REVIEW OF COSMIC RAYS

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I. INTRODUCTION

Photon astronomy is divided into areas covering different energy regimes, beginning with radio astronomy at the lowest, and ending with gamma-ray astronomy at the highest observable energies. The cosmic radiation on the other hand encompasses in a single area nuclear particles and electrons of astrophysical origin over a very wide energy range, extending from superthermal energies that just exceed those of the solar or stellar winds ($\approx 10^6$ eV) to particles that carry the largest quanta of energy observed in any astrophysical radiation, up to 10^{21} eV. Dealing with that wide a range in energy, one should not be surprised that the origin of this radiation and its behavior is likely to involve a variety of different physical phenomena. Also, the spectrum of cosmic rays has two dimensions, one in energy, and one in the species of the particles.

Today we witness rapid and exciting developments in this field. But, in spite of the many advances after several decades of research, we still remain uncertain about the most fundamental issue, the question of the origin of the cosmic radiation.

Three properties of the cosmic radiation are measurable to any desired degree of accuracy--at least in principle. The composition, the energy spectrum for each species, and the directional distribution for any species at any energy. Can one expect that improvement in the measurement of these quantities will lead to a major step toward the identification of the sources of the cosmic radiation? I believe the answer is positive, based on the experience of the past two decades and the findings of recent experimental and theoretical work. The emerging detailed analysis of the unique sample of matter represented by the high energy cosmic rays begins to pinpoint the sites and mechanisms that lead to their origin.

I take it to be my task in this review to address those questions in a broad sense. I shall attempt to summarize the results that form the basis for the work that lies ahead, pointing to the role that

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particle astrophysics is expected to continue to play if one wishes to understand the phenomena that govern astrophysical objects. After all, the very fact that nature accelerates nuclei and electrons to the enormous energies that we observe is by itself most remarkable.

Before discussing the present status and the outlook for the future, I shall briefly look back to the past to remind ourselves of the most important milestones that, at their time, were pioneering advances.

II. THE PAST

Cosmic ray research became a subject of astrophysics when it was recognized that the radiation is of extraterrestrial origin. Beginning at that time, intense efforts were made to elucidate the composition and the energy distribution of the radiation in increasingly finer detail, and by the end of the 1970s enormous progress had been made.

Looking back over the last 30 years we may describe the milestones as follows: By the time it became fully evident that the cosmic rays were of extraterrestrial and extrasolar origin, one also learned that they were strongly influenced by solar system phenomena. Indeed, it was the propagation process in the solar system and its first description by a simple diffusion model which led to the recognition that similar processes must take place on much larger scales in interstellar space. The end of the 1940s brought the discovery of a complex nuclear composition; the '50s gained the understanding of the solar influence through the first quantitative description of the solar wind, its properties, and its role in cosmic ray propagation.

The rapid progress in cosmic ray research that began around 1960 was in part triggered by two important technological developments: (1) the availability of earth satellites and deep space probes, and (2) the great advances in solid state electronics that permitted the design of sophisticated instrumentation with low weight and low power requirements for use on spacecraft and on high altitude balloons. I believe it is fair to say that researchers in the field of cosmic rays were the first to fully exploit and to advance these modern facilities that today play such crucial roles in many areas of astrophysics. Experiments of the 1960s brought, in rapid sequence, the elucidation of increasingly finer details of the elemental composition of the cosmic rays, the discovery of the very rare elements beyond the iron group which we today call the ultra-heavy (UH) nuclei, and the discovery and determination of the energy spectrum of the electron and positron components. Most significant among the many results was the recognition that the nuclear species are produced in nucleosynthesis processes, that their abundance distribution has considerable similarities with the distribution of solar system material, but that the energetic particles also exhibit significant deviations from solar abundances. As a reminder of this situation, Figure 1 shows the present status of the relative elemental abundances for the elements between hydrogen and nickel as measured at energies

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between about 100 and 300 MeV/nucleon together with two compilations of the "solar system" abundances. It is clear that this is the distribution for a sample of matter produced in thermo-nuclear processes in the interiors of stars. But, particularly due to the high abundance of spallation products (i.e., Li, Be, B and 21<Z<26) and the possible charge dependence of the acceleration processes, the elemental distribution cannot discriminate in a unique manner among the different nucleosynthesis processes that have been proposed. Rather, such information is expected to come from measurements of the abundance distribution of the UH nuclei (Z > 28) and from observing the isotopic abundances of those nuclei that predominantly originate in the cosmic ray sources. Both these topics, active areas of present cosmic ray research, are discussed below.

