THE COMPARATIVE SPECTRA OF COSMIC-RAY PROTONS AND HELIUM NUCLEI

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Abstract. We have re-examined and extended the measurements of the primary cosmic ray proton and helium nuclei intensities in the range from a few MeV nuc^{-1} to ~ 100 GeV nuc^{-1} using a considerable body of recently published data. The differential spectra obtained from this data are determined as a function of both energy and rigidity. The exponents of the energy spectra of both protons and helium nuclei are found to be different at the same energy/nucleon and to increase with increasing energy between 1 and 100 GeV nuc^{-1} reaching a value $= -2.70$ at higher energies and in addition, the P/He ratio changes from a value $\lesssim 5$ at 1 GeV nuc^{-1} and below to a value ~ 30 at 100 GeV nuc^{-1}. On a rigidity representation the spectral exponent for each species is nearly identical and remains virtually constant above several GV at a value of -2.70, and in addition, the P/He ratio is also a constant ~ 7 above ~ 3 GeV. The changing P/He ratio and spectral exponent on an energy representation occur at energies well above those at which interplanetary modulation effects or interstellar ionization energy loss effects can significantly affect the spectra. In effect by comparing energy spectra and rigidity spectra in the intermediate energy range above the point where solar modulation effects and interstellar energy loss effects are important, but in the range where there are significant differences between energy and rigidity spectra, we deduce that the cosmic ray source spectra are effectively rigidity spectra. This fact has important implications regarding the mechanism of acceleration of this radiation and also with regard to the form of the assumed galactic spectrum at low energies. The relationship between the proton and helium spectra derived here and the heavier nuclei spectral differences recently reported in the literature is also examined.

If rigidity spectra are adopted for protons and helium nuclei, then the source abundance ratio of these two components is determined to be $\sim 7{:}1$. Some cosmological implications of this ratio are discussed.

1. Introduction

In this paper we shall examine recent measurements of the primary cosmic ray proton and helium nuclei spectra in the energy range from ~ 10 MeV nuc^{-1} to >100 GeV nuc^{-1} with the object of: (1) Determining the spectral exponent of these species as a function of both energy/nucleon and rigidity; (2) Determining the relative abundance of these two components as a function of energy and rigidity; and (3) Determining whether the energy or rigidity parameters best organize these spectral data. This study is of particular importance since several recent investigations have revealed energy (rigidity) dependent differences in the spectra of heavier ($Z \geqslant 3$) cosmic ray nuclei (Juliusson *et al.*, 1972; Webber *et al.*, 1973a; Ormes and Balasubyahmanyan, 1973; Smith *et al.*, 1973). It is also of basic importance in understanding the characteristics of the origin and propagation of these two dominant cosmic ray components, and of estimating their relative source abundance – a ratio which may have important cosmological implications.

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2. Data

A comprehensive study of the spectra of protons and helium nuclei up to ~10 GeV nuc^{-1} was carried out in 1967 by Gloeckler and Jokipii (1967). Since that time much new data has become available at all energies – but particularly at the higher energies. The composite differential proton and helium spectra near Earth obtained from this new analysis using a wide variety of published data (the sources of the data are listed in the figure captions) are shown in Figure 1 as a function of kinetic energy/nucleon at three levels of solar modulation corresponding to: (1) sunspot minimum; (2) an intermediate level; and (3) sunspot maximum. The solid lines provide a smoothed best fit to the data at different epochs. The earlier Gloeckler and Jokipii sunspot minimum spectra are shown as dotted lines. It is important to our later arguments to represent these spectra as rigidity spectra and so in Figure 2 we show this identical data in the form of differential rigidity spectra. For the purposes of comparing energy and rigidity spectra we have assumed that $A/Z=1$ for protons and 2 for helium nuclei. We recognize that up to 10% of the He in question could be He^3 with an A/Z ratio $=1.5$. The mean A/Z ratio for all He could thus be as low as 1.95. The effects of using this value for the A/Z ratio of He rather than 2.0 are less than the present uncertainties in the data.

A considerable body of data also exists in the form of integral intensities. In Figures 3 and 4 therefore we show the integral energy and rigidity spectra using integral measurements only. The two sets of data (differential and integral) should, of course, agree, and a comparison can help to evaluate the uncertainties in the available data. The solid lines in Figures 3 and 4 are obtained directly by integrating the solid lines representing the differential spectra in Figures 1 and 2. The comparison between these solid lines and the actual integral data points illustrates the close agreement between the composite differential and integral spectra. There are, however, some interesting differences in the results from individual experiments at higher energy. For example, the experiment of Smith *et al.* (1973) obtains significantly lower proton intensities in the rigidity range 10–100 GV than indicated by the best fit solid lines in Figure 2. The helium nuclei intensities in this same experiment follow the solid line closely so that the net result is that these experimenters obtain a smaller P/He ratio than we present.

We judge that the overall uncertainty in the absolute intensities and in the ratios of P/He at a given rigidity or energy/nucleon to be $\pm 20\%$ above 10 GV and $\pm 10\%$ below this rigidity.

3. Interpretation Line of the Data Using Energy/Nucleon and Rigidity Spectra

Two important features of the differential spectra are evident upon close examination. At high energies ($\lesssim 50$ GeV nuc^{-1}) both the proton and helium spectra are found to have virtually identical spectral indices n, of -2.70 with an error of ± 0.05 based on the quoted errors of experimenters and the consistency of the various high energy

