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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Composition and Spectra of Primary Cosmic-Ray Electrons and Nuclei above 10 ^{10} eV [and Discussion]

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Composition and spectra of primary cosmic-ray electrons and nuclei above 10^{10} eV

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Recent experiments have extended the knowledge of the flux and energy spectra of individual cosmic-ray components to much higher energies than had previously been accessible. Both electron and nuclear components show a behaviour at high energy which is unexpected, and which carries information regarding the sources and the propagation of particles between sources and observer. Electromagnetic interactions which are suffered by the electrons in interstellar space should steepen their spectrum, a steepening that would reveal the average lifetime a cosmic-ray particle spends in the galaxy. Measurements up to 1000 GeV show no such steepening. It was discovered that the composition of the nuclear species which is now measured up to 100 GeV/nucleon changes with energy. This change indicates traversal of less interstellar matter by the high energy particles than by those of lower energy. We discuss the experimental evidence and its implication.

1. Introduction

The past 10–15 years have seen major advances in cosmic-ray research and have established this field as an important contributor to astrophysics. The oldest problem, a unique identification of the sources of the energetic cosmic-ray particles, has not found its final solution, but much evidence has been gained through increasingly sophisticated experiments that have illuminated fundamental questions and have made new areas accessible to experimental tests.

We owe much of this progress to advances in technology, which have, on the one hand, provided vehicles that enable the experimenter to expose his instruments to the primary radiation, nearly or completely uninhibited by the terrestrial environment. On the other hand, new techniques have led to highly elaborate detectors and data handling systems. The modern scientific balloons, satellites, and deep space probes have been responsible for the progress of the 1960s. Instruments which they carried have yielded a wealth of details of those properties of the cosmic radiation that are the topic of this discussion: the relative abundances and the energy spectra of the individual species. This spectroscopy of cosmic rays has shown that the nuclear composition of the radiation exhibits striking similarities to the solar system abundances and hence to evolved stellar matter of thermonuclear origin. It has also displayed important differences from the solar abundances: (1) There is an overabundance of the heavier nuclei in the cosmic radiation, (2) many nuclear species that are very rare in the Solar System occur with relatively large intensity in the cosmic rays. The second of these features can be understood as a generation of 'secondary' cosmic rays taking place through interactions in interstellar space. From the abundance of these secondaries a measurement of the amount of matter traversed by the particles in their travel between source and observer can be obtained, and hence an estimate of the time which they spend on the average in interstellar space before being lost. If cosmic rays are contained in the galactic disk, this lifetime is estimated to be of the order of 10^6 years. It is clear that such estimates depend on the choice of a model for the Galaxy.

Interestingly, the relative abundances of different particles has until recently been found to be energy independent from a few MeV/nucleon to several GeV/nucleon in energy. Or in other words, the shape of the energy spectrum was observed to be practically the same for all nuclei. The conclusions drawn from this observation are: (1) all nuclei are accelerated with the same efficiency, having spectra of the same form at the sources, (2) the amount of matter traversed in the Galaxy does not depend on the type of particle nor on its energy, and (3) all particles are contained for about the same length of time in the Galaxy before being lost to extra-galactic space.

This evidence has led to several models, the simplest being the so-called 'leaky box' model of the Galaxy, in which all particles are produced uniformly in space and time and have the same probability for escape, independent of their type and energy. Such a model leads to an exponential distribution of leakage path lengths, a distribution which was experimentally found to have a mean value of about 5 g/cm^2. Jokipii & Parker (1969) and Ramaty & Lingenfelter (1971*a*) have provided a physical basis on which such a model can be understood.

This leads to the central topic of my discussion, the behaviour of individual cosmic-ray species at higher energies. This behaviour has an important impact on the problems of the origin and propagation of the cosmic radiation since the experimental evidence forces one to abandon some of the assumptions made in the simple model.

Owing to experimental difficulties work in this direction has started only very recently. The energy spectra of cosmic-ray electrons and nuclei are quite steep at high energy, being well described by power laws in energy of the type $\mathrm{d}J/\mathrm{d}E \approx E^{-\gamma}$ where $\mathrm{d}J/\mathrm{d}E$ is the differential particle flux, E the particle energy, and where γ has a value from 2.4 to 2.8. Hence the flux rapidly decreases with energy and in order to collect samples of particles of sufficient size to obtain statistically meaningful results, it is necessary to expose large area detectors for a reasonable length of time. Further, special techniques are required to determine the energy of particles with more than several GeV/nucleon, and such techniques have only recently been applied to studies of the cosmic radiation. The results of this work have been very rewarding and have led to the evidence that I shall discuss in some detail in the following paragraphs.

2. The experiments

This is not the place to enter a detailed or complete description and comparison of the various experimental techniques in this field of work. I shall therefore only sketch the approaches taken by a few of the groups involved in the effort of measuring the spectra of very energetic cosmic rays, since they are important in interpreting the conclusions and the range of applicability. The method used by the group of the University of California, Berkeley (Smith *et al.* 1973) is conceptionally the most straightforward. They designed a balloon-borne magnetic spectrometer, consisting of a superconducting magnet, in conjunction with a particle telescope of spark chambers and counters and were able to measure spectra of nuclear particles from 2 to 70 GeV/nucleon. With slight modifications, this method can be applied to separately study the spectra of electrons and positrons as well. A different approach to measure particle energy was taken by a group at the Nasa Goddard Space Flight Center (Ormes & Balasubrahmanyan 1973). These scientists constructed and flew a massive ionization spectrometer in which they absorbed within the apparatus a major fraction of the energy of the incident particles and their secondaries. Their instrument lends itself to a study of the energy spectrum of nuclei and of electrons. So far it has covered an energy range from 3 to 60 GeV/nucleon. A third method for energy determination was used by us at the University of Chicago (Juliusson, Meyer & Müller 1972; Juliusson 1974). This method makes use of the velocity dependence of the response of several gas Cerenkov counters filled with different gases to determine energies of nuclei in the 20–100 GeV/nucleon range. Finally, the Earth's magnetic field and its geomagnetic cut-off has been used for energy determination in an experiment carried on a polar satellite (Brown, Stone & Vogt 1973) and in a balloon experiment (Webber, Lezniak, Kish & Damle 1973). This method can be used up to energies of about 10 GeV/nucleon.

