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IMPLICATIONS OF HEAO-3 DATA FOR THE ACCELERATION AND PROPAGATION OF GALACTIC COSMIC RAYS

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Abstract

We re-examine the energy dependence of the mean escape length of cosmic rays from the galaxy in the light of recent measurements of cosmic ray abundances from the Danish-French experiment on HEAO-3. On comparing these data with results of our propagation calculations, we find that the energy dependence is steeper than previously thought. The boron to carbon, nitrogen to oxygen and $21 < Z < 25$ to iron ratios at energies above 2.8 GeV/nucleon are best fit with 95 percent confidence by a rigidity dependence $R^{(-0.7\pm0.1)}$. This, coupled with the absence of structure in the proton spectrum to 10^{14} eV, implies that 1 GeV/nucleon cosmic rays do not diffuse more than a few hundred parsecs from their sources during their 10^7 year lifetime. Further, if the source spectrum is produced by shock acceleration, the shocks must be strong (compression ratio 4 or certainly greater than 3.5). The shapes of the observed energy spectra are well fit by this source spectrum. We also agree with earlier conclusions by the Chicago group concerning the impact of their data from IMP on the decrease in the path length at lower energies (< 1 GeV/nuc). We discuss implications for the shape of the cosmic ray path length distribution at short path lengths and on the galactic wind model for the loss of cosmic rays from the galaxy by convection.

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I. Introduction

Highly accurate new data on the relative abundances of cosmic ray nuclei (boron through nickel) in the energy range 0.9 to 15 GeV/nucleon are now available (Engelmann et al., 1981). These data have been obtained on the Danish-French collaborative experiment (Bouffard et al., 1982) flown on board the HEAO-3 satellite which was launched on September 20, 1979. At the same time, new more accurate measurements of some of the cross sections upon which an interpretation of these data must be based have been made and are available (Webber and Brautigam, 1982; see also survey of total cross section measurements by Letaw et al., 1982). Using these new data and earlier low energy measurements, we have re-examined the nature of cosmic ray acceleration and propagation.

The energy dependence of the secondary to primary ratios allows us to determine the energy dependence of the mean escape length, λ_e. We shall use this, together with the measured proton energy spectrum to infer the source spectrum, i.e., the spectrum of cosmic rays after acceleration. The result will be discussed in terms of predictions of shock acceleration models (Axford, Leer and Skadron, 1977; Bell, 1978a and b; Blandford and Ostriker, 1978 and 1980). The energy dependence of the mean escape length inferred from the data at low energies has previously been shown by the University of Chicago group (Garcia-Munoz et al., 1979) to require a reduction in λ_e with decreasing energy below ~ 1 GeV/nuc. We find this reduction is more rapid than can be accounted for in dynamical halo models. Using the inferred source spectrum and energy dependence of λ_e we will show that the observed energy spectra of primary species can be satisfactorily accounted for.

II. Source Spectra

Cosmic ray energy spectra must reflect the mechanism by which they have been accelerated. The range from 100 MeV/nuc to 1 GeV/nuc, in which particle energies transition from the non-relativistic to the relativistic regime, is particularly crucial in this regard as, at these energies, the effects of the various mechanisms differ and are reflected in the predicted spectral shapes. In this section we shall discuss the shape of the spectra predicted by shock acceleration models over the whole energy range accessible to observation of the galactic cosmic rays.

At energies where individual cosmic ray species may be identified, it is customary to measure their flux as a function of kinetic energy per nucleon, T. Previous analyses of the solar modulation have shown that the demodulated spectrum outside the heliosphere must lie somewhere between a power law in total energy and a power law in rigidity with exponent -2.7. These spectra cannot be distinguished at high energy. Extensive analyses by the University of Chicago group (Garcia-Munoz et al., 1975a and 1975b), taking account of solar modulation and assuming energy independent propagation, give a best source spectrum $\frac{dJ}{dT} \propto \{T + 400 \text{ MeV/nuc}\}^{-2.6}$ at energies below a few GeV/nuc. This spectrum is plotted in Figure 1. However, this is only an empirical fit to the data, and it would be desirable to find a theoretical justification for this shape.

The shock acceleration mechanism gives a definite prediction for the shape of the source spectrum. This, along with our current understanding of the propagation of cosmic ray nuclei allows us to predict the interstellar energy spectra of cosmic ray nuclei. We summarize here the relevant discussion of acceleration of cosmic rays by shocks (see review paper by Axford, 1981).

A plane shock of infinite extent will produce a density of particles, N, which is a power law in momentum, p,

$$dN = kp^{-(2 + \varepsilon)}dp \ , \tag{1}$$

where the exponent depends upon the strength of the shock. Defining r as the ratio of the velocities of the shocked and the unshocked materials, V_1 and V_2 respectively, then

$$\varepsilon = \frac{4 - r}{r - 1} \ . \tag{2}$$

For strong shocks, r = 4, hence ε = 0.

The acceleration mechanism involves momentum rather than rigidity. This is because the relative motion of the shocked and unshocked material provide a momentum increment each time a particle crosses the shock boundary, even though the scattering mechanism which keeps the particle near the shock front may be a rigidity dependent phenomenon due to the magnetic turbulence. A power law results, the high energy particles having traversed the shock many times.

In the event of acceleration by more than one shock, the spectrum will be determined by the strongest shock. Axford (1981) shows that shocks which are strong enough to produce the cosmic ray spectrum occupy only a small volume of space, so it is unlikely that the observed particles have been subjected to more than one strong shock during their lifetime.

The maximum energy to which particles can be accelerated will depend upon how long they can be trapped near the shock front. While the power law produced is <u>independent</u> of the scattering mechanism (hence not a rigidity process), the energy at which the trapping mechanism begins to break down will be rigidity dependent. One of two factors will ultimately limit the rigidity to which particles can be accelerated: a) the gyro-radius of the particles could be so large that the shock no longer looks planar; b) the particles could fail to be trapped near the shock front (diffusion coefficients tend to rise with increasing rigidity) for a sufficiently long time (the higher the energy, the longer the acceleration time required). In either case, the mechanism will break down at constant rigidity. Current estimates for the maximum rigidity that can be obtained by acceleration in supernova shocks are less than 10^6 GV/c (Cesarsky and Lagage, 1981).

As a function of kinetic energy per nucleon, the cosmic ray energy spectrum per unit volume at production (equation 1) becomes:

$$dN = kp^{-(2 + \varepsilon)}(A/\beta c)dT \qquad (3)$$

where A is the atomic mass number of the nucleus and βc is the particle velocity.

Converting from particle density, N, to flux, J, we obtain:

$$dJ = kp^{-(2 + \varepsilon)}(A/4\pi)dT. \qquad (4)$$

We compare in Figure 1 this source spectrum expected for strong shocks ($\varepsilon << 1$) with that obtained from the low energy data as discussed earlier. From 100 MeV/nuc to 1 GeV/nuc the spectra agree within 30 percent when normalized at 1 GeV/nuc.

The spectrum $(T + 400)^{-2.6}$ has been used to interpret cosmic ray propagation data (Garcia-Munoz et al., 1981a and references therein). This spectrum, when propagated in an energy independent manner, gives a reasonable fit to the demodulated spectra. However, it must be modified for energy dependent propagation effects in order to derive a source spectrum. Webber (1981) came to a similar conclusion and showed that the source spectrum at high rigidity should be of the form $dJ/dT \propto R^{-(2+\varepsilon)}$. We use the source spectrum given in Equation (4) to interpret the data at all rigidities.