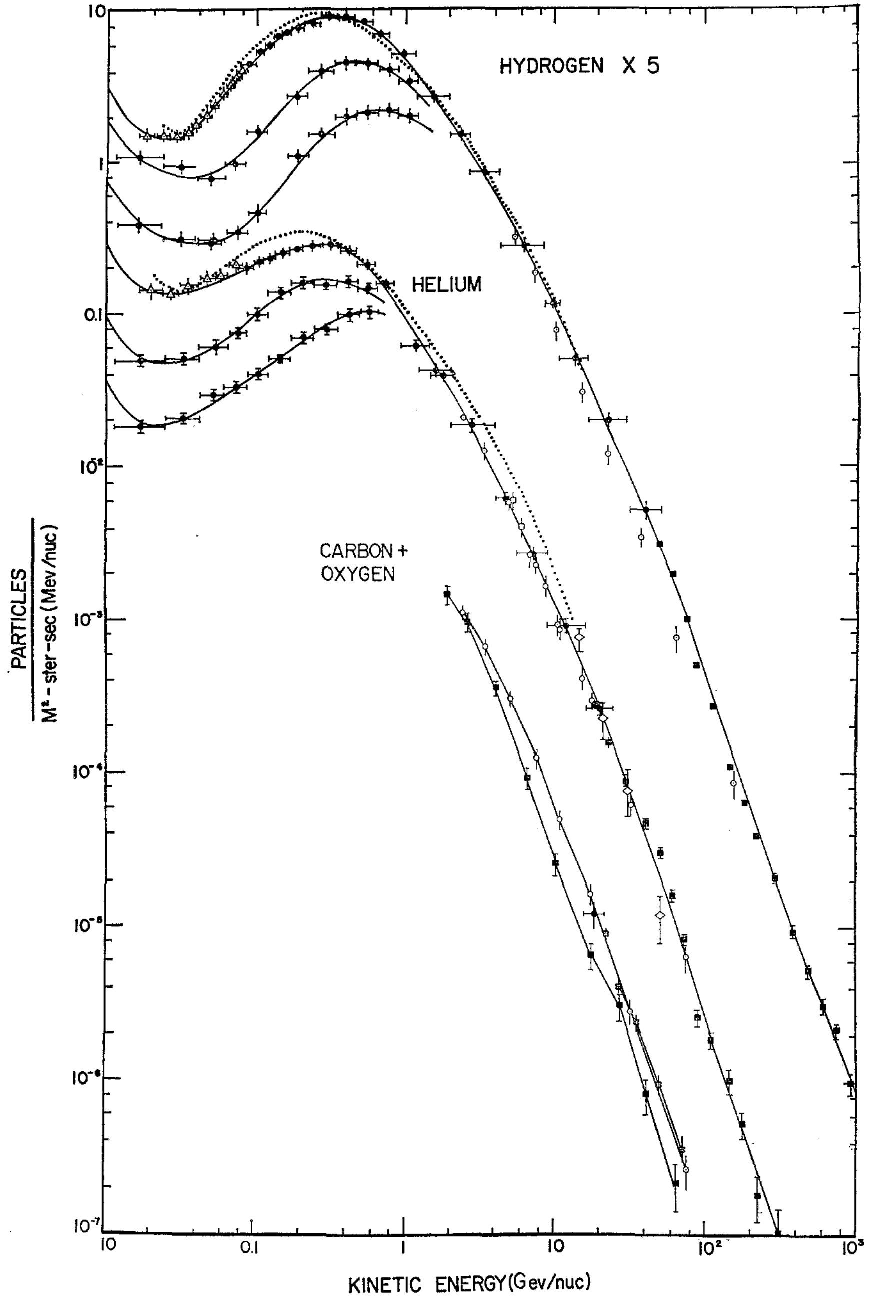

Fig. 1. Differential energy/nucleon spectra for cosmic ray protons and helium nuclei. Data points labelled ▮ are from Ryan *et al.*, 1972; ● are from Ormes and Webber, 1965; von Rosenvinge *et al.*, 1969, and Webber *et al.*, 1973a; △ are from Fan *et al.*, 1966; ○ are from Anand *et al.*, 1968; ○ are from Smith *et al.*, 1973; ◇ are from Verma *et al.*, 1972; for C+O nuclei, ▮ are from Balasubrahmanyan and Ormes, 1973; × are from Juliusson, 1973; ○ are from Smith *et al.*, 1973.

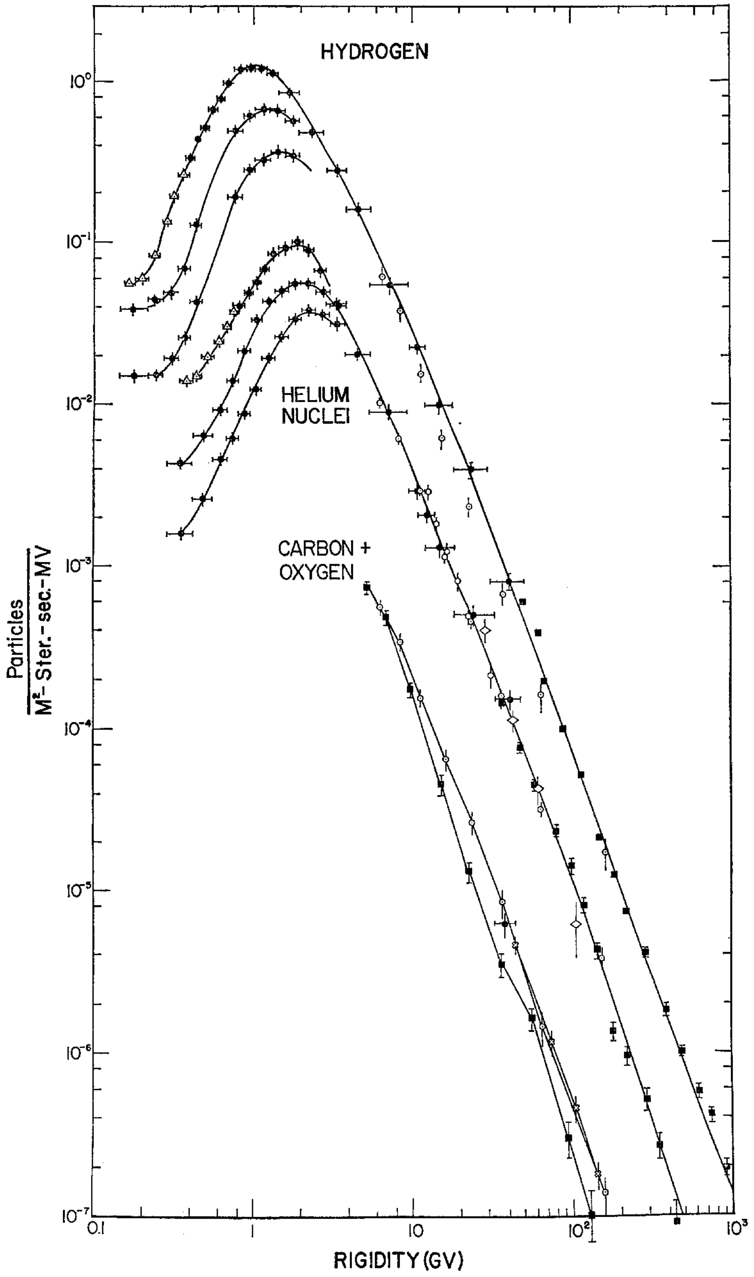

Fig. 2. Differential rigidity/nucleon spectra for cosmic ray protons and helium nuclei. Symbols are the same as in Figure 1.