Techniques slightly different from those needed for measuring nuclear spectra at high energies are required in the study of electrons and positrons. Only magnetic spectrometers achieve the separation of electrons and positrons at high energy. The more recent work that was carried out with this technique (Daugherty, Hartman & Schmidt 1973; Buffington, Smoot, Smith & Orth 1973) up to and around 10 GeV seems to confirm the earlier results of Fanselow, Hartman, Hildebrand & Meyer (1969) that the fraction of positrons in the electron component is of the order of 10% at energies exceeding several hundred MeV. The total electron spectrum has been measured to much higher energy (close to 1000 GeV) by investigating the electron-photon shower which the incident electron develops in a material of high atomic number. In counter experiments, the shower is used for identification of the electron as well as for energy measurement. The pioneering work toward measurements of the electron spectrum at high energies was carried out with nuclear emulsions (Daniel & Stephens 1966) and this technique has been further refined in recent times (Anand, Daniel & Stephens 1973; Nishimura *et al.* 1973). Paralleling these efforts were the developments of electronic counter experiments and the authors who have most recently contributed to this effort are Müller & Meyer (1973), Meegan & Earl (1973) and Silverberg, Ormes & Balasubrahmanyan (1973).

3. Composition and energy spectra

(*a*) *Nuclei at* $E > 10$ GeV/*nucleon*

I shall begin by presenting some of the recent results on the composition of cosmic-ray nuclei which have a bearing on the models of cosmic-ray origin and of propagation and confinement of these particles in the Galaxy. These can be summarized by the following observations: At energies above several GeV/nucleon the nuclear composition of the cosmic rays undergoes large, and readily observable changes. These changes affect most dramatically the abundance ratio of daughter nuclei to parent nuclei, i.e. the ratio of those nuclei that are mostly produced as secondaries in collisions in the interstellar medium, to the primary nuclei which presumably originate in the cosmic-ray sources. The evidence is displayed in figure 1, taken from the work of Juliusson *et al.* (1972) and Juliusson (1974). As can be seen, this ratio is changing by more than a factor of two over the energy range 1–100 GeV/nucleon. One can immediately conclude from this evidence that the more energetic nuclei traverse considerably less interstellar matter than those of lower energy. A possible alternative explanation, that the spallation cross-sections for nuclei around 100 GeV/nucleon may be much smaller than at 1 GeV/nucleon must be rejected, since theoretical considerations predict, and evidence from experiments on accelerators shows, that these cross sections have very little energy dependence above a few GeV/nucleon. In figure 2 we present a comparison of the results from various experimenters for the ratio (B + N)/C as a function of energy. These three elements are adjacent in the periodic table.

Boron is entirely of secondary origin, and nitrogen mostly so, while carbon is essentially a primary nucleus. The same trend that was seen in figure 1 can be observed. The curve in this figure is a fit to the data describing the energy dependence of this ratio as a power law in total energy per nucleon. The success of this fit suggests that the changes in the abundance ratios are smooth functions of energy, which, due to their smallness, could not be ascertained in the earlier composition measurements around and below about 1 GeV/nucleon. This is further confirmed by the absence of any sharp break in the energy spectra of the individual nuclear species.

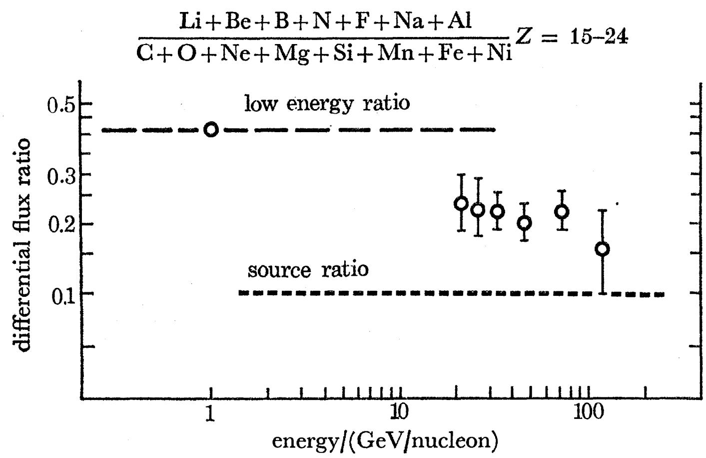

FIGURE 1. Measured abundance ratio of daughter nuclei to parent nuclei as a function of energy. The dashed line indicates the value measured at and below about 1 GeV/nucleon. The dotted line shows the ratio at the source, extrapolated from the low energy data (from Juliusson 1974).