III. Propagation Effects

The cosmic ray spectra outside the heliosphere will be affected by the propagation of the particles from their source through the interstellar medium. For secondary nuclei, which are produced by interactions in the interstellar material, the source spectra will be similar to the equilibrium spectra of the primaries. Above a few GeV/nuc, the spectra of secondaries are observed to be steeper than of primaries (see e.g., Ormes and Freier 1978). In the leaky box model (see Cowsik et al., 1967) or in a diffusion picture (see Ginzburg and Ptuskin, 1976), higher energy particles must leak out of the galaxy more easily (faster) in order to produce equilibrium spectra that are steeper than source spectra (as reflected in the steeper spectra of secondary nuclei).

Assuming for the moment that the mean escape length can be represented as a power law of particle rigidity, $\lambda_e \propto R^{-\delta}$, the observed spectrum at energies above a few GeV/nuc will be

$$\left(\frac{dJ}{dT}\right)_{observed} \propto \left(\frac{dJ}{dT}\right)_{source} R^{-\delta} \propto R^{-(2 + \varepsilon + \delta)} \qquad (5)$$

whenever escape losses are dominant over other possible loss mechanisms. For protons, the interaction length in interstellar matter, λ_{int}, is about 60 g/cm^2 (i.e., $\lambda_{int} >> \lambda_e$) so interaction losses can be ignored, and the high energy proton spectrum can be used to determine $2 + \varepsilon + \delta$. Proton spectral measurements (Ryan et al. 1972; Gregory et al., 1981; Tasaka et al., 1982) up to 10^5 GV/c rigidity (10^{14} eV) give $2 + \varepsilon + \delta = 2.70 \pm 0.05$. We will infer the slope of the injection spectrum of primary species after obtaining δ from the energy dependence of ratios of secondary to primary nuclei in the cosmic rays in the next section.

III-1 Mean Escape Length at High Energy

In the early seventies it was discovered that the mean escape length decreases monotonically with energy above a few GeV/nuc (Smith et al., 1973, Juliusson and Meyer, 1973). On the other hand, at low energies the mean escape length becomes constant (Protheroe, Ormes and Comstock, 1981, and references therein) or even decreases (Garcia-Munoz et al.. 1981b). The new HEAO-3 data cover the energy range 0.9--15 GeV/nuc nd are of very high statistical accuracy. The available data on the energy dependence of the boron to carbon ratio from this experiment are plotted in Figure 2. We also show data obtained on both satellites and balloons. The satellite data at low energy (Garcia-Munoz et al., 1979) are from IMP, and the higher energy data (Engelmann et al., 1981) are from the HEAO-3 cosmic ray experiment for which the quoted statistical errors are less than ±2%. Note how rapidly the HEAO-3 data falls with energy above 1 GeV/nuc. The balloon data are from a variety of observations with individual references listed separately at the end of the paper (original compilation, Garcia-Munoz et al., 1981b, with additions). They are shown in order to indicate the general agreement between these and the new more accurate satellite observations. This agreement is important because of a potential problem with the HEAO-3 data. In order to avoid triggering on delta rays with high Z nuclei, a compromise had to be made in flash tube triggering efficiency for low Z nuclei. As a result, not every low Z nucleus produced a recognizable track in the flash tube array (Rotenberg et al., 1981). Because of this inefficiency, lithium and some of the beryllium data cannot be used. At the quoted accuracies, it is possible that an energy dependent bias in the flash tube efficiency could affect the boron to carbon ratio. Both the agreement with the balloon data and, as we shall see later, other secondary to primary ratios which are not subject to this bias show this is probably not the case.

To determine the mean escape length as a function of energy, we have performed a propagation calculation for the leaky box model which takes into account nuclear interactions, radioactive decay, ionization energy losses and solar modulation. Details of the method of calculation are given in our earlier work (Protheroe, Ormes, and Comstock, 1981). In the present calculation we have used source elemental abundances derived from the HEAO-3 data (Perron et al., 1982). We assumed the isotope ratios at the source to be as in solar material (Cameron, 1980), except for C, O, Ne, Mg, and Si for which we used those obtained by Wiedenbeck and Greiner (1981). For source abundances of the sub-iron group (Sc--Mn) we have taken the local galactic abundances (Meyer, 1979). We have used energy dependent total cross sections calculated from formulae of Letaw et al. (1982). For spallation cross sections, we have used the semi-empirical formulas (Silberberg and Tsao, 1973a, b, 1977a,b,c; Tsao and Silberberg, 1979). The semi-empirical cross sections for spallation of iron have been normalized to the recent measurements of Webber and Brautigam (1982) at 980 MeV/nucleon.

Since the spallation and total interaction cross sections are expected to be almost independent of energy above ~ 2.3 GeV/nuc (Silberberg and Tsao, 1977a), by comparing the results of our propagation calculations with the secondary to primary ratios observed above this energy from the HEAO-3 experiment, we should be able to determine δ very well. We can also determine the normalization of λ_e but, for this, we must take into account a systematic error due to uncertainties in spallation cross sections. For example, the measurements for iron fragmentation cross sections of high statistical accuracy (3-4 percent) at 660 MeV/nuc and 980 MeV/nuc (Webber and Brautigam, 1982) indicate substantial energy dependence in the cross sections which are not matched by a comparable accuracy in the semi-empirical relationships used to calculate cross sections at all other energies. Furthermore there are no measurements of comparable accuracy at energies above 1 GeV/nuc and for many of the other relevant partial cross sections. Because of these limitations, we estimate the uncertainty in the normalization for λ_e due to cross sections uncertainties to be of the order of 10 percent. Previous estimates of the uncertainties are even larger (30 percent, Raisbeck, 1979 and 15 percent Webber and Brautigam, 1982).

In this section, we shall restrict our analysis to the high energy data (2.8-15 GeV/nuc) to probe the assymptotic behavior of λ_e, avoiding biases introduced at low energies by solar modulation effects, strong energy dependence of cross sections, and velocity dependent propagation effects. For a source spectrum appropriate to acceleration by strong shocks, i.e., dJ/dT α p^{-2}, we have calculated the energy dependence of secondary to primary ratios for two possible forms of the energy variation of λ_e:

$$\lambda_e = \Lambda_R R^{-\delta_R}, \tag{6}$$

and

$$\lambda_e = \Lambda_T T^{-\delta_T}. \tag{7}$$

We show in Figure 3 the results of a comparison of these propagation calculations with various secondary to primary ratios obtained from the HEAO-3 data over the restricted energy range 2.8--15 GeV/nuc. The results are given, for three important secondary to primary ratios, in the form of the χ^2 contour plot in the Λ -δ plane. For clarity, only the contour corresponding to the 95 percent confidence interval has been plotted. From this figure, it is clear that for these almost purely secondary to primary ratios (i.e., B/C, N/O, Sc-Mn/Fe) the HEAO-3 data give a best value of δ somewhat higher than previously realized. From all those ratios, we find $\delta_R \approx 0.7 \pm 0.1$ for the rigidity dependent fit (Equation 6) and $\delta_T \approx 0.63 \pm 0.1$ for the kinetic energy per nucleon dependent fit (equation 7). There is sufficient internal consistency between the calculations and the different ratios that we see no reason to question the boron to carbon ratio from HEAO-3 as published.

Previous estimates based on balloon data (see data survey references) of the boron to carbon and other secondary to primary cosmic ray ratios placed δ_T in the range 0.3-0.5. Two problems may have resulted in these lower values of δ_T. First of all, the data were of much poorer statistical significance, and so the structural features were not so pronounced. Second, the data in the atmosphere at high energy is subject to large atmospheric corrections. The latter problem is not present in the HEAO-3 observations. As to the former problem, when we attempted fitting the HEAO-3 data over a wider energy range, consistently poor χ^2 values resulted. Perron et al. (1981) in their analysis of the HEAO-3 Be and B data suggest larger values of δ would fit better, and it is clear from the figures in their paper that they too obtain poor fits with δ = 0.5 variation. If one were to ignore the quoted errors and include data at lower energies in the fit, lower values of δ_T could easily be obtained. Kinematic effects make δ_R larger than δ_T in this energy range. While kinetic energy has often been used because it is the observers variable, magnetic scattering is a phenomenon in which rigidity is the more natural variable and so we presume that is the correct physical variable.