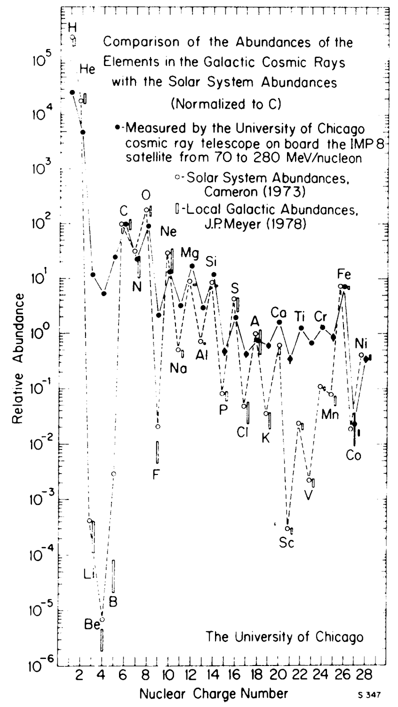

Fig 1: The elemental abundance of the cosmic rays compared with 2 compilations of the solar system abundances.

The accurate, and fully resolved measurement of the cosmic ray charge composition as it is shown in Figure 1 represents one of the milestones of past cosmic ray research. The deviations from solar system abundances are very interesting for several reasons. For example, the abundance of nuclei, originating predominantly in cosmic ray sources, appears to be influenced by the ionization potential of the particular atom, indicating preference for acceleration of nuclei with low first ionization potential. Even more importantly, the study of the spallation products has provided quite accurate knowledge of the average amount of interstellar matter traversed by the particles between source and observer. Comparison of the abundance of different secondary elements yields the distribution of the escape pathlengths with some accuracy.

Just a few years ago, when composition measurements were extended to energies of around 100 GeV/nucleon, it was found that the escape pathlength rapidly decreases with increasing energy. Figure 2 shows the measurement of the escape mean free path as a function of energy as it was obtained in one of the several composition measurements at high energy. The discovery of this rapidly decreasing escape mean free path with increasing energy has interesting repercussions with regard to the

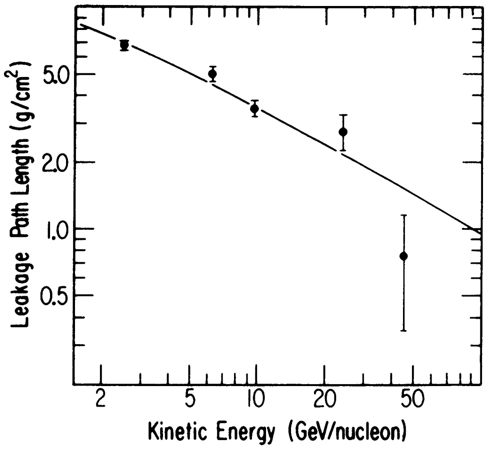

Fig. 2: The escape mean free path as a function of energy. The line is a powerlaw fit in total energy.

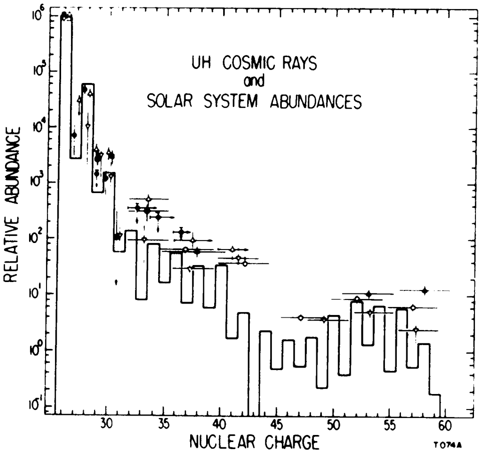

Fig. 3: Cosmic ray UH abundance between Fe and Nd compared with the element abundances in the solar system.

storage and containment time of particles in the galaxy, and hence the configuration of galactic magnetic fields which are the agent responsible for particle containment. Clearly, more accurate information and observations at still higher energy are needed to quantitatively apply this result to propagation models. This is therefore one area of intense research interest at the present time.

The discovery of cosmic ray nuclei beyond the iron group, and up to the actinides was first reported in 1965. The initial findings were based on the study of particle tracks in crystals of meteorite material. A few years later these nuclei could be identified in the contemporary flux of cosmic rays, and, through a series of experiments, their approximate abundance distribution was determined. Although these experiments were not able to resolve individual nuclear charges, they displayed an enhancement of elements around Platinum, a feature that is expected if the r-process of nucleosynthesis plays a dominant role in the production of these nuclei. These discoveries represented a major step forward in cosmic ray research and their details and consequences are not yet fully exploited. An example of abundance measurements up to $Z = 60$ compared with the solar system abundance is shown in Figure 3.