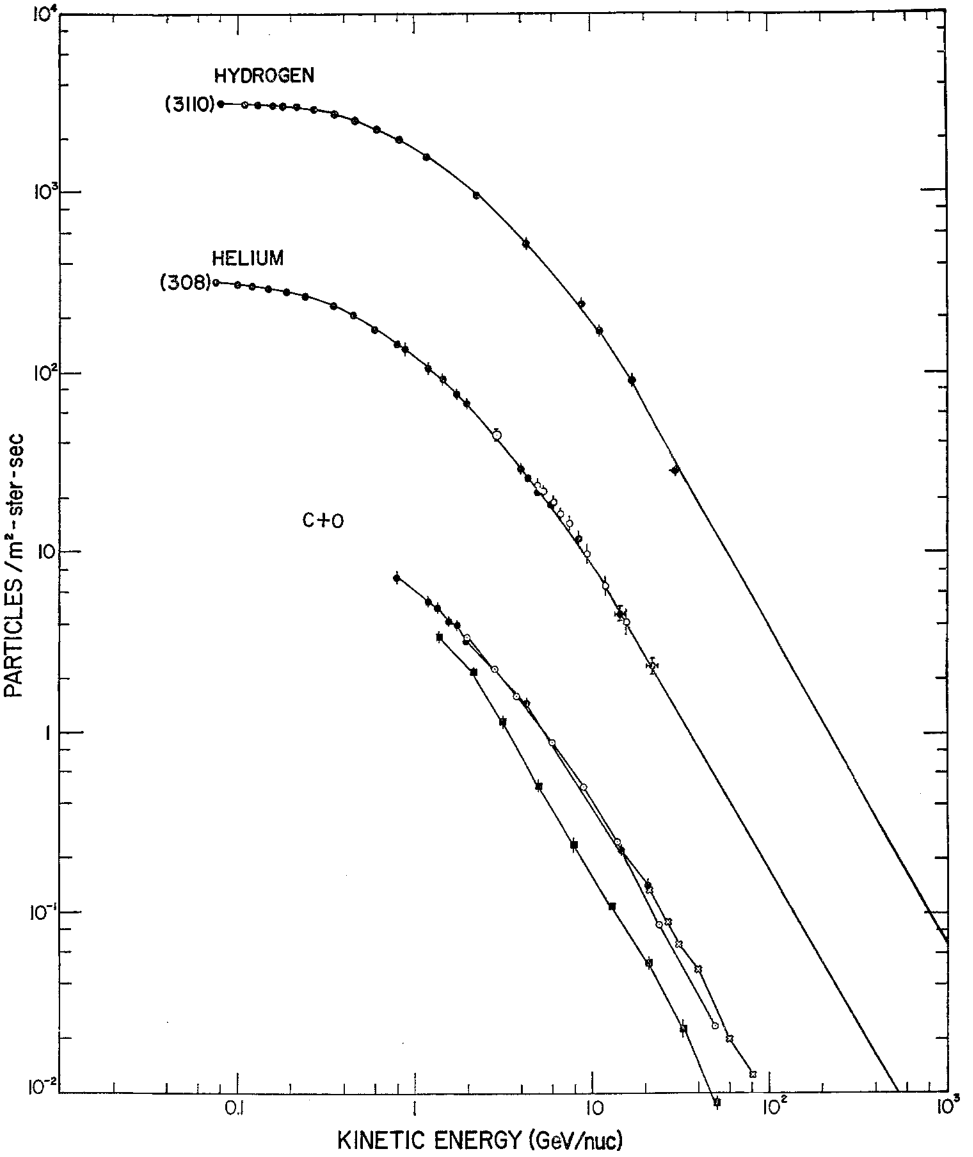

Fig. 3. Integral energy spectra of protons and helium nuclei. Solid lines are based on differential spectra given in Figure 1. Data points labelled ● are from Ormes and Webber, 1965, and von Rosenvinge *et al.*, 1969; ○ are from Anand *et al.*, 1968; ○ are from Smith *et al.*, 1973; for C+O nuclei ■ are from Balasubrahmanyan and Ormes, 1973, × are from Juliusson, 1973, ○ are from Smith *et al.*, 1973, and ◆ are from Webber *et al.*, 1973.

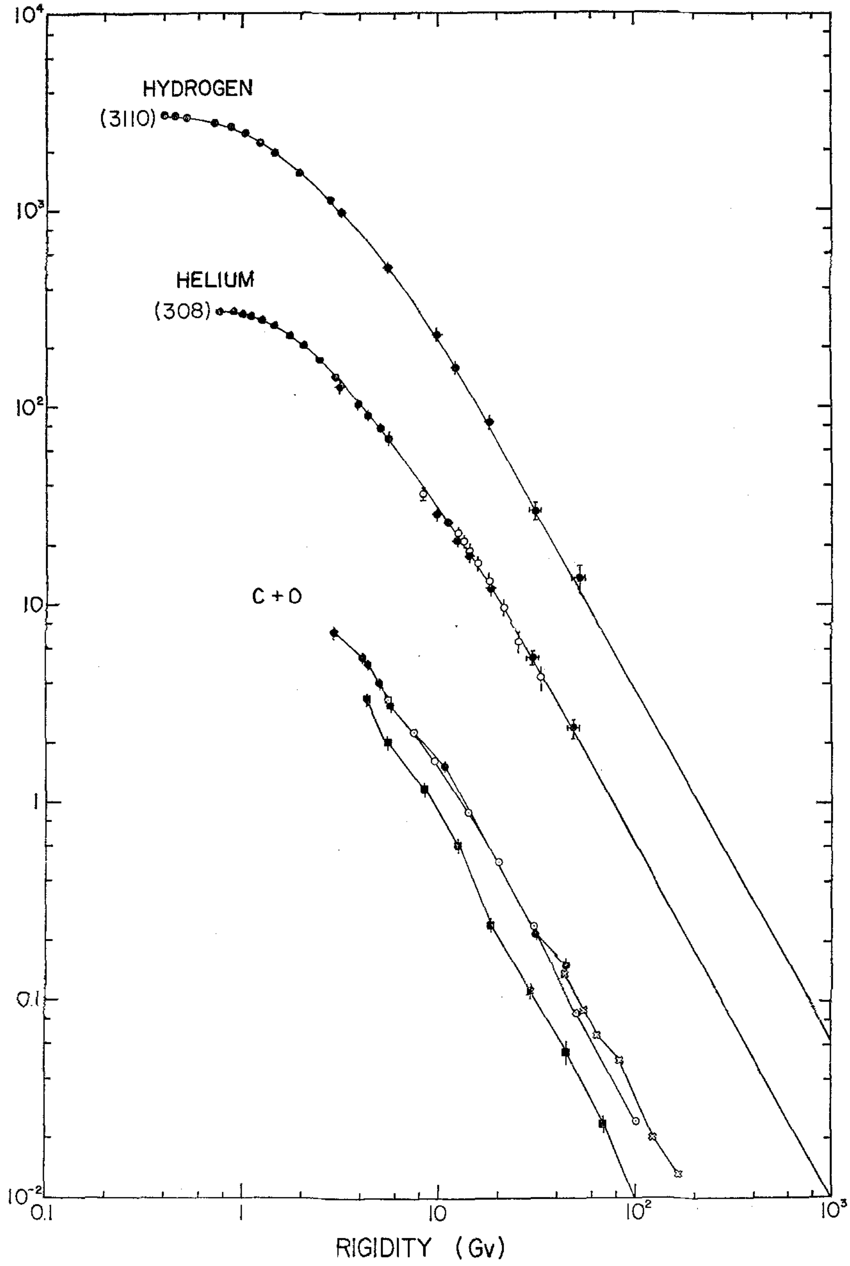

Fig. 4. Integral rigidity spectra of protons and helium nuclei. Symbols are the same as in Figure 3.

measurements. This value of the exponent also applies on a rigidity representation above ~50 GV for both species.* At the lowest energies ($\lesssim 1$ GeV nuc^{-1}) solar modulation effects profoundly alter the spectral shape so that it is difficult to estimate the correct interstellar spectra of these nuclei. At sunspot minimum, these modulation effects are less but could still be quite significant. However, above a few GeV nuc^{-1}, all available evidence indicates that the solar modulation effects should have only a minor effect on the spectra and even less of an effect on the *ratio* of intensities of these two components.

The crucial energy region for our comparison is therefore the intermediate one between ~1 and 50 GeV nuc^{-1}. First, we shall examine the energy spectra and begin

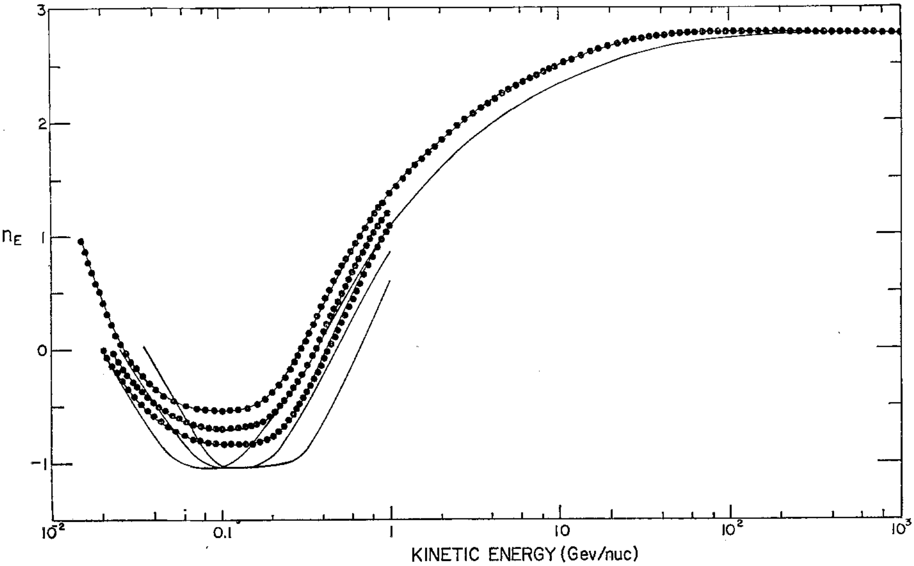

Fig. 5. Variation of protons —— and helium nuclei ●–●–● spectral exponents with energy. Exponents are shown for three levels of solar modulation as derived from the solid lines in Figure 1.