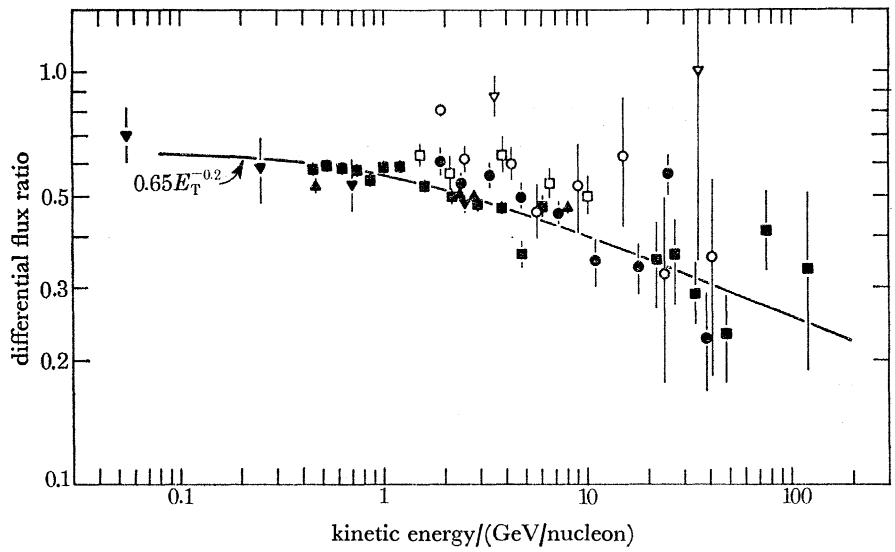

FIGURE 2. Energy dependence of the abundance ratio of boron plus nitrogen to carbon as measured by: ■, Juliusson; ●, Smith *et al.*; ▲, Webber *et al.*; ▼, Mason; ○, Ormes & Balasubrahmanyan; ▽, Badhwar & Osborn; □, Brown *et al.*

A variety of interpretations to these results has been offered. The most straightforward of these (Audouze & Cesarsky 1973; Meneguzzi 1973*a*) assumes that the leakage path length λ (in g/cm^2) of a particle in the Galaxy decreases as the energy of the particle increases. If, as we have suggested above, the secondary to primary ratio decreases as a power law in total

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

energy, then $\lambda(E)$ would also be close to a power law, $\lambda(E) \sim E^{-\alpha}$. The containment time or lifetime τ of a particle in the Galaxy is related to the amount of matter it traverses by $\lambda = \rho\beta c\tau$ where ρ is the average interstellar density in g/cm³ and βc is the velocity of the particles (for most cosmic rays in the energy régime considered in this discussion $\beta \approx 1$). In this picture, the containment time of the cosmic rays in the Galaxy will therefore also be energy dependent, and be of the form $\tau = \tau_0 E^{-\alpha}$. Since the experimental evidence points to values of α between 0.3 and 0.5, this leads to the consequence that the injection spectra of nuclei at their sources must be considerably flatter than the spectra observed at Earth, and that therefore a significantly larger energy input by the sources is required than had been estimated before.

These requirements for an additional input in energy can be avoided if one considers a more complex model which is not described by a single parameter, the leakage path length. Such alternative has been proposed by Cowsik & Wilson (1973) and by Meneguzzi (1973*b*) who consider a 'double leaky box' in which the cosmic-ray sources are surrounded by a relatively dense region from which the energetic particles must escape prior to reaching the interstellar medium. In this picture low energy particles traverse a major fraction of the total amount of matter near their sources, and it is not difficult, by invoking suitable magnetic field configurations, to arrange that this amount of matter depends strongly on the particle energy. If independent evidence should show, for example through measurement of the abundance of radioactive isotopes, that the leakage life from interstellar space is indeed 10^6 years, then this model requires that the average interstellar density of matter be reduced by a considerable amount in order to keep the total amount of matter that the particles traverse fixed. For example, if the low energy particles traverse 4 g/cm² out of a total of 5 g/cm² near the source, as the composition experiments indicate, the average interstellar density must be reduced from about 1 to 0.2 hydrogen atom/cm³. It may be difficult to accomodate this low value with other astrophysical evidence.

Both models that have so far been mentioned are based on the assumption that the cosmic rays are in a steady state, i.e. that they are produced uniformly in space and time and that the production spectrum is the same everywhere in the Galaxy. There clearly exist other alternatives which however would require a more drastic modification of the simple picture that has been successfully used in the past. If, for example, some cosmic-ray sources were located closer to the Solar System, or at least located in positions from which the Solar System is more accessible for energetic particles, and if the spectra emitted from these sources were richer in high energy particles, one would also expect the ratio of daughter to parent nuclei to decrease with increasing energy. A test of the possibility that individual particular sources contribute to the cosmic rays observed at Earth would become available if changes in composition could be found that could definitely not be explained on the basis of propagation models. It is therefore interesting to study the behaviour of the parent nuclei which predominantly originate in the cosmic-ray sources and to investigate whether their relative abundances change to a degree that can only be due to the nature of the sources themselves. The abundance ratios that have been studied at this time and that fall in this class are the carbon to oxygen ratio and the ratio of carbon plus oxygen over the iron group. Figure 3 and figure 4 display the results. At low energies, the cosmic-ray C/O ratio is measured to be close to 1.1. A fraction of the carbon nuclei observed at Earth is due to the spallation of heavier nuclei in interstellar collisions, especially oxygen. Using solutions of the transport equation for the propagation of cosmic rays which contains the nuclear cross-sections involved and the experimentally determined leakage path length, one extrapolates that ratio at the source to be about 0.9. This is indicated by the dashed line in figure 3. One should keep in mind that this extrapolation has considerable uncertainty, particularly due to the poorly known cross-sections. It is interesting to note that the measured C/O ratio around 100 GeV/nucleon falls considerably below the extrapolated source ratio and approaches a value not far from the C/O abundance ratio observed in solar system matter which is approximately 0.5. Clearly, the accuracy of the measurements and of the knowledge of the source ratio are not sufficient at the present time to state unambiguously that one is observing contributions of a source with larger relative abundance of oxygen, but this possibility is indicated.