Another important, though negative result came from the search for antinuclei ($Z > 1$) in the cosmic radiation. Several experiments, using magnetic spectrometers, were able to put upper limits on the flux of antinuclei of 10^{-4} of the nuclei. The elements under study were He, C, and O. The discovery of even one antinucleus would have far reaching astrophysical consequences.

Among the fascinating questions of cosmic ray astrophysics that has been with us for many years is the origin and nature of the extremely high energy primary particles. Instruments able to directly measure energy spectra of individual nuclear species and of electrons now reach up to total energies of about 10^{12} eV. Cosmic ray observations beyond those energies have remained the realm of groundbased instrumentation, through studies of mu-mesons and, beyond 10^{14} eV, extensive airshowers. As a non-expert in this highly developed field, I can only sketch the past achievements for the three most important pieces of evidence (1) composition of the primary radiation, (2) its energy spectrum, and (3) anisotropies.

All evidence on the composition of very high energy primaries is indirect, mostly from observation and analysis of the structure of extensive airshowers (see the reviews by Watson, 1975 and Sreekantan, 1979). It appears that most observations are compatible with an approximate mixture of about 60% protons and 40% heavier nuclei in the primary particles, but the range of uncertainty is wide. A few observations have led to the claim that the abundance of heavier nuclei is enhanced with respect to protons at energies above 10^{13} eV. Very little is known of the composition above 10^{17} eV, and it remains to be seen whether this situation can be improved by new instruments in the years to come.

The accuracy for the shape of the energy spectrum has been steadily improved over the years, confirming a steepening of the spectrum around 2×10^{15} eV. While this steepening of the spectrum seems to be well established, its causes are not clearly understood. In more recent years, on the basis of somewhat limited statistics it was observed that the energy spectrum flattens again around 10^{19} eV. The status of the work on the energy spectrum is shown in Figure 4. If the very high energy cosmic rays are of universal extragalactic origin, this flattening of the

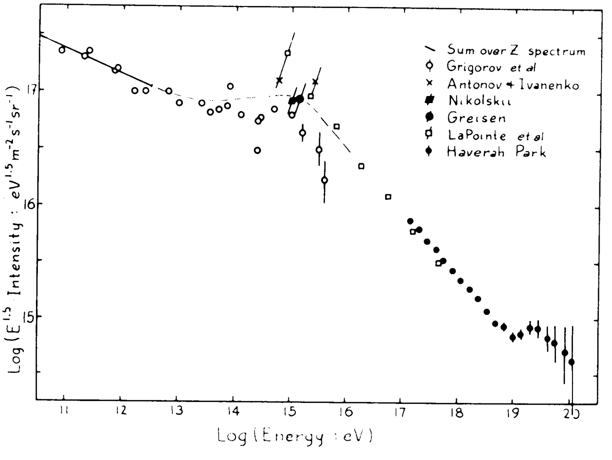

Fig. 4: The energy spectrum of cosmic rays at high energies.

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spectrum is contrary to expectation, since particles that exceed 10^{19} eV should be attenuated due to inelastic collisions with photons from the universal blackbody radiation. One must be concerned whether the flattening of the spectrum around 10^{19} eV represents a real change in the primary spectrum or is introduced in the translation from measured shower size and structure to primary energy. Very little is known about the nature of nuclear interactions at those high energies. This question is still under debate among the experts. An alternate, though speculative explanation would place the sources outside the galaxy, but into relatively nearby objects. Neither of the observed changes in the slope of the spectrums at high energy lends itself to a straightforward astrophysical interpretation.

Observations of anisotropies pose a problem of a different nature. Only at energies above about 10^{14} eV are directional measurements entirely free of solar system influences. Early expectations that a galactic origin would lead to a readily observable anisotropy as the particle energy rises and its cyclotron radius becomes comparable to galactic dimensions were not borne out. In the recent past, anisotropies have been observed at energies beyond 10^{19} eV where the flattening of the spectrum occurs. The preferred arrival direction appears to be from the north galactic pole, which happens to be the direction towards the local supercluster. While these observations have led to numerous speculations, they are difficult to interpret.

The question of the origin of cosmic rays of very high energy has therefore remained in a state of flux (for details see Sreekantan,1979; Watson, 1975; and Wolfendale, 1979). While evidence has been mounting, corroborated by observations in gamma-ray astronomy, that low and intermediate energy cosmic rays are a galactic phenomenon, it remains difficult to accomodate the origin of the highest energy particles within the framework of a galactic model unless the prevalent views on particle containment in the galaxy and its vicinity are drastically revised. Understanding the origin of the highest energy cosmic rays therefore remains an important challenge for the future.

III. THE PRESENT

In active scientific fields, the present is a shortlived span of time, its achievements being quickly superceded and relegated into the past. This very much applies to cosmic ray research. Today several new avenues are being opened and new techniques are applied that lead to insights that were inaccessible even in the recent past. These provide the first glimpses into new facets of fundamental importance in understanding the origin of the radiation.

I shall divide this snapshot of the present status into two parts, first dealing with the origin question, and then with the containment in the interstellar medium, although these are not unrelated questions. The most important tool that leads to an understanding of the sources of the cosmic radiation is the precise determination of the composition of the particles, and the extrapolation of this composition to the sources. The following factors lead to the elemental and isotopic abundance distributions that one observes near earth and that were displayed in Figure 1:

a) the abundance distribution in the sources prior to, or during acceleration,

b) the charge dependence of the acceleration mechanisms, and

c) modifications that occur as secondary particles are produced and primary particles are lost in the collisions of source nuclei with the interstellar gas.

Item (c) depends on the amount of matter that the particles traverse. It is a most important input to study the nature of the interstellar medium and the particle containment, but it is an unwelcome complication in obtaining the source abundances. An indication for the role of item (b), the charge dependence of the acceleration, is found in the systematic increase of the cosmic ray abundance over the solar system abundance with increasing charge number Z. This increase is not only observed in the galactic cosmic rays, but also for energetic solar particles and is probably an effect of preferential acceleration. These two effects make it difficult to pinpoint the detailed nature of the nucleosynthesis processes that led to the composition of the source particles in spite of the fact that there now exist well resolved elemental abundance measurements for all elements from H to Ni of a precision that is better than for any other sample of extraterrestrial matter. Such insight, however, may be gained from investigations of the isotopic distribution, and from the element distribution of the UH elements. The UH elements, although extremely rare (see Figure 3), are not as contaminated with spallation products as the elements with $Z < 26$, since their abundances decrease almost monotonically with increasing Z. There is no equivalent to the Fe-peak. This area of research is now at the threshold of important advances from work carried out with experiments on two spacecraft, HEAO-3 and Ariel-6. Both these experiments are expected to provide the first resolution of individual nuclear charges in the UH range. Such charge resolution is needed to make unambiguous statements on the relative role of the r-process or other types of nucleosynthesis in the production of these elements. The earlier experiments, through the observation of an enhanced abundance of elements around platinum, and the actinides have indicated a dominant role of the r-process in producing the cosmic ray UH elements. But the Pt-peak is not far from a peak in Pb that would be expected from the s-process. A definitive answer can therefore be given only when Pt and Pb are individually resolved. Several other elemental abundances would greatly contribute to answer this problem. For example, the abundance ratio of Xe/Ba, which is 1 in the solar system, is expected to be 10 if the elements are exclusively produced in the r-process, and 0.1 if they are s-process products. The latest advances in this area will be discussed in more specialized papers at

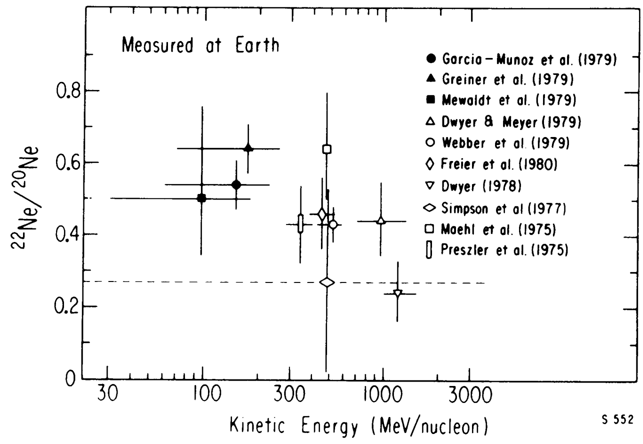

Fig. 5: Measurements of the $^{22}Ne/^{20}Ne$ ratio as a function of energy.

this conference.