by noting that the value of the spectral exponent n begins to decrease at ~50 GeV nuc^{-1} below its nearly constant high energy value of -2.70 and decreases continuously with decreasing energy becoming zero at about 300 MeV nuc^{-1}. At a particular energy, however, the value of n for protons and helium nuclei is *not quite the same* – the n for helium nuclei is always larger – sometimes by ~0.3. This variation in spectral exponent with energy for the two species is shown in Figure 5. The spectra exponent is derived by constructing the tangent to the continuous curve representing the differen-

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* Ryan *et al.*, 1972, quote an average energy spectral index $= -2.75$ for protons and -2.77 for helium nuclei above ~50 GeV nuc^{-1}. In a later paper (Ramaty *et al.*, 1973), these same workers suggest that this index $= -2.64$ for both nuclei at about 50 GeV nuc^{-1} – increasing somewhat above several hundred GeV nuc^{-1}. This slight steepening, although significant if true, does not concern us here.

tial spectrum in Figure 1. This is equivalent to defining $n = \mathrm{d}\ln(\mathrm{d}j/\mathrm{d}T)/\mathrm{d}\ln(T)$. On the basis of the data presented in Figures 1 and 3, we estimate that the error in the spectral exponents at any one energy is $\lesssim \pm 0.1$.

These differences in proton and helium nuclei energy spectral exponent will directly manifest themselves in a proton/helium nuclei ratio that changes with energy. This ratio is shown in Figure 6 as a function of energy again at three levels of modulation to illustrate the changes taking place at low energies due to solar modulation. The proton/helium nuclei ratio is observed to change continuously from a value $\gtrsim 30$ at energies > 50 GeV nuc^{-1} to values < 5 at low energies. In effect only small differences in the spectral exponents of the two species are amplified into large changes in the P/He ratio – a quantity that can be measured to an accuracy of at least $\pm 10\%$.

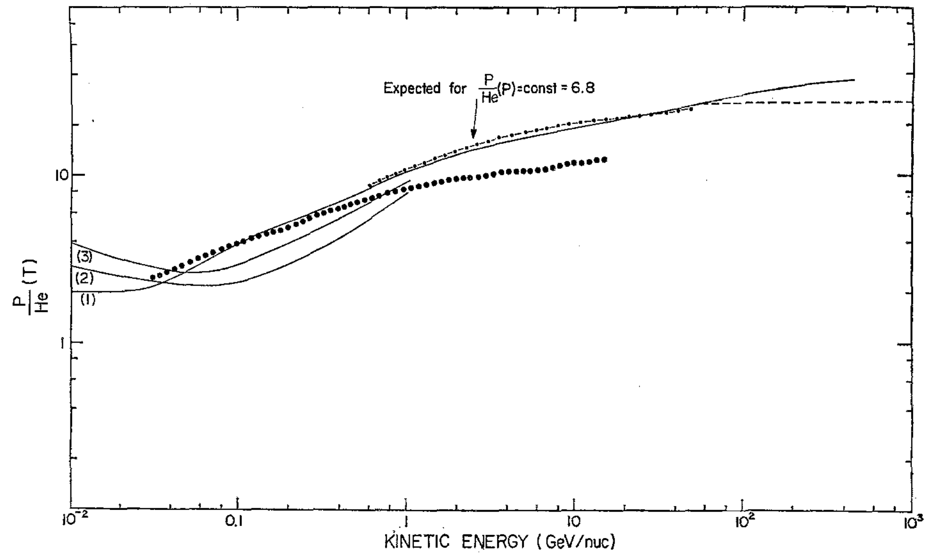

Fig. 6. Proton/helium nuclei ratio as a function of energy/nucleon. Ratio is obtained from solid lines in Figure 1. Ratio obtained from Gloeckler and Jokipii (1967) spectra shown as a beaded line for comparison.

Now consider the rigidity spectra. The average value of $n = -2.70$ observed at high rigidities continues almost unchanged down to ~10 GV, below which the exponent begins to decrease, slowly at first, until it drops precipitously to zero at a rigidity ~2 GV at the peak in the differential spectra. In addition, the spectral exponent of *both* the proton and helium differential rigidity spectra are identical within experimental errors down to ~2 GV. This variation of spectral exponent with rigidity is shown in Figure 7. Again as in the case of the energy nucleon spectra we estimate the error in these exponents at any one rigidity is $\gtrsim \pm 0.1$.

In Figure 8 we show the observed proton/helium nuclei ratio as a function of rigidity. The constancy of this ratio at a value of $\sim 7 \pm 1$ at rigidities above ~2 GV

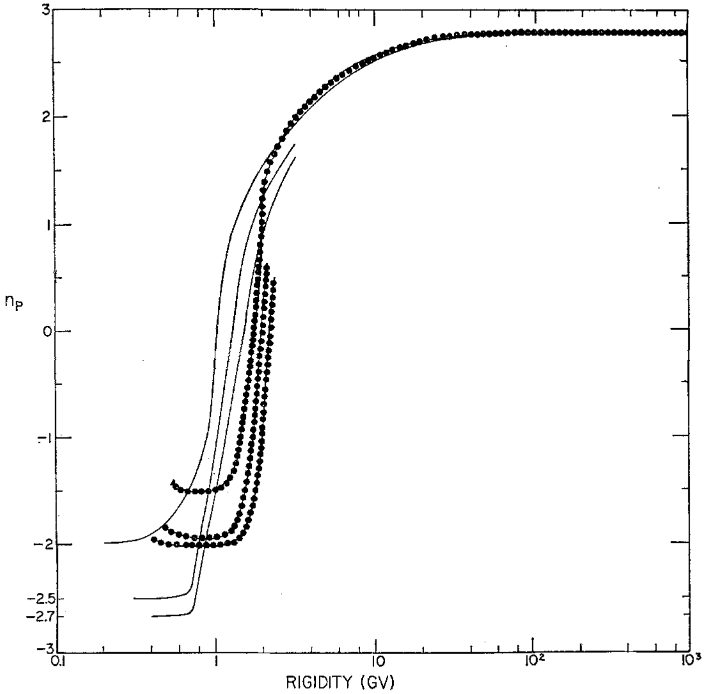

Fig. 7. Variation of proton —— and helium nuclei ●-●-● spectral exponents with rigidity. Exponents are shown for three levels of solar modulation as derived from the solid lines in Figure 2.

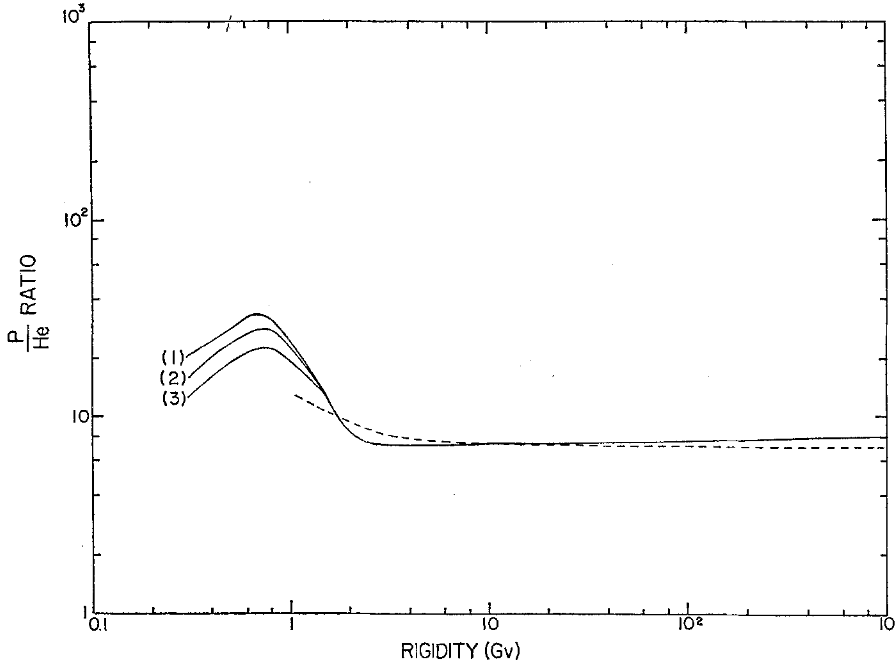

Fig. 8. Proton/helium nuclei ratio as a function of rigidity. Ratio is obtained from solid lines in Figure 2. Dashed curve is *P*/He ratio predicted using a rigidity dependent escape model for cosmic rays in Galaxy (see text).