From the results of our propagation calculation, as shown in Figure 3, we find that the best value of Λ as obtained from the ratio of iron-secondaries to iron is about 10 percent higher than that obtained from the boron to carbon ratio. This is consistent with a slightly truncated pathlength distribution, for example as expected in the nested leaky box model (Cowsik and Wilson, 1973). It would imply about 8 percent of λ_e could be in the source region. Unfortunately, this conclusion cannot be reached because of previously mentioned uncertainties in spallation cross sections. To illustrate this point the acceptable range of Λ_R, obtained from the boron to carbon data allowing for a 10 percent uncertainty in the partial cross sections, has been added to Figure 3(a) and includes the region between the two dashed lines. The 'best' values of Λ_R obtained from the three secondary to primary ratios shown in Figure 3(a) appear to be entirely consistent if uncertainties in spallation cross sections of ~ 10 percent are taken into account. For further discussion of truncated pathlength distributions, see Protheroe, Ormes, and Comstock (1981) and Garcia-Munoz et al. (1981a).

Care must be taken in interpreting the normalization constants given in Figure 3. The fits are valid at 2.8 GeV/nuc and above, and the normalization constants apply to much lower energy (rigidity). From the B/C contour in Figure 3b and Equation (7), one can readily show that the value of λ_e at 5 GeV/nuc is about 6 g/cm^2, consistent with previous analyses.

III-2 Mean Escape Length at Low Energies

Before interpreting the abundances of the lower energy nuclei in terms of the propagation of cosmic rays in the interstellar medium, we must allow for the effects of solar modulation. We use the simple force field approximation (Gleeson and Axford, 1968) to calculate modulated spectra (observed spectra) from interstellar spectra. Throughout the remaining work, we will adopt a deceleration parameter ϕ = 600 MV appropriate to near solar maximum conditions (Urch and Gleeson, 1973). This corresponds to a mean energy loss of 300 MeV/nuc for nuclei with A/Z = 2.

The variation of λ_e with energy below a few GeV/nuc is difficult to determine reliably. This is because the precise energy dependence of many of the important spallation cross sections are not measured as a function of energy and because the secondary to primary ratios are altered by solar modulation. It is clear, however, that the escape length must flatten off or decrease with decreasing energy below a few GeV/nuc. This is indicated in Figure 4 where we plot the energy dependence of the boron to carbon ratio obtained from the satellite experiments. In the figure we show the result (solid curve labelled n = 0) of extrapolating the rigidity dependence of λ_e derived in Section III-1 (from the high energy data) to lower energies where the calculated boron to carbon ratio is seen to lie significantly above the data. We will now discuss the deviation of λ_e from a simple power law in rigidity.

A power law rigidity dependence of the mean escape length, $\lambda_e \propto R^{-\delta}$, is expected in diffusion models (e.g., Ginzburg and Ptuskin, 1976) for a rigidity dependence of the diffusion coefficient of the form

$$\kappa = \kappa_0 \beta R^{\delta}. \tag{8}$$

This does not give the required flattening or reduction in λ_e at low energies. Jones (1979) and Freedman et al. (1980), following the suggestions of Jokipii (1976) and Owens and Jokipii (1977), realized that if the cosmic rays were convected outward in the halo, at some low energy the escape length would turn over because the time to escape would become independent of particle velocity, and hence the escape length would be proportional to velocity. The relative importance of convection and diffusion may be given in terms of a parameter q_o (Kota and Owens, 1980) given by

$$q_o = V_{conv}\, s/\kappa_o \qquad (9)$$

where s is the size of the halo propagation region. In Figure 4, we show (dashed lines) results for a dynamical halo model calculated for $q_o = 1$ and 3 such that in the diffusion dominated regime (high energies) the variation of λ_e with rigidity is as determined above (Equation 6). These results indicate that the rapid reduction in λ_e required by the low energy data (Garcia-Munoz et al., 1979) cannot be reproduced by the slower variation produced by the dynamical halo model.

In order to parameterize how rapidly λ_e must decrease at low energies, we will compare the low energy observations of secondary to primary ratios and the spectral shape with a mean escape length which involves a power of the particle velocity. The form we adopt is

$$\lambda_e = A\{1 + (R_o/R)^2\}^{-n/2}\, R^{-\delta} \qquad (10)$$

where $R_o = 1.88$ GV/c. For nuclei with A/Z = 2; this corresponds to

$$\lambda_e = \Lambda \beta^n R^{-\delta} \tag{11}$$

where βc is the particle velocity. We have taken $\delta = 0.7$ and $\Lambda = 35$ g/cm^2 of interstellar matter, consistent with the high energy boron/carbon data. We show in Figure 4 results for $n = 1$ and 3. For the degree of solar modulation assumed here, we find a reasonable fit may be obtained for $n = 3$ although lower indices would apply if the modulation were less than we have assumed here.

We now show in Figure 5 how the escape length parameterized in this way agrees with the observed nitrogen to oxygen and sub-iron to iron ratios. Nitrogen is present at the cosmic ray source, and so the observed ratio is not expected to be as steep as the boron to carbon ratio. The energy dependence of the nitrogen to oxygen ratio is in good agreement with the result for $n = 3$ while that of the sub-iron to iron ratio does not require such a marked flattening in λ_e as the boron to carbon ratio or the nitrogen to oxygen ratio. The reason for this is at present unknown, but it might be due to variations in the iron spallation cross sections with energy.

III-3 Spectra and Solar Modulation

We will now see how well the predicted interstellar spectra agree with those observed. In the previous section we found that the mean escape length varied steeply with energy, and that $\delta_R = 0.7 \pm 0.1$, implying a source spectrum of the form $dJ/dT \propto R^{-2}$ as expected from shock acceleration by strong shocks. We now can calculate the spectra of cosmic ray nuclei expected outside the heliosphere.

In Figure 6 we have plotted (open circles) the energy spectrum of protons observed at high energies (Ryan et al., 1972; this spectrum is consistent with the more recent results: Gregory et al., 1981, Tasaka et al., 1982) and at low energies we show three estimates of the interstellar proton spectrum derived after taking into account solar modulation (Morfill, Volk and Lee, 1976; Fisk, 1976; Gloeckler and Jokipii, 1967). We have plotted (solid lines) the energy spectrum of protons we expect (normalized to the high energy data) for a variation of mean escape length with rigidity as given by Equation (10). The cross hatched region represents the variation over the range $1 \leq n < 3$. We find general agreement with the demodulated spectra at low energies (i.e., the general features are reproduced).

Because of the competition between nuclear interaction and escape, the energy spectra of primary nuclei are expected to be somewhat flatter than of protons even up to several hundred GeV/nuc. Again, in Figure 7, we have plotted the energy spectra of oxygen and iron observed by Simon et al. (1980) and Orth et al. (1978) which are indeed flatter than the spectrum observed for protons (Figure 6). We have added to Figure 7 the spectral shapes expected from our propagation calculation which are seen to be in good agreement with the data. The normalization of these curves is determined by the source abundances; we have made no attempt here to optimize those abundances.

IV Conclusions

We have used the highly accurate new data on secondary to primary ratios from the Danish-French experiment on HEAO-3, to determine the energy dependence of the mean matter traversed by cosmic rays in the galaxy. The final results are shown in Figure 8. We have found that above 2.8 GeV/nuc, the variation with energy may be as steep as $\lambda_e \propto R^{-0.7}$ which would imply that primary cosmic rays may be produced with a p^{-2} spectrum as expected for acceleration by a first order Fermi mechanism in strong shocks.