Research to measure isotopic abundances of cosmic rays also progresses rapidly at this time. Several balloon experiments, and experiments on four spacecraft, IMP 7 and 8, ISEE-3, and HEAO-3 are directed toward measurements of isotopic abundances. The species for which we already have the first results on isotopic abundances include Ne, Mg, Si, and Fe, all of which predominantly originate in the cosmic ray sources. Additional results are available for the elements Be, B, and N, but I shall discuss these in connection with the questions of propagation (only the isotopes of hydrogen and helium had been studied in earlier years). These initial investigations of isotopic abundances have already

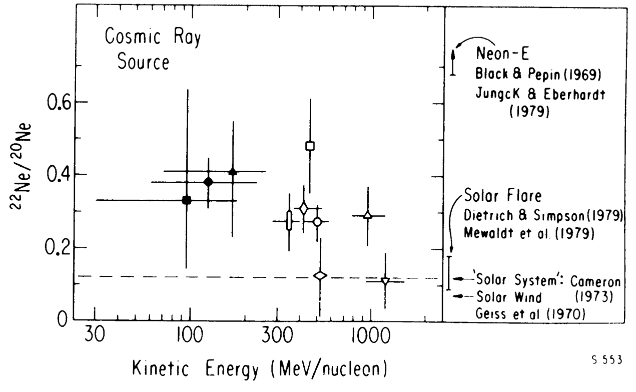

Fig. 6: The $^{22}Ne/^{20}Ne$ ratio extrapolated to the cosmic ray sources.

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displayed one significant difference between the isotopic composition of solar system material and of the cosmic ray source nuclei. The results for the element Ne point to an overabundance of ^{22}Ne. In Figure 5 is shown the observed $^{22}Ne/^{20}Ne$ ratio measured at different energies by different observers. To obtain this ratio at the cosmic ray sources, one needs the help of a propagation calculation that takes into account the best information on the interaction cross-sections for spallation occurring in interstellar space. Figure 6 shows the result after this type of extrapolation, indicating that the ratio $^{22}Ne/^{20}Ne$ at the source of the cosmic rays is enhanced over the solar system abundances by about a factor of three. The isotopic ratio is also distinctly different from that found in the solar wind, and in solar flare particles. It is not sufficiently large to have any similarity with the Ne-E observed in some meteorites.

A display of the results for the ratio $^{26}Mg/^{24}Mg$ as measured at or near earth is shown in Figure 7, together with the expectation if the sources exhibit a solar system ratio. One experiment claims an enhancement of the neutron-rich isotope, and a second experiment marginally indicates this possibility. Obviously, further measurements are required that unambiguously determine even small deviations from solar system abundances for this important isotopic abundance ratio.

Few measurements of the isotopic abundance distribution of Si are available, and all are compatible with the solar system ratio of $^{30}Si/^{28}Si$ at the cosmic ray sources. However none of the experiments is sufficiently precise to rule out small but significant anomalies. These results are shown in Figure 8.

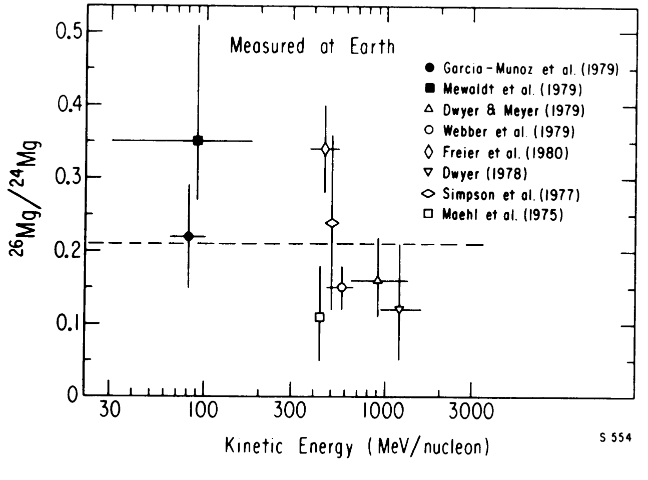

Fig. 7: Measurements of the $^{26}Mg/^{24}Mg$ ratio as a function of energy.

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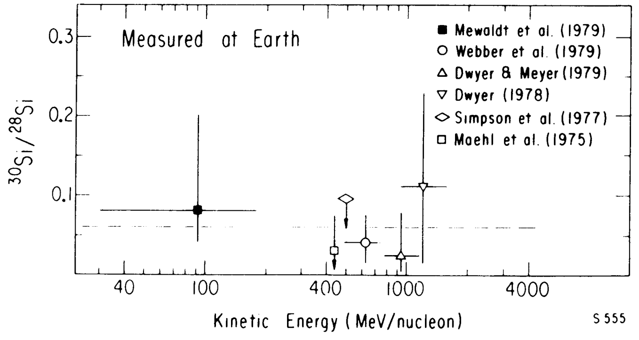

Fig. 8: Measurements of the $^{30}Si/^{28}Si$ ratio as a function of energy.

Major success has recently been achieved through the first convincing measurements of the isotopic abundance of the element Fe. Fe plays a special role in astrophysical nucleosynthesis processes as the end-product of exothermic nuclear burning. Its isotopic abundance distribution has been shown to critically depend on temperature, neutron concentration, and the density of the objects from which the cosmic rays have been ejected. The large enhancement of ^{56}Fe that exists in solar system matter, is now also established for the cosmic ray particles. Figure 9 is an example of a recent experimental result by the Cal Tech group. While containing only a small sample of particles it displays the advances in experimental technique by the excellent mass resolution that was achieved. It is important to note that several other recent experiments agree with the result that ^{56}Fe is by far the most abundant iron isotope in the cosmic rays. The quantitative question of the precise amount of admixture of ^{54}Fe and ^{58}Fe cannot yet be answered, except to say that neither isotope constitutes more than a few percent of ^{56}Fe.

It is quite clear from the results that are on hand that among the nucleosynthesis processes that have so far been theoretically investigated none can by itself explain the entire spectrum of cosmic ray abundances. Rather, as is the case for solar system material, a superposition of various processes is needed to describe the observations. For example, while the charge spectrum of the heaviest cosmic rays can be reasonably described by an r-process source, the nuclei with Z between 30 and 40 are found to be too abundant to fit any well understood model. The actinides, an important indicator for r-process material, show, however, a surprising underabundance in very preliminary results from the latest experiments.

Where has the present work on nuclear composition led us with respect to the problem of cosmic ray origin? Disregarding an extragalactic origin of the bulk of the cosmic radiation the two main potential sources that must be considered are (1) supernova explosions, (2) acceleration of particles from the interstellar medium. Clearly, these two sources may also simultaneously contribute in any mixture, since interstellar material, swept up in the shells of supernovae, might well be accelerated to

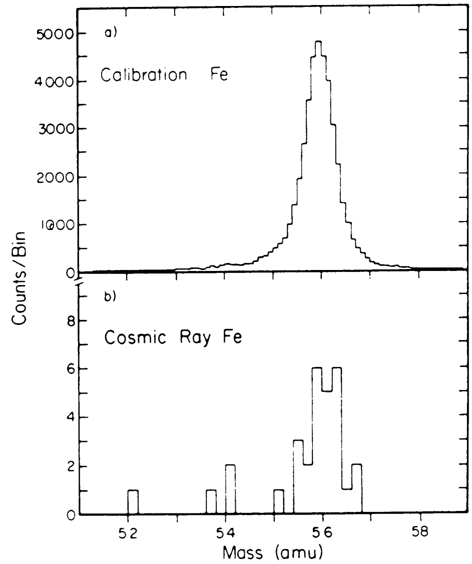

Fig. 9: The isotopic abundance distribution of Fe as measured by Cal Tech group.

cosmic ray energies. This is not the place to discuss these problems in detail. But we may summarize as follows. Measurements of the isotopic composition and of the UH composition point toward the fact that the sample of material that constitutes the primary cosmic rays has features in its composition that distinguish it from solar system material, but, perhaps more importantly also from interstellar material. The most convincing of these features are the over-abundance of ^{22}Ne, the apparent peak in the Pt region, and the high abundance of the actinides, if that is substantiated. Each of these features is difficult to explain if the cosmic rays were entirely of interstellar origin. It must be kept in mind, though, that they probe the interstellar medium of the past 10^6 to 10^7 years, rather than 10^9 years as is the case for solar system material. Hence, they must represent a sample of interstellar gas at a different stage of evolution. The work on isotopic and elemental abundances is discussed in the reviews by J.P. Meyer (1975), Waddington (1977), Müller (1977) and Balasubrahmanian (1979).