A similar situation is encountered when one investigates the ratio of the medium nuclei (essentially C+O) with respect to the iron group as shown in figure 4. While the scatter of

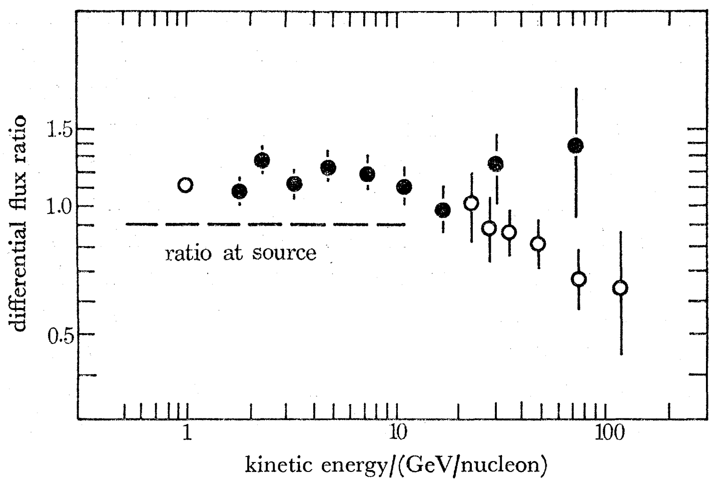

FIGURE 3. Measured abundance ratio of carbon to oxygen as a function of energy. ●, Smith *et al.* (1973); ○, Juliusson & Meyer (1973). The dashed line shows the ratio at the source, extrapolated from the low energy data.

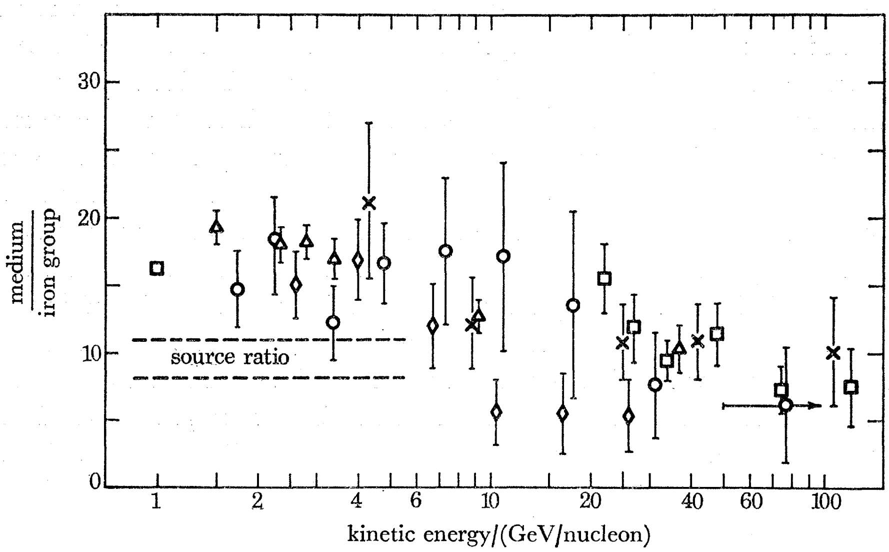

FIGURE 4. Energy dependence of the abundance ratio of the medium nuclei (essentially C+O) to the iron-group nuclei (Mn+Fe+Ni) as measured by various observers (from Garcia-Munoz 1973).

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

data from different experimenters is large, it is still evident that this ratio drops by more than a factor of two in the interval from 1 to 100 GeV/nucleon, and reaches a level below the source ratio as extrapolated from the observed abundances at lower energies. The very small values of this ratio obtained in one experiment (Ormes & Balasubrahmanyan 1973) have led Ramaty, Balasubrahmanyan & Ormes (1973) to claim that it shows contributions of iron-rich cosmic-ray sources. Our own measurements, while lying below the extrapolated source ratio at the highest energies, can not support any such claim. They, of course can neither rule it out. One can hope that improved accuracy in the observations together with better determinations of nuclear cross-sections will answer this important question in the future.

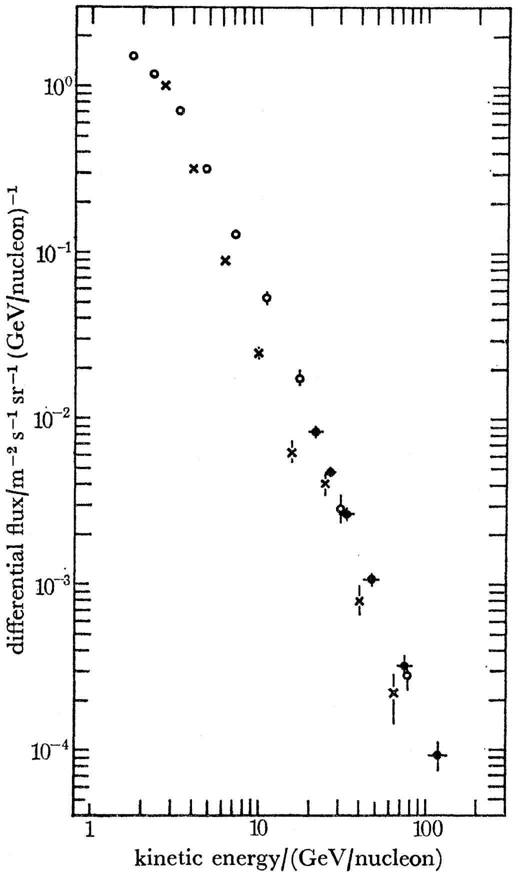

FIGURE 5. Measured differential energy spectrum of carbon plus oxygen at high energy. ○, Smith *et al* (1973); ×, Ormes & Balasubrahmanyan (1973); ●, Juliusson (1974).

