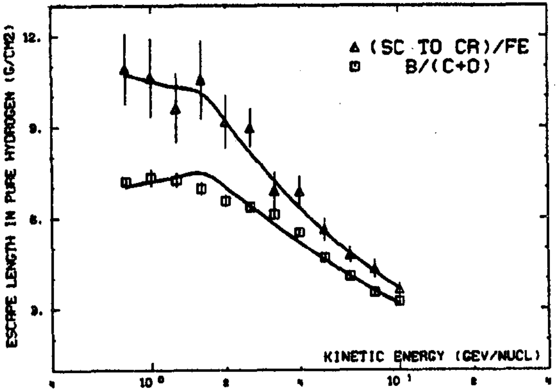

FIG 3- ESCAPE LENGTH IN PURE HYDROGEN FROM THE HEAO DATA.
Data points:escape length values from observed ratio of fig 1 and fig 2. Uncertainties: statistical only. Full lines:calculated from formula(1) (bottom) and formula(2) (top).

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