Cosmic ray propagation and containment are only indirectly linked to the question of origin. I shall review them here briefly, and begin with a discussion of the abundances of those nuclides that are spallation products, originating from collisions in interstellar space. The abundances of the stable secondary particles not only provide a measure of the average amount of material that the particles traverse during the time they are contained in the galaxy, but, through the requirement of consistency between different species, and measurements of the energy dependence of the abundances, they may yield the distribution of pathlengths (see Raisbeck 1979 for a recent discussion). The highly precise elemental abundances that new measurements provide, and the forthcoming work on isotopic abundances are greatly improving this knowledge. However, such efforts will be fully successful only if the knowledge of interaction cross-sections which enter any propagation calculation is improved to a similarly high precision. A particularly interesting sample of secondary nuclei is the radioactive nuclides with half-lives comparable to the cosmic ray containment time. These lend themselves as clocks for a direct measurement of the time of containment. Among the several isotopes that can in principle be used for this purpose, only the ^{10}Be ($\tau 1/2 = 1.6 \times 10^6$years) abundance has been measured with sufficient accuracy. Several reliable measurements for the ^{10}Be/Be abundance now exist, which agree that the containment time of cosmic rays has an unexpectedly high lower limit of about 10^7 years at energies below 1 GeV/n. Combined with the determination of the escape length, this leads to an average density of the matter in which the cosmic rays spend their life of only about 0.3 g/cm^3. The evidence for a long cosmic ray containment is corroborated by recent measurements of the cosmic ray electron energy spectrum. The observed steepening of this spectrum around 30 GeV to a power law with spectral index of 3 or greater, interpreted as being due to synchrotron losses and Compton collision losses, also leads to a containment time of about 10^7 years.

The combined evidence of an energy dependent escape pathlength and of a minimum containment time of 10^7 years places stringent conditions on the characteristics of the interstellar medium in which the cosmic rays spend their life. The requirement for a low average matter density has led to models that include a dynamic galactic halo, and special low density regions as possible places where the cosmic rays dwell for a large fraction of their life. The proposed alternatives, and the spectrum of models that deal with cosmic ray confinement have recently been reviewed by Cesarsky (1980).

Finally, a word must be said about two rather special secondary components: positrons and antiprotons. Both of these components originate in inelastic collisions of, mainly, protons with the interstellar gas, and, if the proton spectrum is known, their spectra can be calculated. The positron spectrum has been measured up to a few 10's of GeV, and is compatible with a secondary source. The determination of the positron spectrum has led to some qualitative tests of solar modulation models. The recent observation of a strong electron-positron annihilation line, emitted from the region of the galactic center has raised the question of the possible role of the primary positrons and their origin. The presence of antiprotons in the cosmic rays was established experimentally only very recently. Their flux and energy spectra are not yet well determined. Preliminary results indicate, however, that the antiproton flux is compatible with expectations for a purely secondary component.

IV. THE FUTURE

The discoveries of the past years that were sketched in the preceding paragraphs form the basis for the future search toward understanding the origin of the cosmic radiation. They also show that today we are at the threshold of very important advances. Directions in which this research is likely to proceed in the next decade are well defined and the technology of experimentation has reached a stage where several new paths can be implemented. In addition, there is always the potential for unexpected discoveries. Such discoveries have often proven to be the most exciting. The future areas of endeavor that are expected to have great impact on the understanding of the origin of cosmic rays can be readily named:

1. The full exploration of the isotopic composition of cosmic ray nuclei, both of primary and secondary origin.

2. Precision measurements of the elemental composition, (a) in the UH regime, including the actinides, and (b) at lower atomic numbers, extending to yet unexplored high energies where interactions with interstellar material appear to become rare and where one may hope to narrow or even close the gap with airshower experiments.

3. The introduction of novel methods in the investigation of the spectrum, composition and arrival directions for cosmic rays with energies above 10^{14}eV and up to the highest energies.

We saw that the first exploratory experiments on the isotopic composition already contribute to the questions of nucleosynthesis and to the determination of timescales that are relevant to cosmic rays. Results that one may expect in a few years from isotopic studies of the elements Mg, Si, S, Fe and Ni will sensitively reflect the conditions under which these elements were synthesized and in addition provide one of the few available tests for the well developed theories of nucleosynthesis. Whether it will eventually turn out that the energetic particles originate predominantly in the interstellar medium, or are ejecta from supernova explosions, they represent a unique sample of material, sent on its way to the observer some 10^7 years ago, a time very short compared to the age of solar system material.

The first contributions to cosmic ray chronology using long lived radioactive isotopes have just been made with the abundance measurement of ^{10}Be. Several isotopes exist whose half-lives are comparable to the time of cosmic ray containment in the galaxy and which therefore are of interest for astrophysical studies. Examples of such, as yet unobserved, or marginally observed isotopes are: ^{26}Al, ^{35}Ar, ^{36}Cl, ^{41}Ca, ^{44}Ti, ^{49}V, ^{51}Cr, ^{53}Mn, ^{55}Fe.

The work on cosmic ray isotopes should not remain restricted to the very low energy regime where solar modulation effects and strongly energy-dependent cross-sections complicate the extrapolation to the sources.

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Proposals exist to develop magnetic spectrometers that provide good mass resolution for isotopic abundances at energies well above 1 GeV/nucleon. The first pioneering experiments using these tools have already been carried out.

The topics of nucleosynthesis and cosmic ray chronology will greatly advance through detailed studies of the abundance of the UH elements. The next generation of experimental work is expected to yield this abundance distribution with individual element resolution and good statistical accuracy and thus contribute decisively to the nucleosynthesis problem, as was discussed above. Cosmic ray chronology gains a powerful new tool, once it becomes possible to measure, for example, the U/Th ratio or the abundances of the unstable nuclides ^{93}Np, ^{94}Pu and ^{96}Cm. Whether this generation of scientists will see a determination of UH isotopes is a question I would not dare to answer, but I would be surprised if inroads were not made into this promising and challenging regime, at least with the more abundant species of that group of elements.

Magnetic spectrometers are the tool that provides positron and antiproton spectra. The unique property of both these components comes from the fact that their production spectrum can be calculated from the known spectrum of their progenitors, high energy protons. Measurements of both components to high energies therefore yield independent information on particle propagation, and, in the case of positrons, on confinement. The discovery of a strong positron annihilation line from a region around the galactic center has again raised the question whether all positrons observed in the vicinity of earth are of secondary origin. This question may be answered with very precise measurements of the positron spectrum.

Moving up in energy, we expect the next decade of research to provide information of the elemental composition at energies exceeding 1 TeV/nucleon. This work will show whether the escape mean free path that was observed to decline between 10 and 100 GeV/n continues to decrease beyond 100 GeV/nucleon, thus leaving only source nuclei in the cosmic rays at those energies. Or, alternatively, shall one find a residual amount of matter that particles of all energies traverse? Clearly, such evidence permits quite detailed conclusions on the distribution of fields and matter around the cosmic ray sources as well as in the galaxy as a whole, since these are the agents that determine containment time and containment volume.

Nothing is known about the composition of the cosmic ray sources at and beyond 1 TeV/n. It is particularly interesting to ascertain whether this composition remains the same as observed at low energies, or, for example, becomes very abundant in Fe. Experiments that are now being developed will provide this information in the coming years, and may eventually extend sufficiently high in energy to provide an overlap with the lowest energies that can be observed in airshower experiments. Such overlap would provide a calibration that is needed if one wishes to put the conclusions on composition that are obtained indirectly from measurements of shower structure, on a solid base.

This brings me finally to a discussion of the future work on ultra high energy cosmic rays, a topic that will get a detailed treatment in a later paper. In this area, we can expect considerable advances when the new instrument of the Utah group, the Fly's Eye is in full operation. I recently learned that one year of operation of this instrument is expected to collect as much information as all the world's shower detectors together have gathered in the past. Not only can we hope to gain statistically significant information on the shape of the primary spectrum up to the highest energies, and on the distribution of arrival directions, but also on the primary composition. Through observation of atmospheric scintillations, the Fly's Eye investigates the shower structure in three dimensions, and hence extracts details of this structure that are needed to estimate the composition of the primary particles. Any information on the cosmic ray composition at energies much beyond 10^{14} eV will continue to come from indirect methods due to the paucity of particles.

V. CONCLUSION

Although a field with a long history, cosmic ray research today is in a phase where entirely new avenues are being opened. Experiments that were recently completed, that are underway, and that are in the planning stage let one expect that some of the crucial questions on the origin of this radiation will soon be answered. While much of the information will continue to come from particle observations, increasingly important contributions to the problem will be made through the work in gamma ray astronomy, X-ray astronomy and radio astronomy. Observations in these fields provide the means to gain insight into the phenomena that take place at the sites of potential sources.

This paper is the written version of a talk and is not a review of the field. Its contents are not balanced, are incomplete, and biased by the interests of the author. Important topics, like the anomalous low energy cosmic ray components, and the role of solar particle investigations in understanding acceleration mechanisms were omitted. No attempt was made to properly reference the large body of work on which this paper is based, except for refering the reader to a selection of review papers where references to the literature can be found. I wish to thank the many colleagues who provided me with preprints and the latest information on their work. I apologize to all of them for using, but not specifically quoting their work. My special thanks go to Dr. John Wefel for critically reading the manuscript and for many suggestions. Several of the figures were prepared by him. This work was supported in part by NASA under grant NGL-14-001-005.

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*ICR stands for International Conference on Cosmic Rays.

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