The variations of the nuclear composition with energy imply different energy spectra for different nuclear species. There is no indication of any sudden changes in the shapes of these spectra and one may therefore assume that changes in composition do not occur abruptly above a certain energy. As an example we show in figure 5 experimental results for the differential energy spectrum of carbon and oxygen. The difficulties in determining such a spectrum are seen from the discrepancies in spectral form as well as absolute values of the fluxes as determined by different observers. All nuclear spectra were approximated by power laws in total energy, and table 1 includes values of the spectral index γ for a selection of elements as they were determined in the work of Juliusson (1974). As expected, the largest values of γ are found for the daughter nuclei boron and nitrogen. The flattest spectrum is observed for iron. One should keep in mind that those spectral indices are obtained from best fits to measurements of the differential energy spectrum ranging from a few GeV/nucleon to about 100 GeV/nucleon.

Table 1. Spectral indices measured for some cosmic-ray species

	energy	spectral index	references
electrons	$E > 30$ GeV	2.75 ± 0.1	Müller & Meyer (1973)
B	$E > 1$ GeV/nucleon	2.95 ± 0.07	Juliusson (1974)
C		2.65 ± 0.02	
N		2.74 ± 0.03	
O		2.53 ± 0.02	
Si		2.50 ± 0.03	
Fe+Mn		2.39 ± 0.04	

(*b*) *Electrons at* $E > 10$ GeV

The cosmic-ray electron component has properties that significantly differ in several respects from those of the nuclear components. Electromagnetic interactions are the dominant mode of interplay with the interstellar medium. While nuclei, through their strong interactions, are affected by the distribution and density of interstellar matter, the electrons interact with interstellar magnetic fields and interstellar photons (throughout this discussion we are dealing with particles of kinetic energy above several GeV, and we have therefore everywhere neglected the comparatively insignificant energy losses by ionization). As mentioned before, the interaction cross-sections of high energy nuclei are nearly energy independent. The interaction of electrons with interstellar magnetic fields and photons on the other hand has a strong energy dependence. This interaction leads to the emission of synchrotron radiation (magnetic bremsstrahlung), and to Compton collisions. The energy loss rate due to both processes is proportional to the square of the electron energy and can be written as

$$\frac{\mathrm{d}E}{\mathrm{d}t} \sim \left(\frac{B_\perp^2}{8\pi} + W_{\mathrm{ph}}\right) E^2$$

where $B_\perp$ is the component of the magnetic field perpendicular to the electron trajectory and W_{ph} is the energy density of photons (the expression is correct only in the limit of Thomson scattering). At electron energies of concern in this discussion only the photon field of the universal 2.7 K black-body radiation will be of importance. Photons from starlight have a much higher energy; their collision with the energetic electrons can no longer be treated by Thomson scattering and the energy loss rate depends only weakly on energy. As a consequence of energy losses the life of electrons at a particular energy will not only be determined by the escape life from the Galaxy τ, but by their radiative lifetime

$$t(E) \simeq E/\dot{E} \quad \text{where} \quad \dot{E} = \mathrm{d}E/\mathrm{d}t$$

is the rate of energy loss. We plot that radiative lifetime as a function of energy in figure 6 using conditions that are assumed to prevail in the Galaxy, i.e. an average magnetic field $B_\perp$ of about 5×10^{-10} T, and an energy density of black-body radiation photons $W_{\mathrm{ph}} \approx 0.25\ \mathrm{eV/cm^3}$.

It follows from figure 6 that for an average containment time of cosmic rays in the Galaxy of a few million years, the time arrived at from the nuclear composition measurements, electrons with energy in excess of about 100 GeV will mostly be removed by sliding down the energy scale, long before being physically lost from the Galaxy. For the simplest model of galactic containment – the leaky box model with its energy independent containment time – it can be shown that the observed equilibrium energy spectrum is expected to steepen and increase its power law exponent by 1 around the energy where escape life and radiative life become equal, provided that the production spectrum of electrons at their source is a power law spectrum over the entire range. This fact is an important impetus for the attempts to measure the cosmic-ray electron spectrum at high energy, since the radiative life of the electrons can be estimated from the knowledge of the interstellar photon and magnetic field energy densities and hence observations of a change in spectral slope would yield a value for the cosmic-ray escape life from the Galaxy.

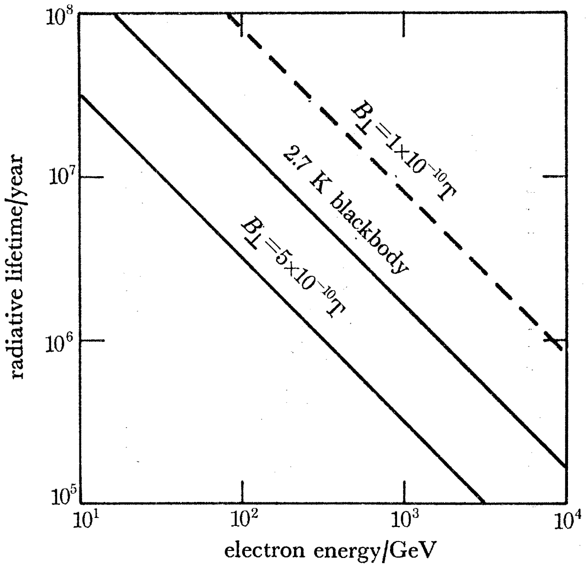

FIGURE 6. Radiative lifetime of electrons against energy losses by synchrotron radiation in interstellar magnetic fields and by inverse Compton scattering with the 2.7 K black-body radiation.