is a manifestation of the similarity of the proton and helium nuclei rigidity spectra. The small changes in the value of the spectral exponent of these nuclei above a few GV could easily arise from the residual solar modulation remaining at sunspot minimum (the much larger variation in this exponent on the kinetic energy representation, extending up to much higher energies *could not*). Thus, one can argue that the interstellar proton and helium rigidity spectra appear not only to be identical but have a nearly constant spectral exponent (~ -2.70) from several GV up to several hundred GV. The variations of the spectral exponent and the P/He ratio below a few GV on a rigidity basis are obviously related at least in part to solar modulation effects at low rigidities and cannot be so easily interpreted. We will return to this point later.

4. Interpretation of Energy and Rigidity Spectra

What is the significance of this different behavior of the proton and helium spectra when compared as a function of energy/nucleon or rigidity? To investigate this point it is instructive to examine the theoretically expected behavior of the spectral index ratio n_P/n_T, for protons and helium nuclei separately and the ratio of proton to helium nuclei differential intensities $j_{\mathrm{H}}/j_{\mathrm{He}}$ as a function of both kinetic energy/nucleon and rigidity for arbitrary input spectra. In defining the spectral index ratio let us consider differential spectra of the form $\mathrm{d}\ln(j_{P_i})/\mathrm{d}\ln(P) = -n_{P_i}(P)$ where $n_{P_i}(P)$ is the index at a particular rigidity when the spectrum of the ith charge component is expressed as a rigidity spectrum, and $n_{T_i}(T)$ the index at a particular kinetic energy/nucleon when the spectrum of the ith charge component is expressed as a function of kinetic energy/nucleon ($\mathrm{d}\ln(j_{T_i})/\mathrm{d}\ln(T) = -n_{T_i}(T)$). Then we find that

$$n_{P_i}(P) = \frac{\gamma + 1}{\gamma}\, n_{T_i}(T(P)) - \frac{1}{\gamma^2}, \tag{1}$$

where $\gamma = (T + E_0)/E_0$ (E_0 is the rest mass energy) and $T(P)$ signifies that the spectra are compared at the rigidity equivalent kinetic energy/nucleon for the different charge species. This expression allows for a continuously varying spectral exponent.

In determining the differential intensity ratio $j_{\mathrm{H}}/j_{\mathrm{He}}$ we again start out with a spectral definition of the form $\mathrm{d}\ln(j_{P_i})/\mathrm{d}\ln(P) = -n_{P_i}(P)$ so that

$$j_{P_i}(P) = j_{P_i}(P_0)\exp\left(-\int_{P_0}^{P} \frac{n_{P_i}(P)}{P}\,\mathrm{d}P\right). \tag{2}$$

After some manipulation and conversion from rigidity to kinetic energy/nucleon we arrive at

$$R_T(T) = R_P(P_0)\tfrac{1}{2}\exp\left(\int_{P_{\mathrm{H}}(T)}^{2P_{\mathrm{H}}(T)} \frac{n_P(P)}{P}\,\mathrm{d}P\right), \tag{3}$$

where

$$R_T(T) \equiv \frac{j_{T_{\mathrm{H}}}(T)}{j_{T_{\mathrm{He}}}(T)}, \qquad R_P(P) \equiv \frac{j_{P_{\mathrm{H}}}(P)}{j_{P_{\mathrm{He}}}(P)},$$

$P_{\mathrm{H}}(T)$ being the rigidity corresponding to the kinetic energy T for protons. We have assumed that the rigidity spectral index $n_P(P)$ is the same for protons and helium nuclei so that $R_P(P_0)$ may be evaluated at an arbitrary rigidity P_0. This expression allows for a continuously varying spectral exponent which must be evaluated between the limits of integration. If, for example, this index changes linearly with ln (P) over the integration limits – e.g., for $n_P(P) \approx a + b \ln(P)$ – the above expression reduces to the form

$$R_T(T) = R_P(P_0)2^{a-1} \exp\{b/2[(\ln(2P_{\mathrm{H}}(T)))^2 - (\ln(P_{\mathrm{H}}(T)))^2]\}, \tag{4}$$

and if the index is independent of rigidity we obtain $R_T(T) = R_P(P_0)2^{n_P - 1}$.

Consider now the spectral index ratio. We may take the proton and helium spectra to be fundamentally either rigidity or kinetic energy/nucleon spectra and we may consider that the spectral exponent is constant or varies with energy. In Figure 9 we show the spectral index ratio n_P/n_T for protons to be expected if the proton spectrum is really a rigidity spectrum with a given exponent *constant* with rigidity. The ratio n_P/n_T is seen to vary as a function of kinetic energy. If we now take the actual data on the variation of spectral indices as a function of kinetic energy/nucleon and rigidity as compiled in Figures 5 and 7 for sunspot minimum conditions and form the observed ratios n_P/n_T for protons and helium nuclei separately, then we obtain a variation as

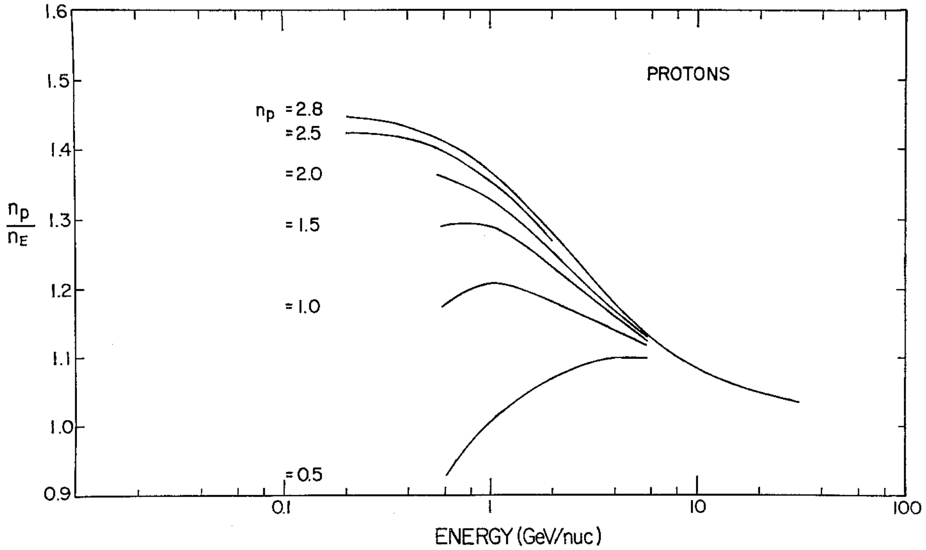

Fig. 9. The ratio of spectral indices n_P/n_T for protons derived assuming the proton spectrum is a rigidity spectrum with constant exponent. The ratio is shown for several values of this exponent and is plotted as a function of energy/nucleon to facilitate comparison with the data.