A turnover in λ_e at lower energies proportional to the cube of the particle velocity is required to fit both the lower energy HEAO-3 ratios and the observations around 100 MeV/nuc of the boron to carbon ratio made with the IMP experiment (Garcia-Munoz et al., 1979). As they stated in that paper, if the solar modulation is as strong as generally believed (200 to 300 MeV/nuc energy loss), the turnover at about 1 GeV/nuc is very rapid, i. e., much more rapid than can be accounted for by the dynamical halo model.

A slight truncation of the pathlength distribution may be indicated by the HEAO-3 data, as well as by the IMP data (Garcia-Munoz et al., 1979). For example, in the nested leaky box model about 8 percent of the mean matter traversed could be around source regions. However any conclusion is premature because of uncertainties in spallation cross sections.

Now that cosmic ray data are available with a statistical accuracy approaching 2 percent, it is important to measure the energy dependence of the major spallation and total cross sections to a similar accuracy so that more explicit conclusions can be drawn.

The steep rigidity dependence of the escape length derived here has some important consequences regarding the distance cosmic rays can propagate under the assumption of their diffusive storage in the galaxy. Given an age of the cosmic rays and the assumption that this age corresponds to the escape time from a given storage volume, one can derive an upper limit to the size of that storage volume based on the fact that the cosmic ray age must be greater than the speed of light crossing time for the region. Since there is no observed structure (e.g., change of slope) in the proton spectrum up to 10^5 GV/c (Gregory et al., 1981, Tasaka et al., 1982), we conclude that the rapid decrease of λ_e with rigidity continues up to this energy. The lifetime of cosmic rays is proportional to the escape length. Extrapolating from the 10^7

year age (Wiedenbeck and Greiner, 1980 and Garcia-Munoz et al., 1981c) at 1 GV/c using the $R^{-0.7}$ dependence derived in this paper, the age at 10^5 GV/c is about 3000 years and the size of the "storage region" must be less than 1 kpc. Since particles which diffusively propagate must strongly satisfy this inequality, the cosmic rays we observe locally probably come from within a few hundred parsec and are lost (i.e., have a low probability of returning to the solar system) once they diffuse very far from the disk of the galaxy. If the escape law were $R^{-0.5}$, as previously believed, this size limit would be an order of magnitude larger.

We have also shown that the HEAO-3 data cannot be fit in detail by the combination of diffusive and convective losses postulated by the dynamical halo model. This statement is even stronger if we try to fit the IMP data at the same time. This is consistent with the conclusion about the scale size of the storage volume in the following sense. The convection picture discussed above and compared with data in this paper is assumed to be due to a large scale galactic wind. Such a wind might reduce the probabilty that particles can return to the disk from the halo, but the effect of such winds may be unobservable locally because of the small region sampled by the cosmic rays observable at the solar system. However, a conclusion that the dynamical halo model cannot fit the observations must be tempered with the realization that the predictions themselves are subject to the uncertainties introduced by the simplifying theoretical assumptions. Our conclusion is the same as that of the Chicago group: the only way the observed decrease in the boron to carbon ratio below 1 GeV/nucleon can be fit is if the modulation parameter is assumed to be very small ($\phi \lesssim 100$ MV, for n = 0), a result inconsistent with our current understanding of solar modulation.

The injection spectrum derived here may be inconsistent with the observations based on the electron spectrum. Recent observations (Nishimura et al., 1980, Prince, 1979, Mauger, 1981) of the electron spectrum at high energy (> 30 GeV) give a spectral exponent $\gamma = 3.2$ or 3.3. The simplest interpretation is that this assymptotic high energy slope should be one power steeper than the injection spectrum just due to the energy dependence of synchrotron losses, indicating a source spectrum of slope 2.2 or 2.3, consistent with the previously quoted rigidity dependence of the escape length ($R^{-0.5}$), but inconsistent with our result ($R^{-0.7}$). An alternative explanation, however, is that the propagation time from the nearest source is sufficiently high (perhaps due to an absence of nearby sources) that the electron spectrum we see at Earth is steeper. Such a steepening would be consistent with a slight truncation in the path length distribution. This will be explored further in a subsequent paper.

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FIGURE CAPTIONS

Figure 1. Comparison between source spectra inferred from low energy cosmic ray data (Garcia-Munoz et al., 1975a,b) and that expected from acceleration with strong shocks (see text).

Figure 2. Boron to carbon ratio measured by HEAO-3 and IMP satellites are compared with a survey of balloon observations (see separate data survey reference list).

Figure 3. Comparison of boron to carbon, sub-iron to iron, and nitrogen to oxygen ratios observed from 2.8-15 GeV/nuc by HEAO-3 with results of the present propagation calculations. The figure shows the goodness of fit when the parameters of Equation 6 (part a) or Equation 7 (part b) are varied. The closed curves are contours of constant χ^2 corresponding to 95 percent probability. In Section a, the dashed lines show the effect on the fit to the boron to carbon ratio of assuming a 10 percent uncertainty in the cross section for spallation of carbon to boron. Care must be taken in interpreting the normalization constants, which assume the rigidity (energy) dependence extends to lower rigidity (energy). The value of λ_e at 5 GeV/nuc is 6 g/cm^2, consistent with previous analyses.

Figure 4. Boron to carbon ratio (replotted from Figure 2). Dashed curves show predicted energy dependence for diffusion/convection model (q_o is defined in Equation 9). Solid curves show prediction for variation of λ_e with energy given by Equation 10. The solid curves are not based on any model but attempts to find empirical fits. The modulation parameter assumed is ϕ = 600 MV.

Figure 5. Energy dependence of nitrogen/oxygen and sub-iron/iron ratios (data from HEAO-3 experiment). Curves give prediction for variation of λ_e with energy according to Equation 10 (numbers attached to curves give value of n).

Figure 6. Interstellar proton spectrum. Three estimates of low energy demodulated spectrum and high energy measurements are given. The hatched area corresponds to our prediction for a p^{-2} injection spectrum and a variation of λ_e with energy given by Equation 10 with n in the range 1 to 3.

Figure 7. Observed iron and oxygen energy spectra (open circles: Simon et al., 1980; full circles: Orth et al., 1978). Dashed lines: predicted interstellar spectra; solid lines: modulated spectra (model as in Figure 6).

Figure 8. Summary of the derived mean escape length as a function of energy. The curve is the empirical fit based on Equation 10 with n = 3. The best escape length derived from each individual HEAO-3 data point and those of IMP above 100 MeV/nuc are shown based on ϕ = 600 MV modulation parameter.