Turning to the experimental evidence, figure 7 gives a summary of the work on the electron spectrum at very high energies that was most recently presented at the 13th International Cosmic Ray Conference at Denver. We have included data from about 20 GeV to almost 1000 GeV, but, as can be noted, the results at the highest energy are of poor statistical quality. None of the authors claims to have observed deviations from a single power law spectrum, but the spectral indices attributed to individual measurements vary by a substantial amount, and range from 2.7 to 3.2. Inspection of this figure shows that obviously no clear decision can be made at this time, on whether or not a change in spectral slope occurs around 100 to 200 GeV. Our own measurements (Müller & Meyer 1973) yield a best fit with a single power law of index γ = 2.7 up to 900 GeV (table 1). Should better measurements agree with this evaluation, one would indeed have to accomodate in one's models particles with an average age of considerably less than 10^6 years.

There is another interesting aspect of the electron component. In the past years it could be shown that only a small fraction of the electrons can be of secondary galactic origin, and that most of these particles must originate in cosmic-ray sources. Secondary electrons are surely produced in the Galaxy, since collision processes lead to the production of π-mesons, and the subsequent π-μ-e decay of the charged pions produces electrons. Such secondary electrons will consist of approximately equal parts of negatrons and positrons. Measurements of the positron fraction that were carried out in the past years (Fanselow *et al.* 1969) and which are confirmed by more recent work (Daugherty *et al.* 1973; Buffington *et al.* 1973) have shown that about 10% of the electrons consist of positrons and hence that only a fraction of this component (*ca.* 20%) can be secondary in origin. One must conclude therefore that there exist sources of cosmic-ray electrons, and further, that these sources must be located within the Galaxy. The second conclusion is due to the fact that energy losses by Compton collisions with the 2.7 K universal black-body radiation would prevent high energy electrons from surviving in inter-galactic space for a time sufficiently long to reach our galaxy from extra-galactic objects. Also, as was first noted by Felten & Morrison (1966) an extra-galactic electron density at cosmic-ray energies comparable to that observed within the galaxy would lead to the production of X-rays at an intensity much above what is observed. Electrons and super heavy nuclei are the two cosmic-ray components whose galactic origin seems to be assured.

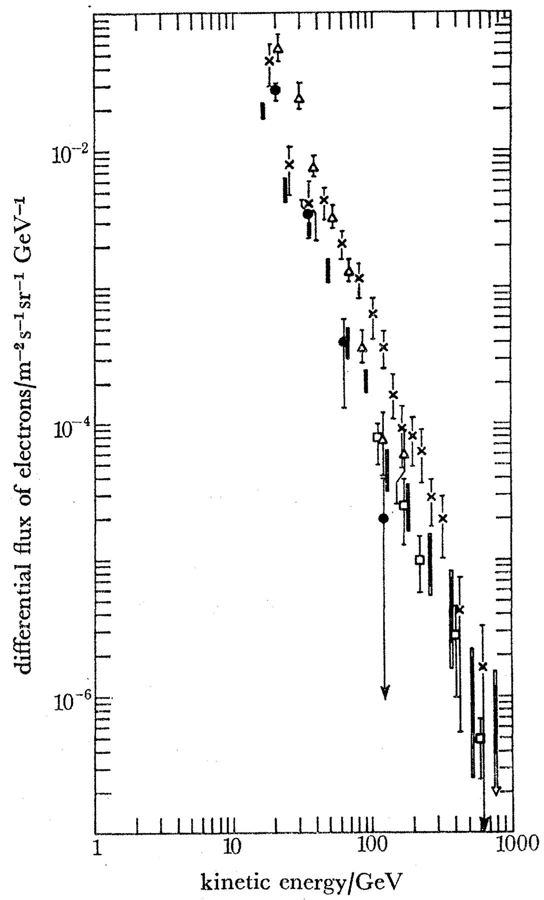

FIGURE 7. Measured differential energy spectrum of cosmic-ray electrons between 20 and 1000 GeV. ×, Anand *et al.* (1973); ●, Meegan & Earl (1973); ■, Müller & Meyer (1973); □, Nishimura *et al.* (1973); △, Silverberg *et al.* (1973).

4. CONCLUSIONS

At this stage I shall try to summarize the experimental evidence and to discuss the alternatives that present themselves for explaining the observations. Obviously one must expect connexions between the behaviour of high energy electrons and high energy nuclei. While it is not certain that cosmic-ray nuclei and electrons originate in the same sources within the

Galaxy, their propagation in the interstellar medium has much in common. If, for example, one considers the possibility that the containment time of cosmic rays in the Galaxy is a function of energy of the form $\tau(E) = \tau_0 E^{-\alpha}$ as discussed in §3*a* for explaining the changing relative abundance between daughter and parent nuclei, this energy dependent containment time would apply to electrons as well. Solutions of the transport equation for electrons which include this energy dependent τ exhibit two important properties: (*a*) at low energies the observed power law spectrum will have a spectral index $(\gamma+\alpha)$ and hence already be steeper than the source spectrum of index γ. Therefore, the change in slope of the spectrum around the energy where radiative life and escape life become comparable is much less than in the case of constant τ; (*b*) the energy where radiative life and escape life are the same is now shifted to considerably higher energies and actually lies outside the range where measurements exist. Silverberg & Ramaty (1973) and Juliusson, Meyer & Müller (1973) have treated this possibility more quantitively and have concluded that the observation of an electron energy spectrum with a single power law up to 1000 GeV would not be surprising under these circumstances. This explanation would have an obvious consequence which will be subject to future tests. The present experiments show that around 100 GeV/nucleon the abundance distribution of the nuclear cosmic rays is already close to the source composition. Not much further change of the relative abundances should then be expected at still higher energies, provided that the simple assumption is correct that all cosmic-ray source spectra are the same. Should future experiments at still higher energies not confirm this expectation, then it is clear that the changes in composition can no longer be explained by effects of propagation, but must be due to either energy dependent source compositions or to different sources with different element abundances. At this time no experiments have been performed at sufficiently high energies and good charge resolution to shed light on this question.