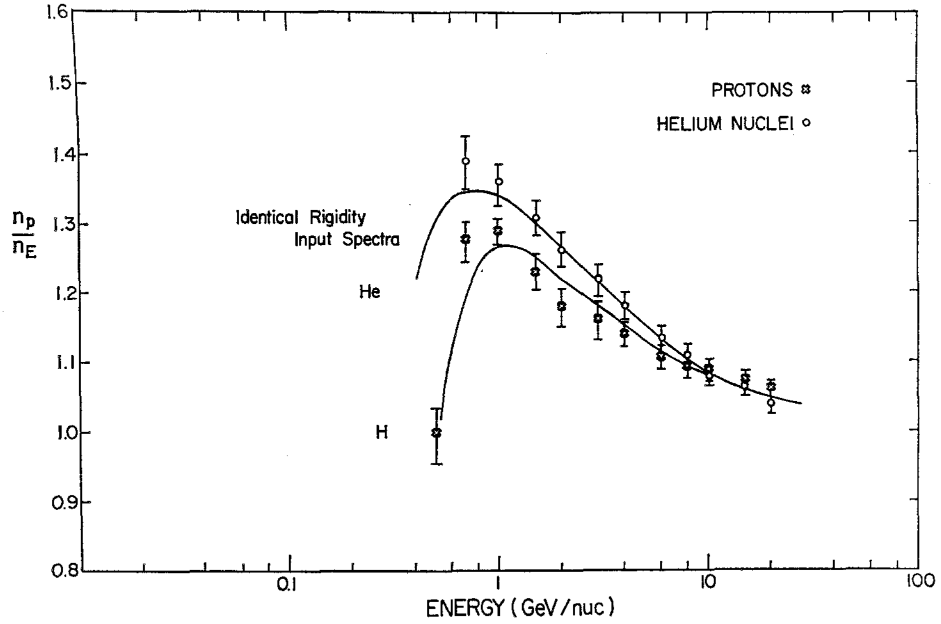

Fig. 10. Observed ratio of spectral indices n_P/n_T for protons ×, and helium nuclei ○. The solid lines are predicted spectral index ratios for each species assuming identical rigidity spectra with rigidity spectral index decreasing at low rigidities (see Figure 7).

shown in Figure 10. The errors in the data points in Figure 10 here are our estimates of the uncertainty in the data. Suppose we now assume that the input spectra for protons and helium nuclei are *identical* rigidity spectra but allow the spectral index to decrease as lower rigidities similar to that shown in Figure 7. The solid lines in Figure 10 show the calculated n_P/n_T variation as a function of energy/nucleon. The agreement between the data and the calculation further demonstrates that the input spectra are fundamentally rigidity spectra. This provides an understanding of the reasons for the decrease in the spectral index of both the proton and helium nuclei spectra at relatively high energies when examined as a function of energy/nucleon, and more importantly for the fact that the spectral index of the proton and helium nuclei is different at the same energy/nucleon (e.g., Figure 5).

Let us now view the same situation in terms of the intensity ratios. The data presented in Figures 6 and 8 indicate a continuously changing ratio $R_T(T)$ with energy T whereas the ratio $R_P(P)$ is nearly constant above ~ 2 GV at a value ~ 7. Using Formula (3) given above we may evaluate the behavior of the ratio $R_T(T)$ assuming that $R_P(P)$ is constant. This result is shown as a beaded curve in Figure 6. The agreement again makes it clear that if the fundamental proton and helium nuclei spectra are rigidity spectra, the behavior of the experimentally determined j_H/j_{He} ratio as a function of energy/nucleon or rigidity can also be understood.

We believe therefore that we have succeeded in demonstrating from the data in the range 2–50 GeV nuc^{-1}, where energy/nucleon and rigidity differences will be evident for particles of different charge to mass ratio, that the basic spectra of protons and helium nuclei are rigidity spectra.

In the following sections we will examine the implications of this point.

5. Local and Propagational Effects on the Proton and Helium Nuclei Spectra

Before we can attach any significance to the rigidity spectra in terms of characteristic spectra related to the acceleration of cosmic ray protons and helium nuclei, we must examine how local or interstellar propagation effects can modify the spectra.

In this case, local effects refer to the residual solar modulation that is almost certainly important even for the sunspot minimum spectra. There is considerable uncertainty as to the magnitude of this residual solar modulation, although perhaps less uncertainty as to its spectral form wherein the leading term in the modulation is basically a rigidity term. This can be seen from the data on the $j_{\mathrm{H}}/j_{\mathrm{He}}$ ratio displayed at several levels of modulation in Figure 6 (energy/nucleon) and Figure 8 (rigidity). It is clear that there is a much smaller change in the ratio $R_P(P)$ than in the ratio $R_T(T)$ as a function of the level of modulation.

Nevertheless, it seems quite clear that the solar modulation will introduce non-rigidity dependent changes in the spectra at low energies and most certainly will modify – perhaps considerably – the spectral shape at low energies (below ~ 1 GeV nuc^{-1}). On the basis of the present limits on the magnitude of this residual modulation, deduced from the electron modulation (Urch and Gleeson, 1972) we do not believe that residual solar modulation effects are significant above ~ 1–2 GeV nuc^{-1}, where we have carried out our comparison. We shall return to the very interesting details regarding the solar modulation and possible limitations on the low energy proton and helium spectra in a later section.

The problem of interstellar propagation is basically a very complex one. If one considers the usual diffusion in a leaky box (steady state) model for galactic confinement (e.g. Cowsik *et al.*, 1967; Gloeckler and Jokipii, 1969), then two aspects of this propagation are important from the point of view of modifying the shape and/or rigidity dependence of the cosmic ray spectrum. The first concerns the fact that the cosmic rays appear to pass through an average ~ 5 g cm^{-2} of interstellar hydrogen during their lifetime with a resultant ionization energy loss. The second concerns the manner in which the cosmic rays are believed to escape from the Galaxy and whether this escape is dependent or independent of energy/nucleon or rigidity.

It can be shown that the ionization energy loss effects are much too small to significantly affect the spectra above a few hundred MeV nuc^{-1} (Comstock *et al.*, 1972). Thus, this will not affect the preceding spectral comparisons which apply at higher energies; however, as with the solar modulation effects, it will be important in shaping the low rigidity part of the spectrum.

The confinement or escape problem will very definitely affect the properties of the spectra at high rigidities, however, and is in fact a question of much current interest. This interest arises because of spectral differences observed for various groups of nuclei with $Z \geqslant 3$ as noted in the introduction. These spectral differences are such that the abundance ratios of the so-called secondary nuclei such as Li, Be, and B to primary or source nuclei such as C, O, ..., Fe become less at higher energies. This has been interpreted as being due to the fact that the higher energy source nuclei have transversed less matter at high energies with a resultant smaller production of secondary nuclei (Juliusson *et al.*, 1972). One possible explanation of this behavior would be that the escape from the Galaxy is rigidity or energy/nucleon dependent and high energy source nuclei escape more easily (Webber *et al.*, 1973; Meneguzzi, 1973; Audouze and Cesarsky, 1973). Since all of the higher Z nuclei have the same charge to mass ratio, they do not help to distinguish between an energy/nucleon or a rigidity dependent type of escape. Diffusion theory, however, argues that rigidity should be the appropriate parameter (e.g. Jokipii, 1971).

The heavier nuclei data does permit a determination of the confinement time dependence on rigidity required to fit the heavy nuclei spectral differences. This dependence is approximately $\tau \sim P^{-0.5}$. It is not clear from previously published data whether the dependence of confinement time only sets in above a given rigidity P_0, which may be $\gtrsim 10$ GV or whether this dependence applies at lower rigidities as well. Later in this paper, utilizing He and C+O spectral comparisons, we suggest that an extension of this confinement time dependence to lower rigidities can provide an explanation of the data at lower rigidities as well. Thus we shall assume that this dependence applies at all rigidities and we will examine what effect such a rigidity dependent confinement time would have on the ratio $R_P(P)$.

This calculation is carried out using the steady state-exponential path length distribution model for cosmic ray propagation as used to explain the heavier nuclei differences by Webber *et al.* (1973b). Essentially the ratio $R_P(P)$ changes because of the different interaction M.F.P. of protons and helium nuclei. If secondary production is neglected as well as ionization energy loss, then for rigidities > 2 GV

$$R_P(P) = R_P^S(P)\left[\frac{\left(\dfrac{1}{\lambda_{\mathrm{He}}} + \dfrac{1}{\lambda_e(P)}\right)}{\dfrac{1}{\lambda_{\mathrm{H}}} + \dfrac{1}{\lambda_e(P)}}\right], \tag{5}$$

where λ_e (the escape length in g cm^{-2}) $= 7.5/P^{0.5}$ and the interaction M.F.P. for protons and helium nuclei in hydrogen, λ_P and λ_{He} are 80 and 18 g cm^{-2} respectively.

This variation is shown as a dashed curve in Figure 8 normalized to an initial source abundance, $R_P^S(P)$, ratio of 7.0. It is evident that the observed ratio of these components (with its attendant errors) is consistent with the expected small variation with rigidity to be expected from this effect. A similar conclusion holds for the spectral exponent *differences*. Improved measurements of the proton and helium nuclei spectra should be able to confirm or disprove these expected variations.

Note that if there were a changeover to a rigidity dependent escape *only* above some limit $P_0 \gtrsim 10$ GV one would observe, in addition to the above small effects, a gradual change (increase) in the spectral exponent by at least 0.5 of the proton and helium nuclei rigidity spectra. This is not observed in the data. Furthermore, if instead an energy/nucleon dependent escape is assumed to set in above some limit $E_0 \gtrsim 5$ GeV nuc^{-1} then large changes in the ratio $R_P(P)$ should be observed. This is also not the case.

Only a simple propagation model wherein the confinement time is rigidity dependent and this rigidity dependence has nearly the same functional form, e.g. $\sim P^{-0.5}$ over essentially all rigidities $\gtrsim 1$ GV, would be consistent with the observed P/He ratios.

6. Comparison of Proton and Helium Spectra with C+O Spectra

It seems appropriate at this point to further relate the proton and helium nuclei data compiled here with the heavier nuclei spectral differences recently reported. To do this we shall utilize only the C+O spectral data since all of the other heavy nuclei spectra and ratios may be referenced to those of the more abundant C+O. The differential intensities of C+O nuclei at higher energies expressed as both energy and rigidity spectra have been shown along with the proton and helium nuclei intensities in Figures 1 and 2. In Figure 11 we show a compilation of the He/C+O ratios from this high energy data and other lower energy C+O data presented by Webber *et al.*, 1973b. There are some important differences in the data from different experimental groups

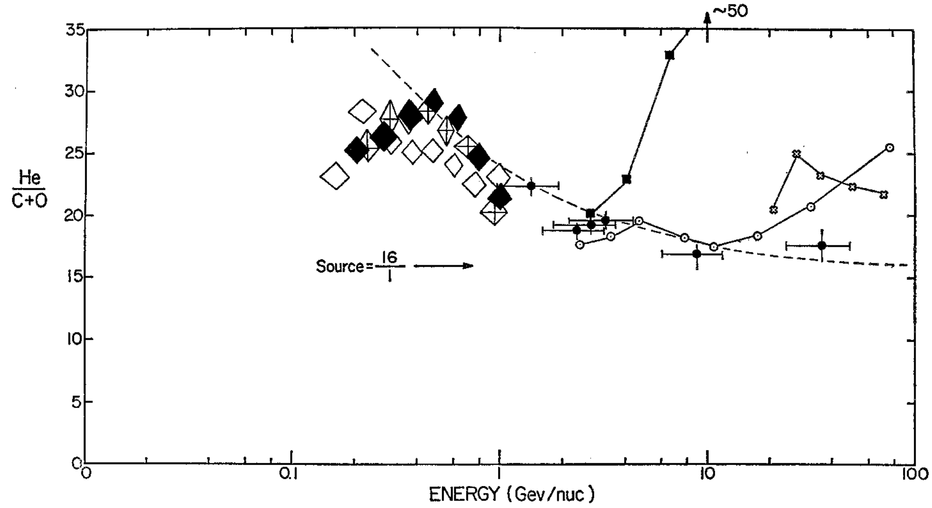

Fig. 11. He/C+O ratio as a function of energy. Symbols used for data refer to the same references as in Figure 1.

as can be seen by comparing the C+O intensities given in Figures 1 and 2 as well as the ratios in Figure 11. In particular the He/C+O ratios (and the C+O intensities) measured by Balasubrahmanyan and Ormes, 1973, do not agree with the other data. These differences must be cleared up before a complete picture can emerge; nevertheless it appears that, if one considers the remaining data from several different experimenters, the He/C+O ratio clearly decreases with increasing energy and the C+O spectrum is, therefore, less steep than that for He.

It is important to recognize that this is a spectral difference between two groups of primary or source nuclei. If indeed the rigidity dependent confinement time model is the correct explanation of the changes in secondary to source nuclei ratios of heavier nuclei as discussed earlier, then the source nuclei ratios should also change in a systematic and predictable manner. We have already indicated that this change is below the limits of detectability for the $R_P(P)$ ratio. However, the effect is much larger for the heavier nuclei because of their shorter interaction M.F.P. In Figure 11 we show calculations of the expected change in the He/C+O ratio for a similar propagation model to that used for protons and helium nuclei (with the confinement time $\tau \sim P^{-0.5}$) *but including the effects of interstellar ionization energy loss* (Webber *et al.*, 1973b). It is assumed that He and C+O have identical source spectra and the ratio He/C+O at the source = 15.6. The agreement between the data and the theory is generally good.

A similar energy dependence has been observed for another source nuclei ratio, C+O/Fe+Ni (e.g. Ormes and Balasubrahmanyan, 1973; Webber *et al.*, 1973a) and recently Juliusson and Meyer (1973) have reported changes in the C/O ratio that are also consistent with the effects attributable to an energy dependent confinement time. The present study confirms a systematic trend to steeper spectra for lower Z source nuclei including not only C+O and heavier nuclei but extending to He as well.

7. Behavior of Proton and Helium Nuclei Spectra at Low Rigidities

A major and very important point of interest regarding the interstellar proton and helium nuclei spectra concerns their behavior at low rigidities (energies). For example, how are the relatively constant exponents of −2.70 which apply to these interstellar rigidity spectra above ~10 GV modified at low rigidities, by interstellar ionization energy loss effects, and later by solar modulation effects. The question of the form of the low rigidity interstellar spectrum is a complex problem and has been a subject for extended discussion for several years. Combinations of rigidity spectra, energy and total energy spectra have been invoked, based on arguments involving the acceleration and escape of the cosmic rays from their sources, interstellar propagation and the effects of solar modulation (e.g. Hayakawa *et al.*, 1958; Apparao and Ramadurai, 1964; Balasubrahmanyan *et al.*, 1965; Durgaprasad *et al.*, 1967). As the models for solar modulation have improved and particularly with the advent of modulation models including the effects of energy loss it has been realized that to explain the observed spectra at Earth the input spectra of protons and helium nuclei to the solar system must be relatively flat at low rigidities (Goldstein *et al.*, 1970; Urch and Gleeson, 1972; Lezniak and Webber, 1971; Comstock *et al.*, 1972). Similar conclusions regarding the flattening of the low-energy proton and helium spectra can be made from studies of the He^3 and H^2 components of cosmic rays (Meyer, 1970; Comstock *et al.*, 1972). Thus the differential energy or rigidity spectra observed at higher rigidities cannot continue to the lower rigidities without a change (decrease) in exponent.