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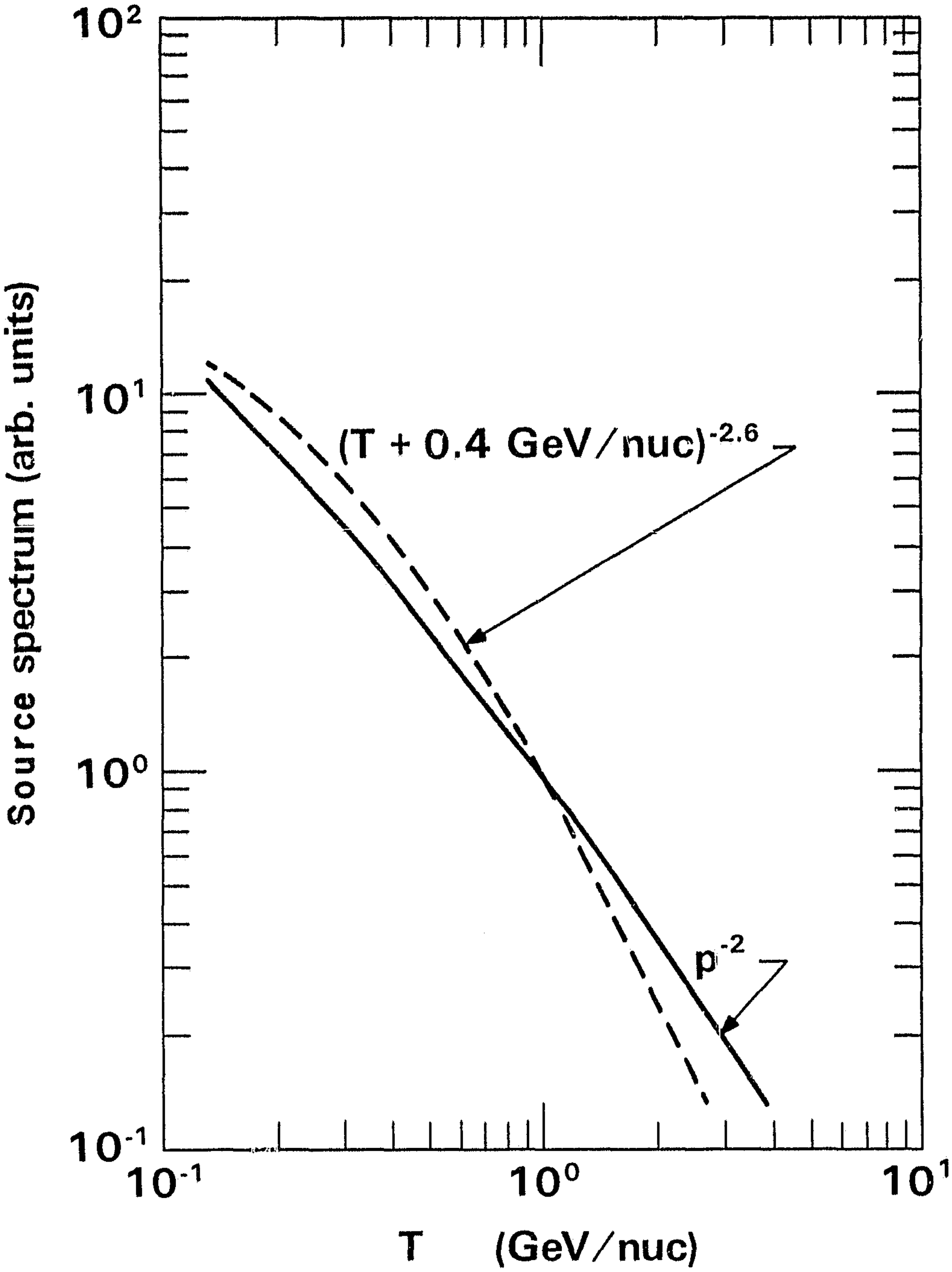


Fig.1

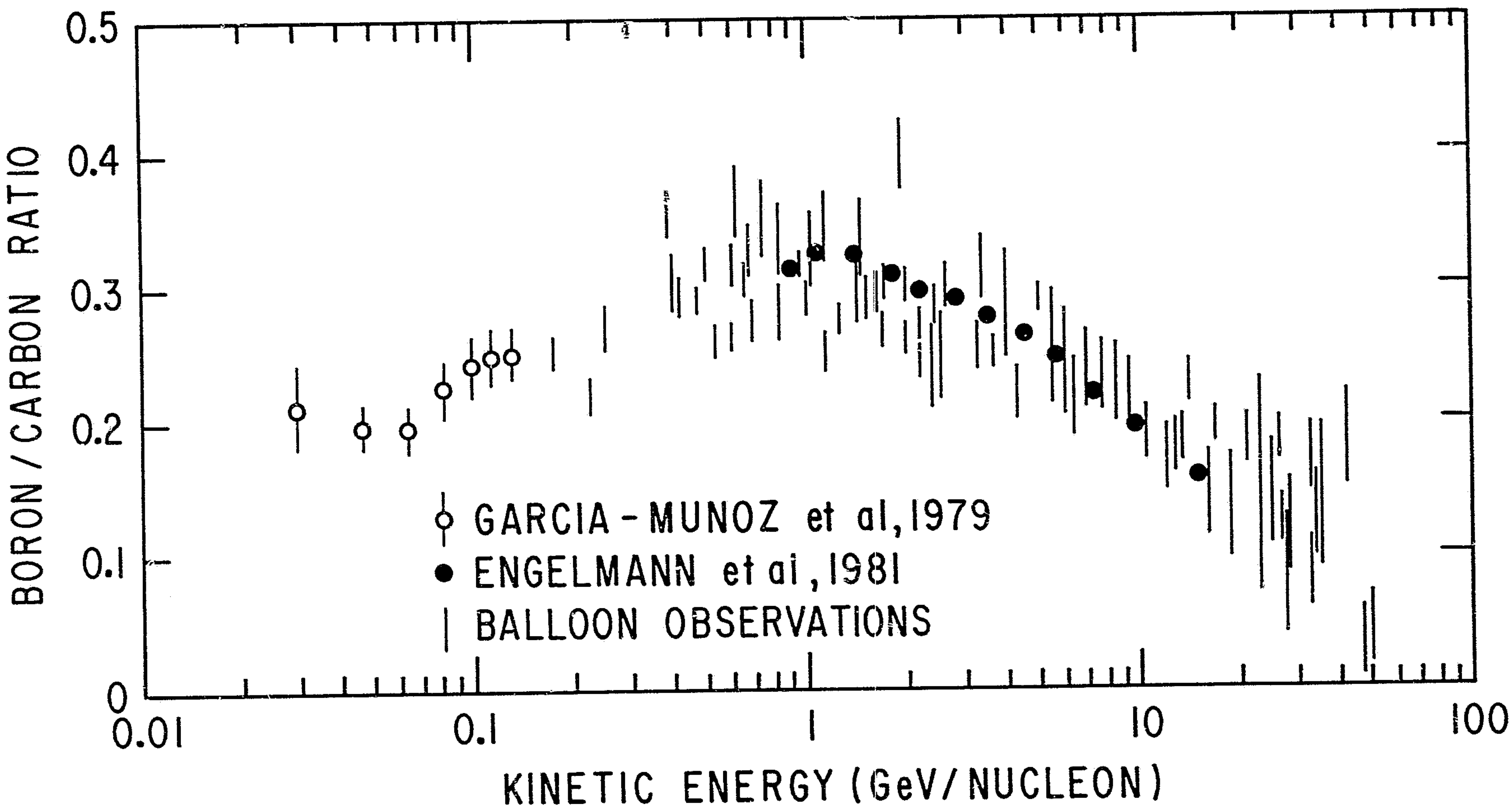
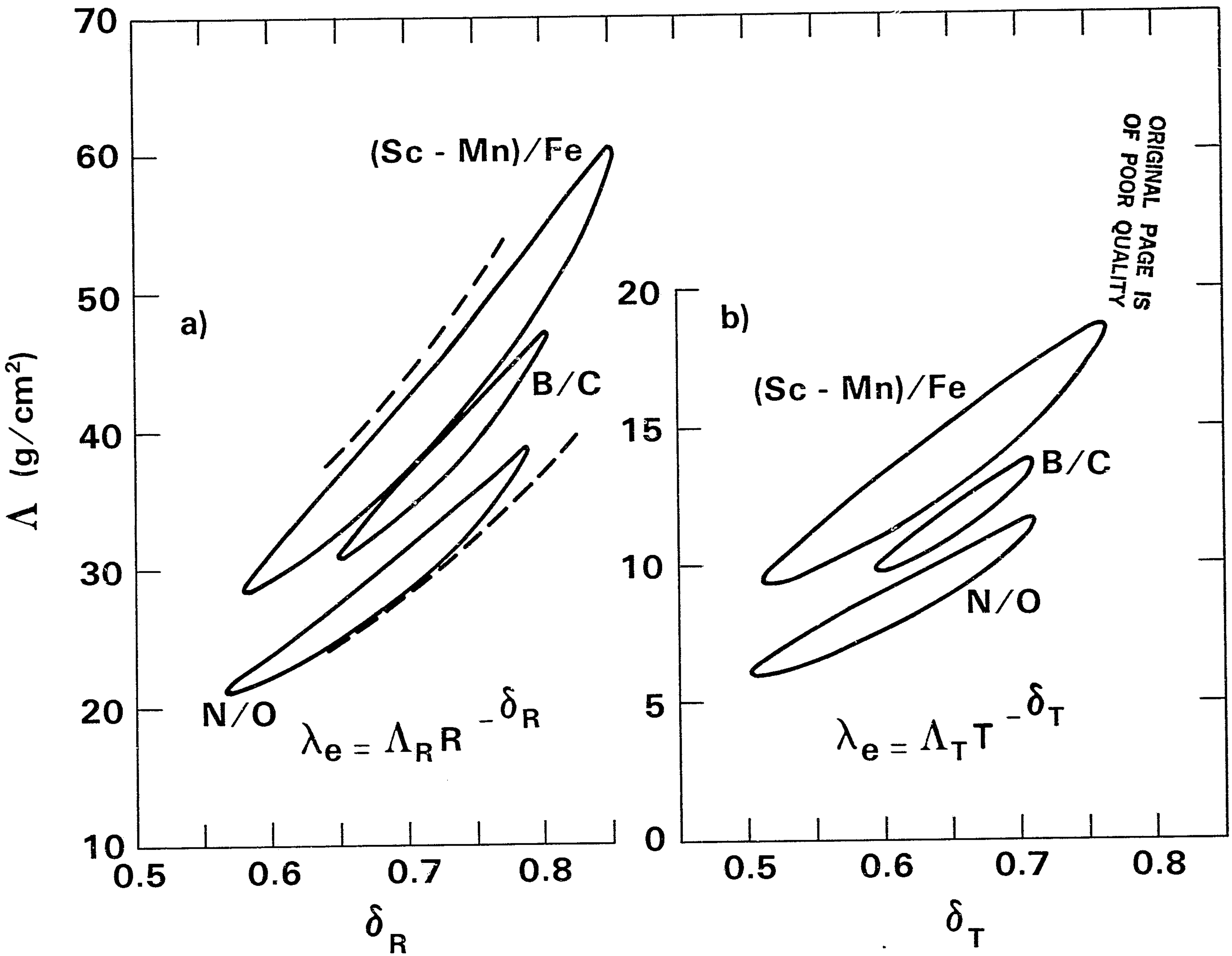
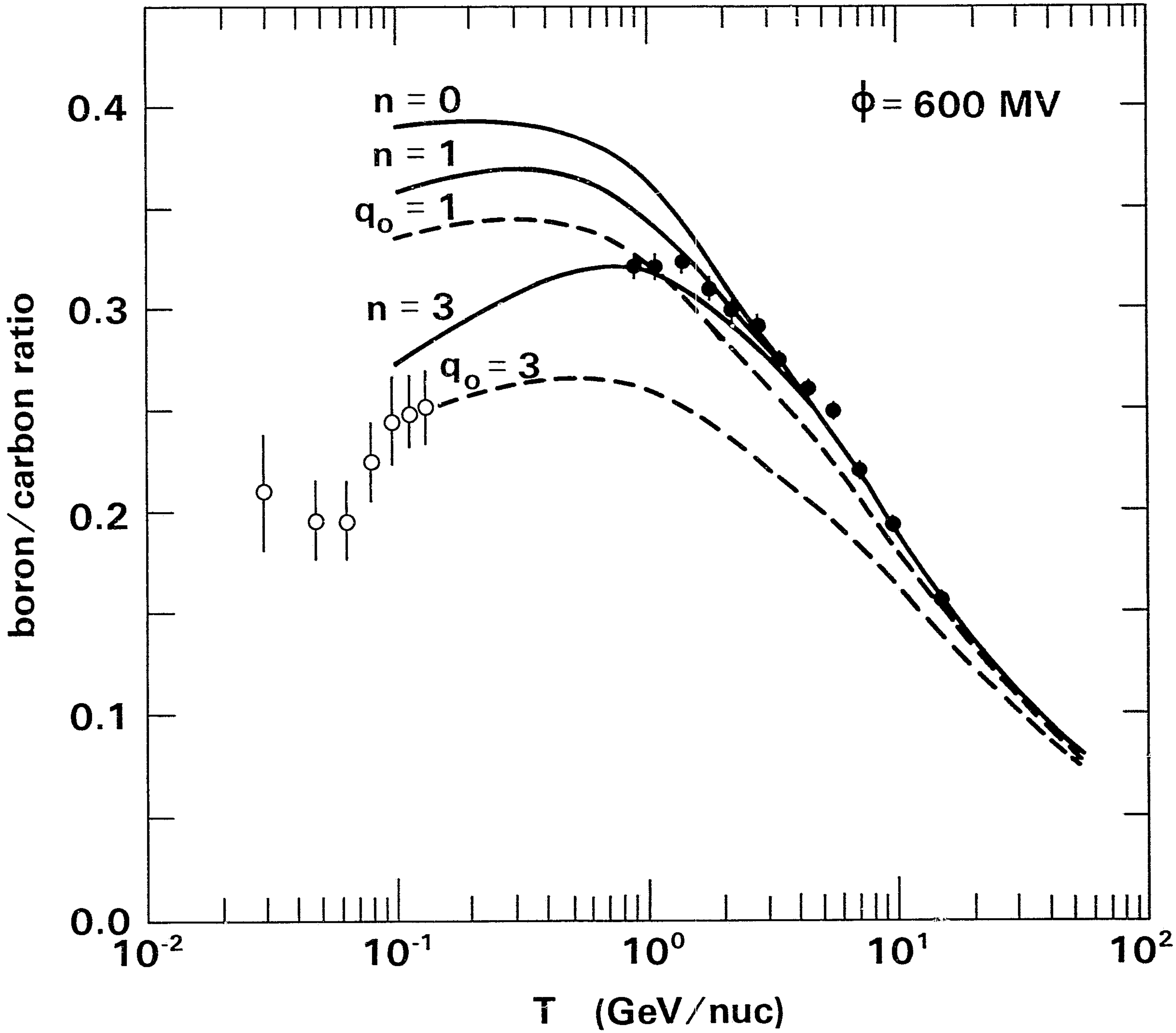

BORON / CARBON RATIO
0.5
0.4
0.3
0.2
0.1
0
0.01
0.1
1
10
100
KINETIC ENERGY (GeV/NUCLEON)
GARCIA-MUNOZ et al, 1979
ENGELMANN et al, 1981
BALLOON OBSERVATIONS

Fig. 2



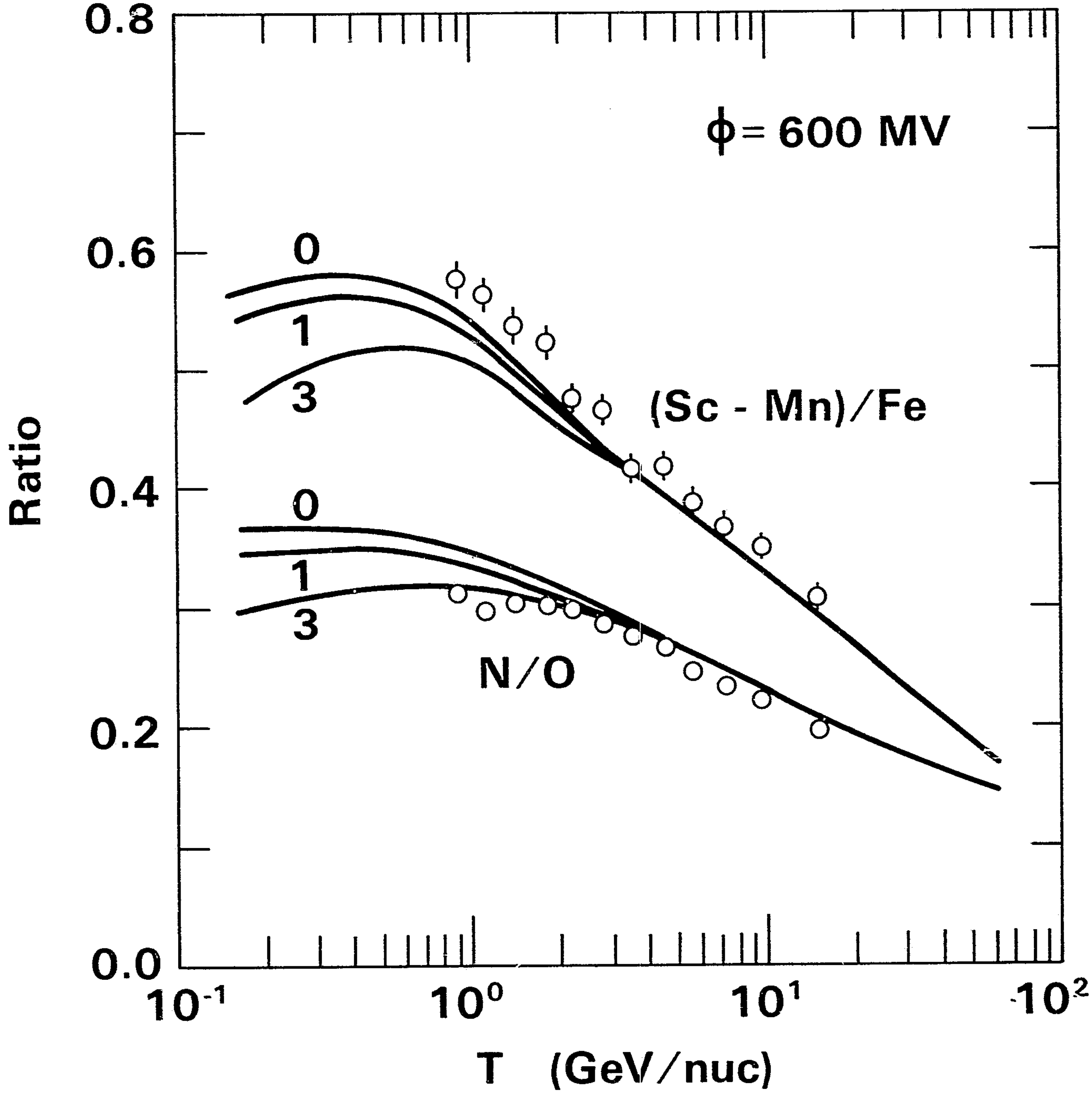
70
60
50
40
30
20
10
Λ (g/cm²)
a)
(Sc - Mn)/Fe
B/C
N/O
λe = ΛR R -δR
0.5
0.6
0.7
0.8
δR
20
15
10
5
0
b)
(Sc - Mn)/Fe
B/C
N/O
λe = ΛT T -δT
0.5
0.6
0.7
0.8
δT

Fig.3



boron/carbon ratio
0.4
0.3
0.2
0.1
0.0
n = 0
n = 1
q_o = 1
n = 3
q_o = 3
φ = 600 MV
10^-2
10^-1
10^0
10^1
10^2
T (GeV/nuc)

Fig.4



0.8
0.6
0.4
0.2
0.0
Ratio
ϕ = 600 MV
0
1
3
(Sc - Mn)/Fe
N/O
10-1
100
101
102
T (GeV/nuc)

Fig.5

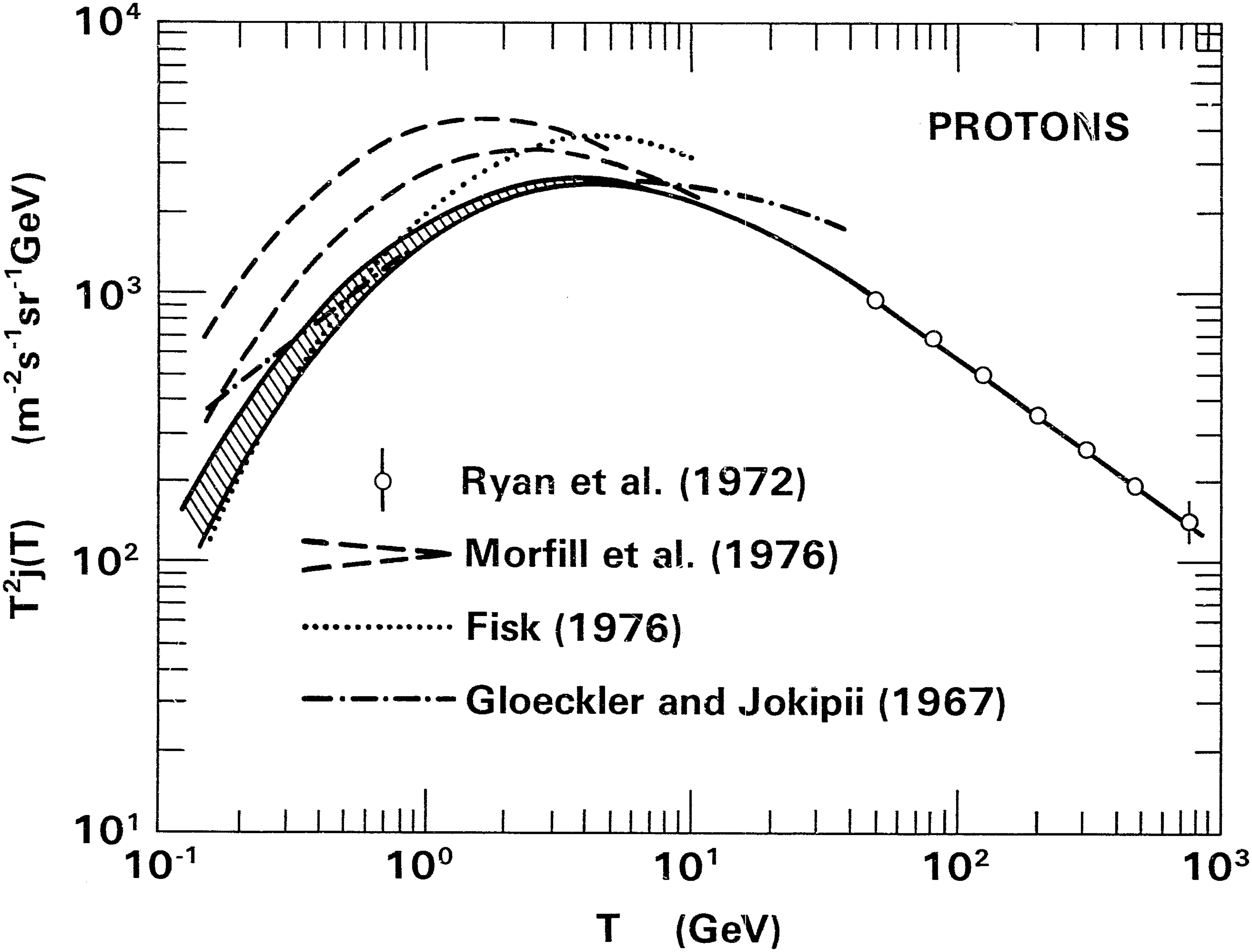
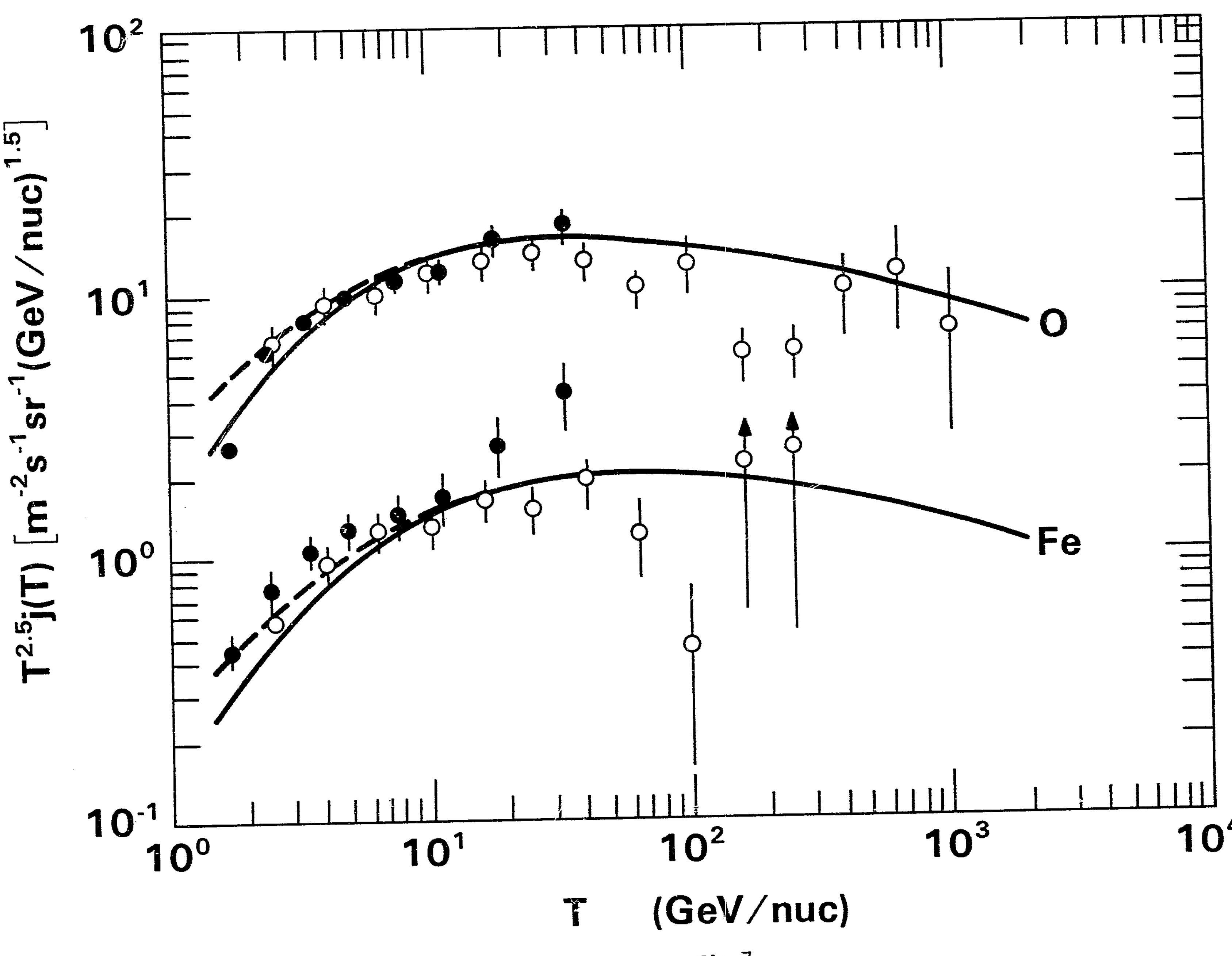
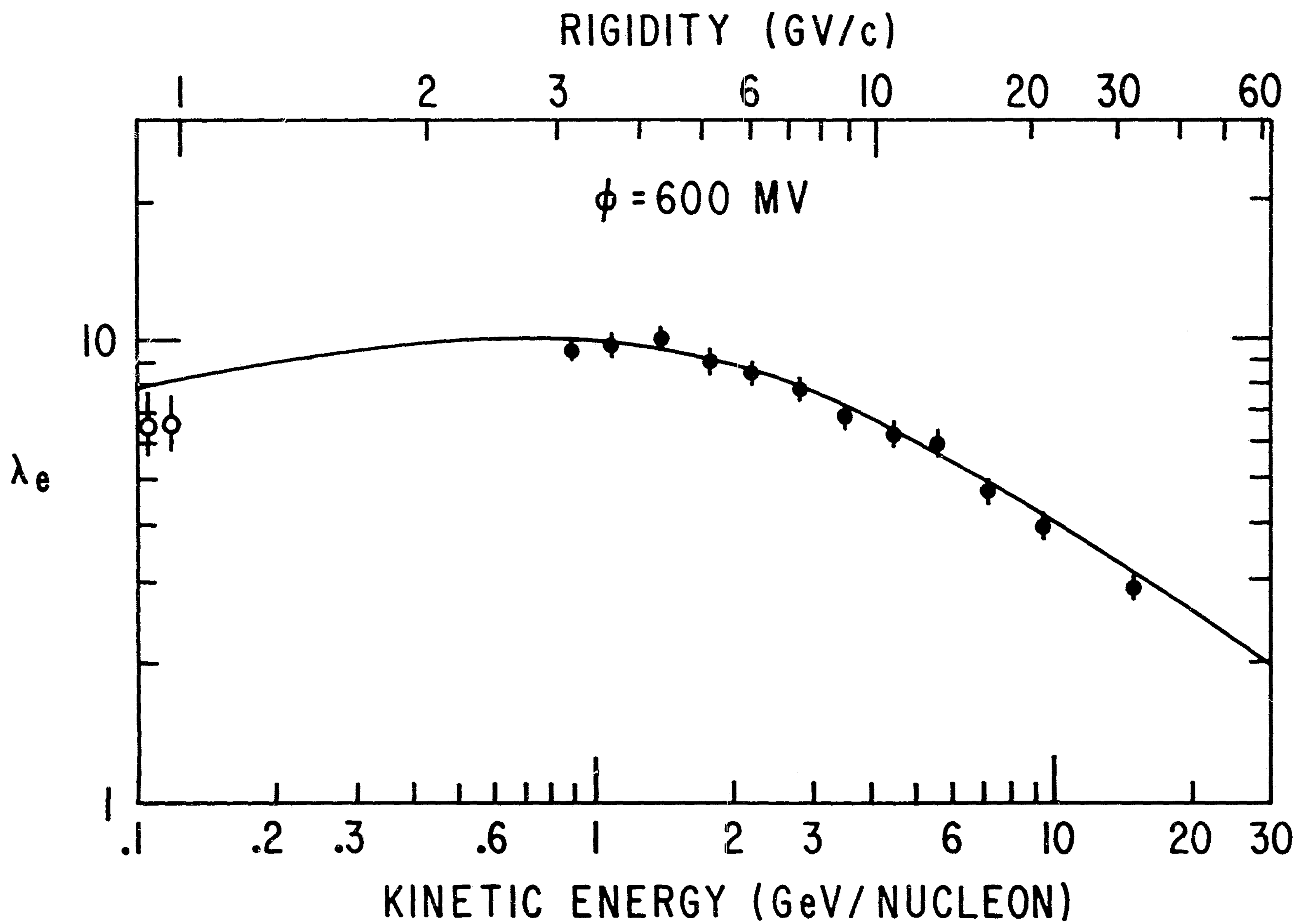

PROTONS
10^4
10^3
10^2
10^1
$T^2j(T)$ $(m^{-2}s^{-1}sr^{-1}GeV)$
Ryan et al. (1972)
Morfill et al. (1976)
Fisk (1976)
Gloeckler and Jokipii (1967)
10^{-1}
10^0
10^1
10^2
10^3
T (GeV)

Fig.6



$T^{2.5}j(T)$ $[m^{-2}s^{-1}sr^{-1}(GeV/nuc)^{1.5}]$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
10^{4}
T (GeV/nuc)
O
Fe

Fig.7



RIGIDITY (GV/c)
1
2
3
6
10
20
30
60
φ = 600 MV
10
1
λe
.1
.2
.3
.6
1
2
3
6
10
20
30
KINETIC ENERGY (GeV/NUCLEON)

Fig.8