The interesting alternative explanation that we just mentioned and which would interpret the observations as indicating contributions from different cosmic-ray sources, would to some extent eliminate the very successful stationary state model of cosmic-ray production and loss which does not include contributions from individual sources to the observed flux of energetic cosmic rays. This possibility has already been considered in the past when Ramaty & Lingenfelter (1971*b*) and Shen & Mao (1971) suggested that the high energy electron spectrum might be explained as due to young particles coming from a nearby supernova remnant, for example the Vela supernova. Clearly, if the confinement time of all cosmic rays in the Galaxy is of the order of a few million years, then an electron spectrum that shows no deviation from a single power law much beyond several hundred GeV most likely consists of recently injected particles. Such sources could also lead to nuclei that are accompanied by few secondaries.

There is little doubt that we are at the threshold of some significant discoveries in cosmic-ray research to which the study of spectra and composition of individual cosmic-ray species at high energy will contribute. The question of the containment time of cosmic rays in the Galaxy may soon find an independent answer from observations of the abundance of radioactive isotopes which can serve as a clock. ^{10}Be is the most famous example. Measurements of the abundance distribution of parent nuclei at very high energies, and of characteristic isotopic abundances will help to reveal whether individual cosmic-ray sources contribute significantly to the flux of particles observed at Earth. If this were answered in the affirmative the old question of galactic versus extragalactic origin of the major part of the cosmic radiation would have moved much closer to a solution.

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Discussion

C. Dilworth (*Imperial College, London*). Neither in Meyer's nor Shapiro's talk has mention been made of the discrepancy which appears between the flux of positrons of about 1 GeV which one would expect on the basis of the high value of the mean path length derived from the flux of secondary nuclei, and that actually observed. Maraschi, Perola & I have been looking into this problem. There seems to be a real discrepancy in the sense that the observed flux of positrons is too low. It does not seem to be possible to resolve the discrepancy through a variation in the lifetime of the secondary particles, but rather through the site of the interaction of the primary particles (in the case of the positrons these particles are of much higher energy than the secondaries).

A. D. Erlykin (*P. N. Lebedev Physical Institute, Moscow, U.S.S.R.*). Following the initial work of Daniel *et al.* (1974) we (Erlykin & Wolfendale) have analysed muon charge ratio μ^+/μ^- in terms of the neutron–proton ratio n/p in the primary flux.

Assuming that scaling is valid in the range from I.S.R.-energies *ca.* 10^{12} eV to 10^{14} eV, both for pions and for kaons, and that charge ratio for pions produced in neutron–air nucleus interactions is inverse to that for proton–air nuclei interactions, then from the known value of μ^+/μ^- the ratio n/p can be derived. The results are shown in figure 8. One can see that approximate constancy of the muon charge ratio observed by the Durham and Utah groups leads to the conclusion that the fraction of neutrons in the primary flux is increasing with energy in the range studied. In the same figure is shown the n/p ratio expected if we extrapolate all proton and primary nucleus energy spectra with constant exponents from the direct measurement region, 10^{10}–10^{11} eV/nucleon, to higher energies. It is seen that the results obtained from this extrapolation and from the μ^+/μ^- ratio agree qualitatively, although the increase of n/p-ratio expected from the μ^+/μ^- data seems to be more rapid. If future observations show that μ^+/μ^- remains constant about 1.3 above $E_\mu \approx 10^{12}$ eV it will lead to a constant n/p-ratio ≈ 0.5, which will point against the continued growth of the fraction of nuclei in the primary cosmic-ray flux.