For this reason a total energy spectrum has been in the past a very attractive alternative since it naturally bends over and becomes almost flat at low energies (or rigidities). Comstock *et al.* (1972) present a detailed discussion of the possibilities and limitations that exist regarding the interstellar proton and helium nuclei spectra at low energies. It is worth noting that in addition to a total energy spectrum of the form $W^{-2.6}$ they have considered rigidity spectra of the form $P^{-M(P)}$ where M decreases at low rigidities. Identical rigidity spectra of this type for both protons and helium nuclei will produce *different* spectra for these species on an energy/nucleon basis. To illustrate this we show in Figure 12 a typical total energy source spectrum at low energies as well as identical proton and helium nuclei rigidity spectra of the form $P^{-M(P)}$. These rigidity spectra are normalized to give the same energy/nucleon spectra at high

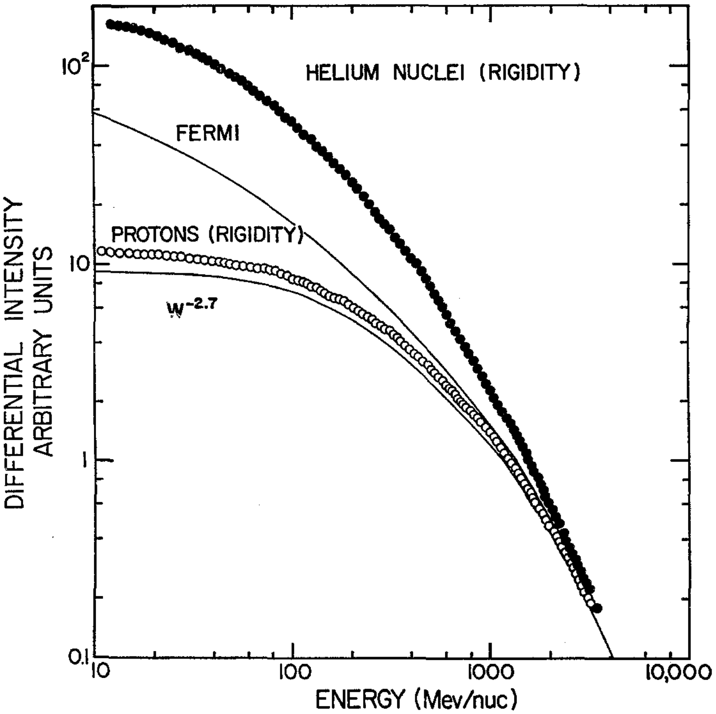

Fig. 12. Identical proton and helium nuclei *rigidity* spectra expressed as a function of energy/nuc. Spectra are set equal at high energies in order to show differences at low energies. Shown for comparison are a total energy spectrum and a Fermi spectrum after Ramadurai and Biswas (1974).

energies. Note that when the spectra are transformed to equivalent energy/nucleon spectra and $M(P)$ is allowed to decrease at lower rigidities, He is enhanced at low energies relative to protons. This type of rigidity spectrum is found to fit the spectral data at Earth at low energies as well or better than a total energy spectrum after the effects of solar modulation and interstellar propagation are taken into account (Comstock, 1972). Along similar lines Lezniak and Webber (1971) find that it is necessary to assume *different* initial total energy spectra for protons and helium nuclei (equivalent to rigidity 'like' spectra) in order to produce the observed spectra of these nuclei at Earth at various levels of solar modulation.

The point of this argument is that there is already some evidence that identical input total energy spectra for protons and helium nuclei might *not* provide the best fit to the solar modulation calculations at low energies. Identical rigidity spectra, but with the spectral index changing at low rigidities can provide an alternative fit to the data.

We note that in the above picture, part of the changing spectral index at low rigidities on a rigidity representation must be due to rigidity dependent effects at the 'source' of cosmic rays and not related to solar modulation or interstellar propagation effects. This is a very important point (see also Hayakawa *et al.*, 1958). In a subsequent paper we intend to examine the details and restrictions on the low rigidity part of the spectrum from the point of view of our findings here which suggest that the spectra are basically rigidity spectra above ~ 2 GV.

8. Acceleration of Cosmic Rays and Their Spectral Form

The preceding arguments have focused on the question of the acceleration and escape of cosmic rays from their sources in terms of the types of spectra that might be expected. In what follows, therefore, we will briefly examine the question of the acceleration of cosmic rays from the point of view of what constitutes a 'natural' spectrum.

It now seems to be generally accepted that all types of cosmic ray acceleration must ultimately reduce to either the Betatron effect or the Fermi mechanism (e.g. Parker, 1958; Hayakawa, 1969). Much interest has centered on the Fermi mechanism because Fermi's original calculations (Fermi, 1949) lead to a total energy spectrum, and a differential total energy spectrum bends over and becomes almost flat at low energies which is similar to the apparent behavior of the interstellar cosmic ray spectra. Such an input spectrum is 'typical' of what is required at the boundary of the solar system to produce the intensities of protons and helium nuclei observed at Earth as we noted earlier. Since Fermi was considering only relativistic particles he did not include the velocity dependence of the acceleration parameter. When this is included the shape of the low energy spectrum is quite different from a total energy spectrum. In Figure 12 we illustrate this modified Fermi spectrum as derived by Ramadurai and Biswas (1974) assuming no energy loss mechanisms during acceleration. Almost certainly some loss mechanisms (e.g., ionization energy loss) are present during acceleration and these will further affect the spectrum (see, for example, Ramadurai, 1967).

The actual situation is most likely much more complicated for either a simple Betatron or Fermi type of acceleration process. Particles could spend a distribution of times in the accelerating region and the form of this distribution function might determine the spectrum. Once the particles have been accelerated, they must escape from the accelerating region, and the manner of this escape may completely determine the shape of the spectrum at low rigidities (Hayakawa *et al.*, 1958). Some idea of the wide variety of spectral forms possible in these acceleration processes may be obtained from the work of Hayakawa (1969) and from Wentzel (1965). It would seem that almost *any* form would be possible for the source spectrum of cosmic ray protons and helium nuclei at low rigidities *except* a pure total energy spectrum.

9. Cosmological Implications of P/He Ratio

If we interpret the value of 7.0 for the ratio $R_P(P)$ above ~ 2 GV as giving an unbiased measurement of the abundances of these two elements at the cosmic ray source, the source He abundance will be 0.12 by number. No such simple abundance interpretation is possible using energy spectra because of the large change in $R_T(T)$ with energy. Likewise it is not possible to accurately determine this ratio for solar cosmic rays because of its great variability from event to event and complicated propagational effects (Biswas and Fichtel, 1965). The solar He number abundance estimated using several other approaches is 0.05–0.08, but with an uncertainty of a factor of 2 (Hirshberg, 1973).

Several calculations of the expected He abundance produced at the time of the primordial fireball (big bang) give a value between 0.06–0.10 (Hack, 1972). Further production in stellar interiors since that time may have produced an additional 0.04 He by number. Direct spectroscopic measurements of the He abundance in celestial objects are difficult to make. The best determinations in young OB stars or in diffuse nebula give values between 0.08 and 0.15 (Hack, 1972). It would thus appear that a cosmic ray source abundance of 0.12 would be typical of an object that has a 'normal' He abundance at this cosmological era. In the theories of nucleosynthesis and the subsequent acceleration of cosmic rays the protons and helium nuclei are usually treated separately. The cosmic ray P/He ratio of 7.0 says, in effect, that a distribution of matter is accelerated that is quite closely a normal stellar distribution of H and He. If this material is in the outer envelope of a massive star in which considerable nuclear burning has taken place this sets a very important constraint on the manner in which the H and He are distributed. Also one could conclude that the acceleration process itself preserves the in-situ abundance and is not significantly dependent on A/Z.

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