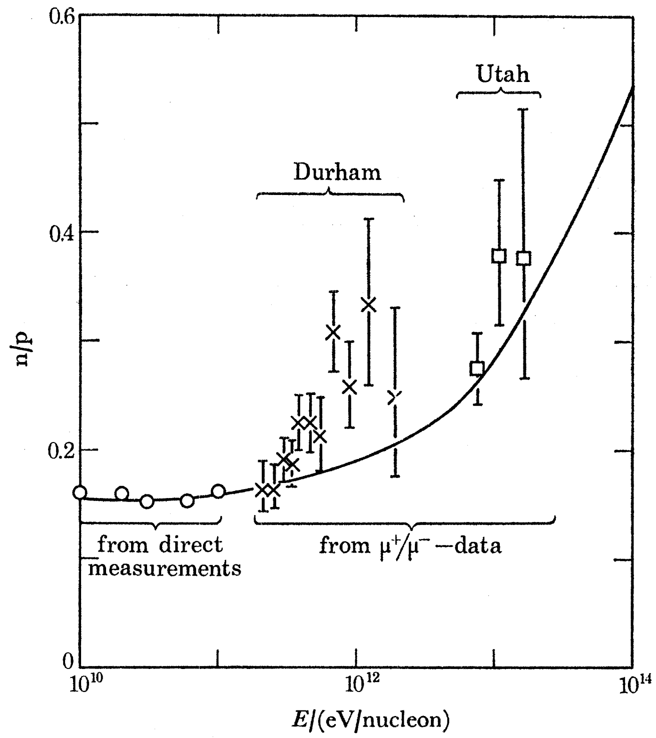

FIGURE 8

F. J. M. FARLEY, F.R.S. (*The Royal Military College of Science, Shrivenham, Swindon, Wiltshire SN6 8LA*). I should like to make some comments on the leaky box. We are all speaking as though our Galaxy was set in a vacuum, so that cosmic rays which leak out disappear for ever. This is of course not the case; our Galaxy is surrounded by millions of other similar galaxies, and we must ask to what extent the leakage of cosmic rays from our own galaxy is compensated for by a returning flux which has leaked out of the other galaxies? Or to put it another way, what is the flux in intergalactic space?

If the Universe were not expanding we should be in the situation of Olbers's paradox: the returning flux would exactly compensate, and there would be no net leakage from the Galaxy. To get a realistic result we must insert the expansion, and then the other parameters such as the size and the separation of the galaxies become relevant.

The result one gets is not the same as for visible light, because the galaxies are largely transparent in the visible, but opaque to cosmic rays. This means that the returning flux is much more important in the case of cosmic rays.

The result of my calculation (*Nuovo Cim. Suppl.* **8**, 466 (1958)) is rather surprising. The returning flux should be about 0.77 of the outgoing flux, so that in effect the leakage from our Galaxy is almost completely compensated.

If this is so, it will have quite a large effect on the leaky box models put forward this morning. I believe that the flux in intergalactic space, and the incoming cosmic rays from other galaxies must be taken fully into account in all these models, and the predictions may then be rather different.

C. F. FICHTEL (*Goddard Space Flight Center, Greenbelt, Maryland, U.S.A.*). For several reasons, including the apparent difficulty of cosmic rays propagating over large distances in the Galaxy before they escape from it, there is now considerable support for the cosmic rays being relatively local on a galactic scale. Also, there seems to be good reason to believe the propagation of cosmic rays, whether by diffusion or whatever process, is energy dependent. Thus, I feel an alternative explanation to the change in the relative abundance of secondary nuclei between 10^{10} and 10^{11} eV may be that the higher energy particles in this range come predominantly from a newer source, from which the lower energy particles have not yet arrived.

T. GOLD (*Space Sciences Building, Cornell University, Ithaca, New York* 14850 *U.S.A.*). Can you say anything about the strength of the galactic magnetic field from estimates of the rate of leakage?

P. MEYER. No, I do not believe that one can.

J. A. HOLMES (*Oxford University Department of Astrophysics, South Parks Road, Oxford*). The decrease in cosmic-ray path length with energy may be explained in terms of containment inside a 'leaky box' governed by the collective effects of the cosmic-ray plasma. When cosmic rays stream at speeds greater than the Alfvén velocity, Alfvén waves of length equal to the cosmic-ray gyration radius are formed in the magnetic field. These waves scatter the cosmic rays, reducing their streaming speed to the Alfvén velocity. But these waves are damped by the neutral atoms in the interstellar medium, and can only begin to form at heights above the galactic plane where the neutral atom density is low enough to reduce the damping rate to below the wave growth rate. The waves in this region form a reflecting boundary around the Galaxy, with a transmission coefficient equal to the Alfvén velocity divided by the velocity of light. Cosmic rays of higher energy have a smaller flux, so the growth rate of their resonant waves is smaller. Hence the neutral particle density has to be smaller in order for the waves to grow, and the boundary is located farther from the galactic plane. Here the Alfvén velocity is larger, so the cosmic rays can escape more easily. Furthermore the average density of interstellar matter inside the boundary is smaller when the boundary is higher above the galactic plane. Consequently the cosmic rays of higher energy encounter less matter before they escape from the Galaxy than those of lower energy.

J. L. OSBORNE (*Durham University*). If the age of cosmic ray electrons were as long as 10^8 years the break in the spectrum due to energy losses would occur at about 3 GeV. Can a break at around this energy be categorically ruled out?

P. MEYER. If a change in slope of the interstellar electron spectrum were to occur around 3 GeV, this would be very difficult to observe near the Earth since that part of the spectrum is influenced by solar modulation.

J. SKILLING (*Department of Applied Mathematics and Theoretical Physics, Cambridge*). I would like to comment on Professor Gold's remarks about low values of the magnetic field strength. I do not think one needs very low values of B to obtain significant sideways diffusion of cosmic rays across field lines. The point is that just a little bit of turbulence in the interstellar field introduces sufficient 'jitter' in the field to make neighbouring field lines diverge. After, say, 100 pc,† field lines initially extremely close together will have diverged widely. The cosmic rays following these field lines will of course have spread out too. Jokipii & Parker have worked on this sort of 'wet spaghetti' field. So one does not *require* very much gradient-B drift (i.e. finite Larmor radius effects) to spread the cosmic rays out across field lines.

F. G. SMITH, F.R.S. (*Nuffield Radio Astronomy Laboratories, University of Manchester, Jodrell Bank, Macclesfield, Cheshire*). Radio astronomy now provides a good description of the galactic magnetic field within about 1 kpc of the Sun. The field is alined along the arm, with irregularities on a scale of some tens of parsecs. The field strength is about 3×10^{-10} T. The irregularities add a random component of about half the mean field, giving a varying direction of the net field.

Beyond the local arm, the polarization of visible starlight shows that the field is well organized and alined along the spiral arms throughout most of the galactic plane.

† 1 pc ≈ 3×10^{16} m.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES