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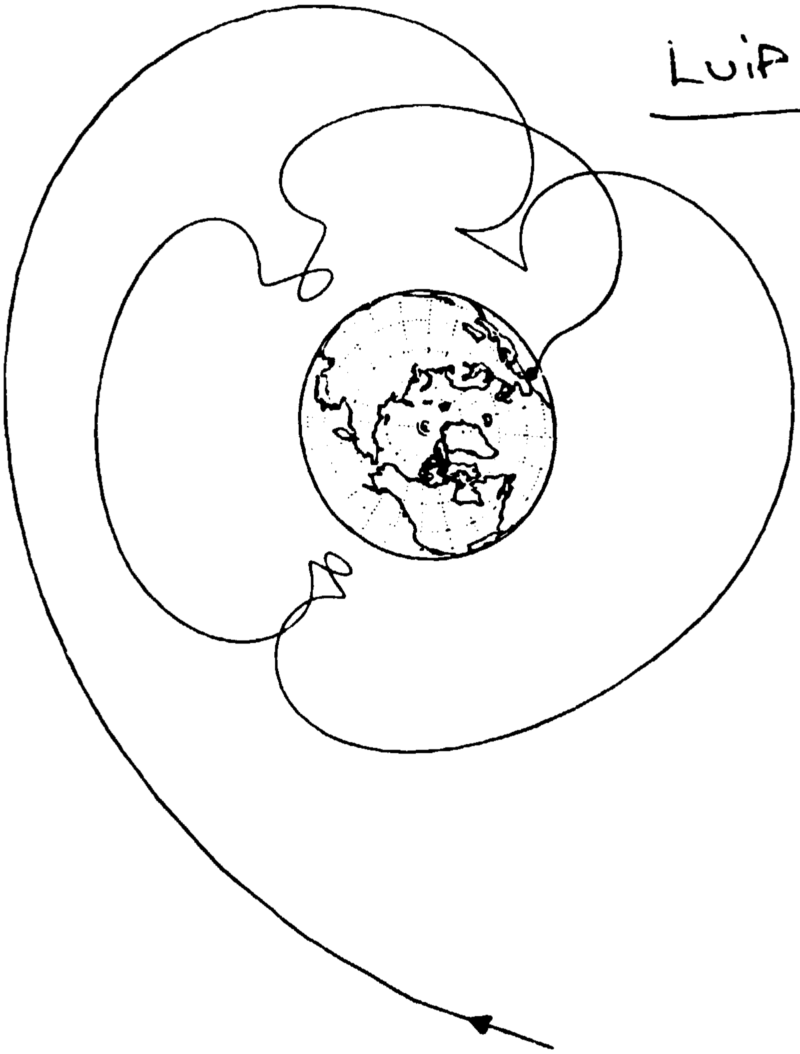

MEASUREMENTS OF THE ISOTOPIC COMPOSITION OF GALACTIC COSMIC RAYS

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Abstract

The galactic cosmic-ray boron and carbon isotopic composition has been measured. The boron measurement is the first ever made in nuclear emulsion. The carbon measurement has substantially improved the statistical accuracy in the determination of the ^{13}C abundance as compared to an earlier measurement using the same technique.
(~~Z Physik A291 (1979) 383~~)

Mass-spectra of cosmic-ray carbon and oxygen in different zenith angle intervals have been compared with calculated spectra. The method makes it possible to study experimentally the atmospheric influence on the primary cosmic-ray isotopic composition.
(~~Physica Scripta 22 (1981) 554~~)

Photometric measurements on fragments from oxygen-induced interactions in nuclear emulsion have been made. Accurate charge assignments have been made on all heavy fragments which has made it possible to study the interactions exclusively event-by-event.
~~(Lund University Internal Report LUIP 8204 (1984))~~

Measurements on the isotopic composition of primary cosmic-ray neon have been made. The data are from the Danish-French instrument on the HEAO-3 satellite. The rigidity dependent filtering of the cosmic rays by the Earth's magnetic field has been used. The energy dependence of the ^{22}Ne/^{20}Ne-ratio and its astrophysical implications are discussed.
~~(Lund University Internal Report LUIP 8501 (1985))~~

Key words Isotopic composition, galactic cosmic-ray boron, carbon and neon, cross-sections, magnetic rigidity, geomagnetic cut-off, HEAO-3 satellite

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FK, Mlm

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Preface

In this thesis four papers dealing with three different experiments are included.

I. The Cosmic Ray Boron and Carbon Isotopic Composition Measured in Nuclear Emulsions.
Z Physik A291 (1979) 383.

II. A Method to Study the Atmospheric Influence on the Isotopic Composition of Primary Cosmic Rays Applied to the Elements Carbon and Oxygen.
Physica Scripta 22 (1981) 551.

III. Photometric Measurements on Fragments from Heavy Ion Interactions in Nuclear Emulsion.
Lund University Internal Report LUIP 8204 (1984).

IV. The Isotopic Composition of Cosmic-Ray Ne at 2.4 and 6.3 GeV/n as Measured on HEAO-3.
Lund University Internal Report LUIP 8501 (1985).
To be submitted to Astronomy and Astrophysics.

References to these papers in the text are given by Roman numerals.
(HEAO ≡ High Energy Astronomy Observer)

The results have also been presented at the following international conferences:

1) The Conference of the Swedish National Committee for Physics, Gothenburg, Sweden, 1975.

2) The 14th International Cosmic Ray Conference, Munich, Federal Republic of Germany, 1975.

3) The 15th International Cosmic Ray Conference, Plovdiv, Bulgaria, 1977.

4) The sixth European Cosmic Ray Symposium, Kiel, Federal Republic of Germany, 1978.

5) The 16th International Cosmic Ray Conference, Kyoto, Japan, 1979.

6) The eighth European Cosmic Ray Symposium, Rome, Italy, 1982. (NYH representing the Copenhagen-Saclay collaboration).

7) The 18th International Cosmic Ray Conference, Bangalore, India, 1983.

1. Introduction

The Earth is constantly bombarded by radiation in a variety of forms. It is of Solar, Galactic and also Extragalactic origin and includes both electromagnetic and particle radiation. The electromagnetic radiation is now known to cover all types of wavelength from the radio waveband ($\lambda \approx 1$ m) to the hard γ-ray band ($\lambda \approx 10^{-15}$ m). The optical part ($\lambda \approx 5 \cdot 10^{-7}$ m) consequently constitutes only a small fraction of the electromagnetic spectrum but is of course the most apparent to us.

Photons from the different wavebands give information about the processes involved in galactic evolution and in the formation of the Universe. In this field our knowledge has been continuously increasing, especially since launching the detectors in outer space made it possible to avoid the absorption of the radiation in the Earth's atmosphere.

The particle radiation, or cosmic radiation, mainly consists of hydrogen (87 %), helium (12 %), heavier elements (1 %) and electrons. The flux of electrons is about 1 % of the proton flux. The composition of the heavy cosmic-ray component constitutes a basis of this thesis. Detailed knowledge of the elemental and isotopic abundances may give important clues about origin (galactic and/or extragalactic), sources (flare stars, novae, supernovae, interstellar medium), synthesis of the elements, acceleration and propagation.

The cosmic rays also serve as probes for the structure and properties of the interstellar regions of our Galaxy where they propagate. The interstellar medium is by no means empty but contain ≈ 10 % of the mass of the Galaxy in the form of gas and dust. The gas is mainly atomic hydrogen and ≈ 10 % helium, but regions with heavier nuclei and even complex molecules are also known to exist.

The cosmic-ray flux is constant in time, except at low energies. It is the same in all directions - the radiation is isotropic - except at the extreme high energy tail where the flux is very low. The energy density of the cosmic rays is ≈ 1 eV cm^{-3} which is comparable with the energy density of the starlight in the Galaxy.

To detect the primary particles it is necessary to place the instrument as high up in the atmosphere as possible, since radiations from outer space cannot penetrate the lower layers of the atmosphere. The analysis can be divided into two parts: one concerning the detector and one dealing with the correction of the measurements for the different effects involved during the transport from the source to the detector at the vicinity of the Earth. Below follows a list of possible stages for the cosmic radiation on its way to the Earth.

- nucleosynthesis in stars

- injection

- acceleration

- propagation

- influence from the Solar Wind

- influence from overlying atmosphere (balloon data)
- influence from the detector material
- detection

We are interested in the source composition of the cosmic rays. If the processes above are independent of each other then it is possible to determine the composition in a straightforward way. If this is not the case, things will get much more complicated. Let us assume for the moment that the different parameters indeed are independent. If we then follow the particles from the source towards the Earth step by step, the following will happen.

The particles are synthesized by some objects in the Galaxy. Some particles are selected and injected into the acceleration process in which they are accelerated to relativistic energies. These nuclei will now propagate through the interstellar medium and the composition is altered due to collisions with atomic nuclei in the medium. Some of the particles will escape from the Galaxy. When the cosmic rays are close to the Solar System, ≈ 100 AU (1 Astronomical Unit is the mean distance between then Earth and the Sun), they are influenced by the Solar Wind and decelerated. If the energy is low enough, they will also lose energy by ionization. A small fraction of the particles having survived this ≈ 10^7 year-journey will be detected by our instrument. Some particles interact within the detector and thereby the composition is altered once more.

The aim is to take the measured composition, elemental or isotopic and step by step correct the data for each of these processes, in the reverse order, to obtain the original composition at the cosmic-ray source [I,IV]. This requires knowledge about detector response, reaction- and production cross-sections [II,III] (including the energy dependence), the amount of matter traversed and the influence of the Sun on the radiation.

In the following Sections (3-8) each of these processes is described in the same order as experienced by the experimentalist. Only particles with charge Z in the interval $3 \leq Z < 30$ and with energies less than ≈ 1000 GeV/nucleon (hereafter GeV/n) are considered. It should be noted that the picture given below is by no means the only interpretation of the data, but to me it seems to be a plausible one. Much work still remains to be done and the next generation of detectors may well change the picture on some, but hopefully not all, points.

Section 9 contains some thoughts about future experiments in the field of cosmic radiation. In the last Section a summary of Papers I-IV is given, but let us first start in the past with a short historical review of the development from the beginning of the 20th century.

2. History of the Cosmic Radiation

Many important new discoveries were made in the science of physics from the beginning of the 1890s, such as the X-rays by Wilhelm Röntgen in 1895 and the natural radioactivity by Henri Becquerel in 1896. It was soon shown that the radiation emitted in radioactive decay consisted of three types of particle - the α-, β- and γ-radiations. Becquerel also showed that the β-rays were electrons and by 1909 Sir

Ernest Rutherford had shown that the α-particles were in fact helium nuclei.

About 1900 the ionization and electrical conduction of gases was studied extensively. It was found that gold-leaf electroscopes kept discharging even if they were kept in the dark. This "dark current" was measured by noting the rate at which the electroscope lost its charge. The ionization did not change even if the electroscope was kept well away from known sources of natural radioactivity or if it was put in a tunnel. Later, Rutherford showed that the major part of the ionization was after all due to natural radioactivity, either in the rocks or from the equipment. The idea that the effect could be ascribed to γ-rays, originating at the surface of the Earth, was abandoned after an experiment in 1910 by T Wulf. As he ascended the Eiffel Tower, the ionization fell only a factor of ≈ 2 compared to a factor of ≈ 16 as was expected if the effect was due to γ-rays from the Earth.

The real break-through came the following years when it was definitely established that the source was situated above the Earth. In 1911 and 1912 the Austrian physicist Victor F Hess made several manned balloon ascents [1]. The most successful flight was made on August, 7th, 1912 with a maximum height of 5350 m. He found the remarkable result that the average ionization increased above a height of ≈ 1.5 km as compared to the sea-level value. Hess drew the conclusion that the radiation originated somewhere above the atmosphere of the Earth. The observations were confirmed in 1913 and 1914 when the German physicist Walter Kolhörster made quite dangerous ascents up to 9300 m [2].

Because of their immense penetrating power in air the cosmic rays, a name which Robert Millikan had given them in 1925, were first taken to be γ-rays with much higher energies than ever studied before in the laboratories. In 1927, however, J Clay observed a small latitude dependence of the cosmic-ray intensity [3]. This would imply that the radiation was deflected by the Earth's magnetic field, indicating that the cosmic rays consisted of charged particles, rather than γ-rays as was assumed earlier.

The charged particle nature of the cosmic rays became evident in another experiment which, for the first time, used coincidences to reduce the background and other possible systematic errors. It was the invention of the Geiger-Müller detector in 1928 that made it possible to detect individual cosmic rays. By using two GM-detectors in a vertical coincidence experiment, W Bothe and Kolhörster in 1929 observed very frequently simultaneous discharges of the detectors, even when they were separated by 4.1 cm of gold [4]. The events were recorded on film and it was possible to measure coincidences to 0.01 s. Their experiment seemed to definitely rule out γ-rays as the source of the radiation. The particle energies were estimated to be 10^9 - 10^{10} eV.

In the beginning of the 1930s cloud chambers were used in combination with electromagnets and from the curvature of the tracks it was established that the bulk of the particles had energies around 10^9 eV. However, many particles were so energetic that the tracks were practically straight lines.

The work on revealing the true nature of the radiation went slowly. It was however, ascertained that the detected particles at various depths in the atmosphere were in fact not primaries but rather of secondary or even tertiary origin. The understanding of the formation of these showers increased gradually at the end of that decade. In this connection, a new branch of physics began to develop beginning with the discovery of the positron by Carl D Anderson in 1932 [5].

In connection with his investigation on the origin of the aurora borealis, the Norwegian mathematician and geophysisist Carl Størmer had shown that there existed "forbidden" regions around the Earth [6]. These inaccessible regions were out of reach for charged particles of a given energy, arriving from some direction. In 1932, G Lemaître and M S Vallarta applied these calculations to the cosmic radiation assuming it consisted of charged particles [7]. They were able to explain the experimental results from the same year by Arthur H Compton on the variation of the cosmic-ray intensity with the magnetic latitude [8]. He found that the intensity was reaching a minimum at the magnetic equator.

It was now obvious that the cosmic radiation must contain charged particles but their sign was still unknown. Lemaître and Vallarta concluded that for positive particles there must be a predominant amount of rays coming from the west, and conversely for negative particles.

In 1935, T H Johnson discovered that ≈ 10 % more cosmic rays were indeed coming from the west than from the east [9]. Later, in 1939, he first suggested that the primary radiation consisted of protons [10]. In 1941, the lead-penetrating ability of the high-altitude particles led M Schein et al. to the conclusion that the primary cosmic rays could not be electrons but must be protons [11].

In an experiment in 1948 with high altitude balloons reaching ≈ 30 km, P Freier et al. found heavily ionizing tracks in nuclear emulsion which could clearly not be due to protons [12]. It was the first evidence that the cosmic radiation also included a component of multiply charged heavy nuclei. In 1950, H L Bradt and B Peters published a charge histogram of this heavy component for the charges $3 \leq Z \leq 14$ [13]. They found that carbon and oxygen were the most abundant elements in this interval.

In 1961-62 it was also established in a series of experiments that the radiation also contain electrons and γ-rays. The flux of electrons is ≈ 1 % of the proton flux in the multi-GeV range.

For a long time the study of elementary particles was the basic part of cosmic-ray physics. Many new types of particle were discovered in the cosmic radiation including π^+, π^-, μ^+, μ^-, K^+, K^-, K^0 and of course e^+ as mentioned earlier.

From the beginning of the 1950s, the appearance of powerful accelerators has changed the picture. The elementary particle research in cosmic rays has decreased considerably and the study of geophysical and astrophysical aspects of cosmic rays began to dominate cosmic-ray physics.

3. Detectors

During the last 20 years measurements of the cosmic radiation have given us a more detailed knowledge about the composition of the elements present, from hydrogen up to the actinides. Recently, it has also been possible to measure the isotopic composition for the most abundant elements with charge $3 \leq Z \leq 28$. It is, however, much more difficult to perform accurate isotopic measurements of the heaviest elements since the relative mass difference between the isotopes decreases with increasing charge. The most accurate measurements can be made on particles which are stopped within the detectors, which means that the maximum energy is about ≈ 500 MeV/nucleon.

At higher energies where the particles do not come to rest within the detector, it is still possible to accurately measure the elemental composition. To distinguish between different isotopes for a given element is, however, very difficult. The successful experiments at these energies have so far utilized the magnetic field of the Earth as some kind of a giant mass spectrometer, thus being able to, at any rate, determine the mean masses of the most abundant elements.

The use of high altitude balloons, which were flown at 40-50 km above the Earth, was most frequent in the 1960s and the beginning of the 1970s. The exposure times were typically 10-20 hours. Although the residual amount of atmosphere at an altitude of 50 km is less than 2 g cm^{-2} (the total atmospheric depth is about 1020 g cm^{-2}) it is enough for nuclear interactions to take place. Therefore the data obtained at balloon altitudes must be corrected for this change in the composition. Since the end of the 1960s a large number of telescopes have been launched in satellites. This development has made it possible to study the primary cosmic radiation for long periods of time, unaffected by the atmosphere. The satellite orbits are typically 500 km above the surface of the Earth.

Although nuclei with charge $Z \geq 30$ comprise ≈ 2/3 of the elements in the periodic table, their abundance in cosmic rays is only about 10^{-4} of that of iron ($Z = 26$). The study of these elements thus requires large detectors and very long exposure times. The component was first detected in balloon experiments. However, due to the low flux, these investigations are more suitably performed in satellites. At present, only the elemental composition has been studied for energies around 1 GeV/n. Most of the even-charged elements up to $Z \approx 60$ are resolved but for the heaviest elements it is only possible to study charge groups.

The various detector systems used in the experiments can be devided into two groups. On one hand we have detectors of scintillator-, semiconductor- and Čerenkov type, the electronic or active detectors, and, on the other hand, the passive ones like nuclear emulsion and plastics. The active instruments are well suited for long time exposures in space and the data are transmitted back to Earth. The passive detectors must be recovered and then processed in the laboratory which restricts their use.

The active detectors have to be tested and calibrated before launch and in space it is also necessary to correct for long term drifts. This is done by checking the detector signals from the most abundant elements and then corrections can be made in the data analysis.

The secondary production of particles within these detectors may cause some problems. The proportion of incident particles which do interact depends on the amount of matter traversed in the detector and on the charge of the particle, and can be as much as 30-50 %. This means that there must be some system which registers the particle paths through the instrument. In the analysis only "straight-line-events" are accepted and consistency between different detectors within the instrument is required.

For the passive detectors particle production is not a severe problem, since it is possible to visually follow the particle paths in the detector and thereby exclude the interacting primaries. The measurements are in general also very time-consuming. This results in experiments with rather poor statistics as compared to the active systems launched in outer space.

4. Elemental abundances and energy spectra at 1 AU

Fig. 1 shows the abundances of the cosmic-ray elements as measured at Earth [14,15], together with the corresponding abundances of the Solar System [16]. The cosmic-ray data are given at two different energies, 70-280 MeV/n and 1000-2000 MeV/n, respectively. All numbers are normalized to the Si-abundance and the experimental values are given at 1 AU. The balloon data have been corrected for the influence of the overlying atmosphere.

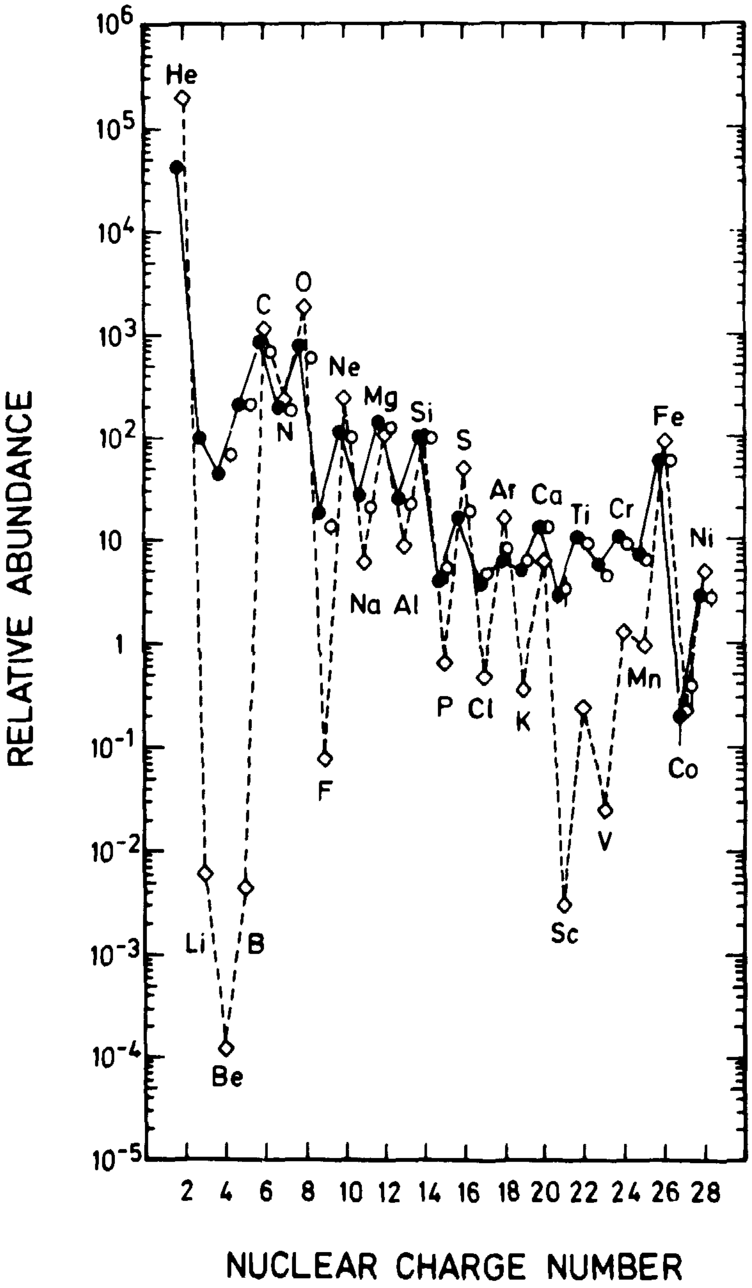

Fig. 1. A comparison between the cosmic-ray elemental abundances measured at 1 AU and the Solar System abundances for He-Ni. Data are normalized to the silicon abundance (Si ≡ 100). (From [15]). Filled circles: cosmic-ray data, 70-280 MeV/n [14]; open circles: cosmic-ray data, 1000-2000 MeV/n [15]; diamonds: Solar System data [16].

The most striking difference between the cosmic-ray and the Solar System abundances are the elements Li, Be, B ($3 \leq Z \leq 5$) and Sc, Ti, V, Cr, Mn ($21 \leq Z \leq 25$). These elements are mainly produced during the propagation from the source to the Earth. The lighter ones, Li-B, are totally absent in the source simply because these nuclei would have been destroyed during the nucleosynthesis in the stars. Most of them are secondaries from C, N and O. For the Sc-Mn group the source abundances are still uncertain and if any of them is present in the source the abundances are very small indeed. The elements in this group are mainly secondaries from Fe.

In both data sets there is a clear odd-even structure: the elements with even charge are much more abundant than the adjacent odd-charged elements. For the Solar System the difference is generally a factor 10-100. The cosmic-ray data are more smooth due to the particle production during propagation and the factors are typically of the order of 5-10.

It is also of great interest to know the distribution of the cosmic rays at the different energies the particles have been detected, from $\approx 10^7$ eV up to $\approx 10^{20}$ eV. This energy spectrum can tell us something

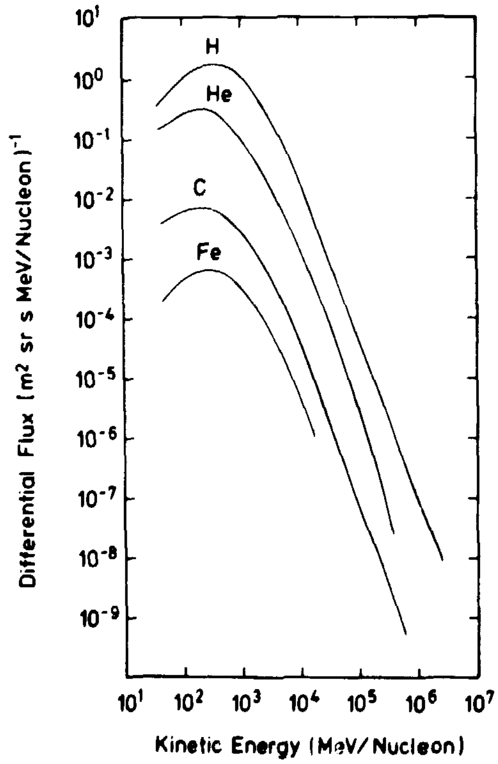

Fig. 2. Differential energy spectra for cosmic-ray H, He, C and Fe. (Adapted from [17]).

about the possible processes responsible for the acceleration of the particles. Fig. 2 shows the ***differential energy spectrum*** (number of particles per ($m^2 \cdot s \cdot sr \cdot MeV/n$)) at Earth for H, He, C and Fe for energies between 10 and 10^7 MeV/n [17]. At energies above $\approx$ 10 GeV/n these spectra may be represented by a power-law $J(E) \approx E^{\gamma}$ with $\gamma \approx -2.7$, where J(E) is the differential flux.

5. Solar Modulation

The fact that the Sun is continuously emitting particles (mostly protons) was predicted in the end of the 1950s. It was experimentally verified the following years when it became possible to launch detectors in the first Soviet and American satellites. The flux of the Solar Wind is $\approx 10^{12}\ m^{-2}s^{-1}$, the density $\approx 5\ cm^{-3}$ and the temperature $\approx 10^6$ K. The particles move with a velocity of $\approx$ 300-500 km s^{-1}. These figures are, however, varying considerably during the 11-year Solar Cycle.

The fact that the arriving cosmic rays are indeed influenced by the magnetic field associated with this outflow of particles, is evident from a comparison between the solar activity (the number of sun spots) and the cosmic-ray flux. This is shown in Fig. 3. The flux of cosmic

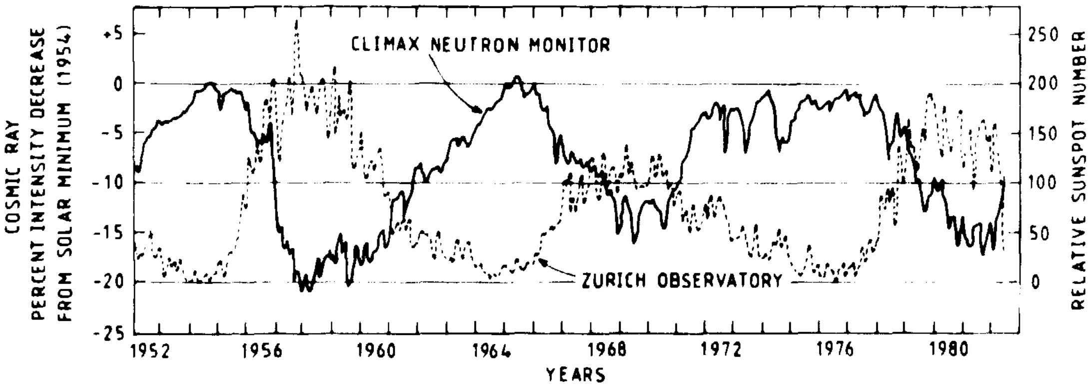

Fig. 3. Correlation between the cosmic-ray flux and the solar activity. (From [17]).

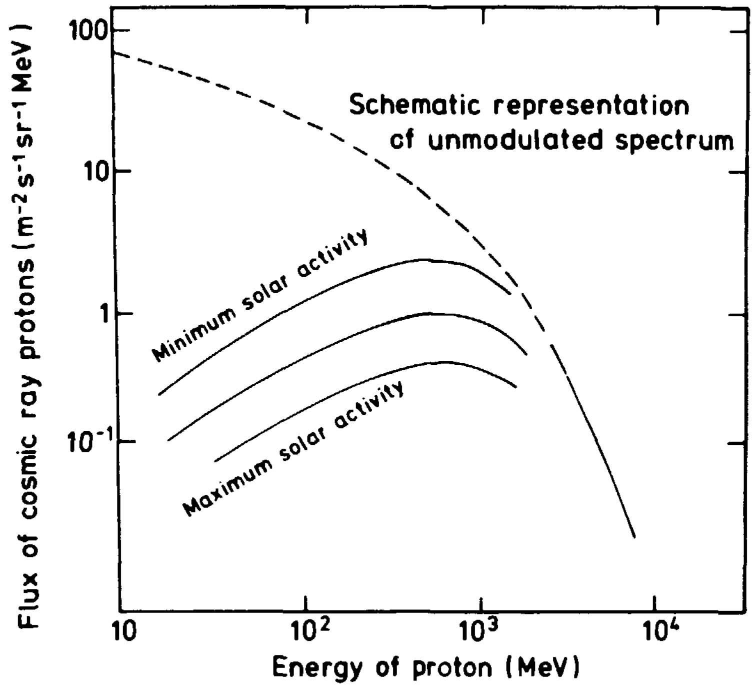

Fig. 4. The cosmic-ray flux for protons at different levels of solar modulation.

rays has a minimum coinciding with maximum solar activity. This effect is called *solar modulation* and has to be considered in the interpretation of the data. Fig. 4 shows a sketch of the proton energy spectrum at different levels of solar activity. It is obvious how the number of low energetic particles decreases as the number of sun spots is increasing.

Unfortunately, the solar modulation is significant for particle energies up to ≈ 10 GeV/n, where we have the bulk of the arriving cosmic-ray particles. Since the level of the modulation is dependent on the mass-to-charge ratio A/Z of the particles, different isotopes of the same element will be modulated differently. This is of importance when the isotopic composition is studied, especially for low-energy particles. At energies below ≈ 500 MeV/n the particles may lose more than 30 % of their kinetic energy.

Although we do not understand the solar modulation in detail it is possible to determine its magnitude by means of the electron energy spectrum measured at Earth. It is then possible to use models for the modulation and determine the local interstellar spectra for the different elements and isotopes in the cosmic radiation. Modulation effects are known from recent experiments to be important at ≈ 25 AU from the Sun and are believed to extend to ≈ 50-100 AU [18]. This region where the solar modulation significantly affects the incoming particles is called the ***heliosphere***.

6. Propagation

When the energy spectra have been corrected for the solar modulation effects, it remains to consider the changes the radiation has undergone during the transport from the source to the heliosphere. These propagation effects include *spallation* by collisions with interstellar matter, *energy loss* by ionization (important at the lowest energies), *radioactive decay* and *escape* from the Galaxy.

Not all nuclei which are detected at Earth originate from the source. Some have been produced during the transport when part of the heavier nuclei interact with the hydrogen (and to some extent helium) in the interstellar medium. This will lead to two effects:

Destruction: Nuclei from all elements will collide and the probability for collision (given by the reaction cross-section) increases with increasing charge.
Production: Isotopes of all kinds are produced and the probability for production of a specific isotope is given by the production cross-section.

Which of the effects is the predominant one depends on the relative abundances, the reaction- and production cross-sections of the elements and the energy of the nuclei since the cross-sections are energy dependent. For the more abundant elements the production by spallation of other elements is less than the depletion due to the interaction with interstellar matter. The production of iron by spallation is negligible since the abundance of elements heavier than Fe is very small. It is different for Li-B and Sc-Mn as mentioned in Section 4: they are mainly produced during the transport and are more or less absent in the cosmic-ray source.

It is possible to determine the changes in the cosmic-ray composition due to the propagation effects. It requires knowledge of the cross-sections involved and the amount of matter traversed by the radiation. The propagation calculation will of course introduce new errors on the abundances which come from the uncertainties in the cross-sections. Normally, the abundances at Earth are accurately known with errors of only some percent, while the errors in the cross-sections are an order of magnitude larger.

The number of cross-sections needed in the calculation is very large. In fact, it exceeds the number of experimentally determined cross-sections by several orders of magnitude. It is not realistic to believe that all these cross-sections will ever be determined experimentally, but hopefully the most important will. Some cross-sections are vital for the propagation calculation but are still missing making some of the results rather uncertain. In some cases measurements exist but results from different laboratories are contradictory. While awaiting new and more accurately determined experimental cross-sections at different energies, we have to use calculated cross-sections instead.

Semi-empiric cross-section formulae were developed over a decade ago and have been used extensively where needed [19]. The deviation from the experimental values is generally less than 20 % but may be as much as 50 %. The standard deviation is 30 %. This large uncertainty is of course most severe for those elements and isotopes which are rare in the source and where the production by spallation is considerable.

The interpretation of the low energy data, where the most accurate measurements have been made, is unfortunately hampered by this uncertainty in the cross-sections. Because of the additional uncertainty in the particle energy introduced by the solar modulation, the uncertainty in the propagation calculation can be quite large.

In order to determine how much matter the cosmic rays have traversed on their way to the Earth we can make use of the fact that some of the elements have very low abundance in the source and are predominantly produced during the propagation. Assuming that all elements traverse the same amount of matter (a uniform "slab"), it is not possible however, to account for both the Li-B and the Sc-Mn abundances as measured at Earth. It turns out that the latter group has passed less amount of matter. Introducing an exponential distribution of pathlengths gives good agreement with the experimental data over the entire charge interval $3 \leq Z \leq 28$. The distribution has the form

$$p(x) = \frac{1}{\lambda_e} \exp(-x/\lambda_e)$$

where λ_e is the mean value of the distribution (see also Section 8).

For the primary elements with charge $6 \leq Z \leq 28$ the propagation calculation of the HEAO-data gives source spectra with index $\gamma = -2.41 \pm 0.05$ [20], cf page 13. This indicates that the major part of these elements have similar origin. Hydrogen and helium do not, however, follow this pattern but seem to have flatter source spectra [21].

Some particles synthesized in the source or produced during propagation are radioactive. These nuclei, the "cosmic-ray clocks", can give important information about various time-scales involved. The most interesting of the radionuclides are ^{10}Be ($\tau_{1/2}$ = 1.5 Myr), ^{26}Al ($\tau_{1/2}$ = 0.74 Myr), ^{36}Cl ($\tau_{1/2}$ = 0.3 Myr) and ^{54}Mn ($\tau_{1/2}$ = 2 Myr) whose presence in the radiation may give information not only about the propagation time, but also the mean density of the interstellar medium.

7. Sources, injection and acceleration

One of the most important aims of cosmic-ray research is to determine the Galactic Cosmic Ray Source composition (GCRS), both elemental and isotopic. The propagation calculation gives us the condition before propagation, that is, at $x = 0$ g cm^{-2} but after nucleosynthesis, injection and acceleration. It is now essential to know if this composition is also representative for the source. There could be atomic or mass biasing effects, presumably during the injection, which modify the elemental or isotopic source abundances. These effects must also be considered in the determination of the GCRS.

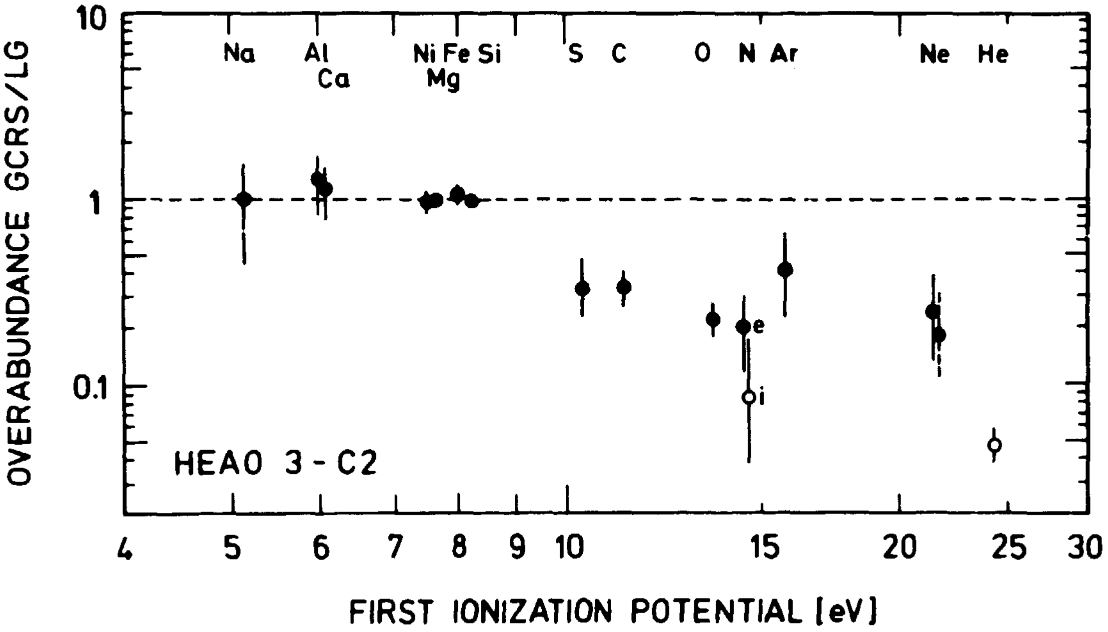

Fig. 5. The ratio between Galactic Cosmic Ray Source and the Local Galactic abundances as a function of the First Ionization Potential. Two different values are given for nitrogen; "e": source abundance based on elemental data and "i": from isotopic data. (From [22]).

The galactic cosmic rays are the only sample of matter from objects outside the Solar System. It is therefore close at hand to compare the GCRS composition with the composition of the matter in the vicinity of the Sun. This is also justified by the fact that the Sun is indeed emitting particles, some of which do in fact have cosmic-ray energies. These particles can be studied in the Solar Wind, Solar Flares and in the corona of the Sun.

The derived GCRS composition is compared with "Local Galactic" (LG) or Solar System matter in Fig. 5, as a fuction of the First Ionization Potential, FIP (which is the energy needed to remove 1 electron from a neutral atom). The LG-data are taken from meteorites and the Solar Photosphere [16,23]. It is evident that for the elements with FIP ≥ 9 eV there is a suppression by a factor of 3-4. The same picture is also obtained if Solar (Flare) Energetic Particles (SEP) are compared with

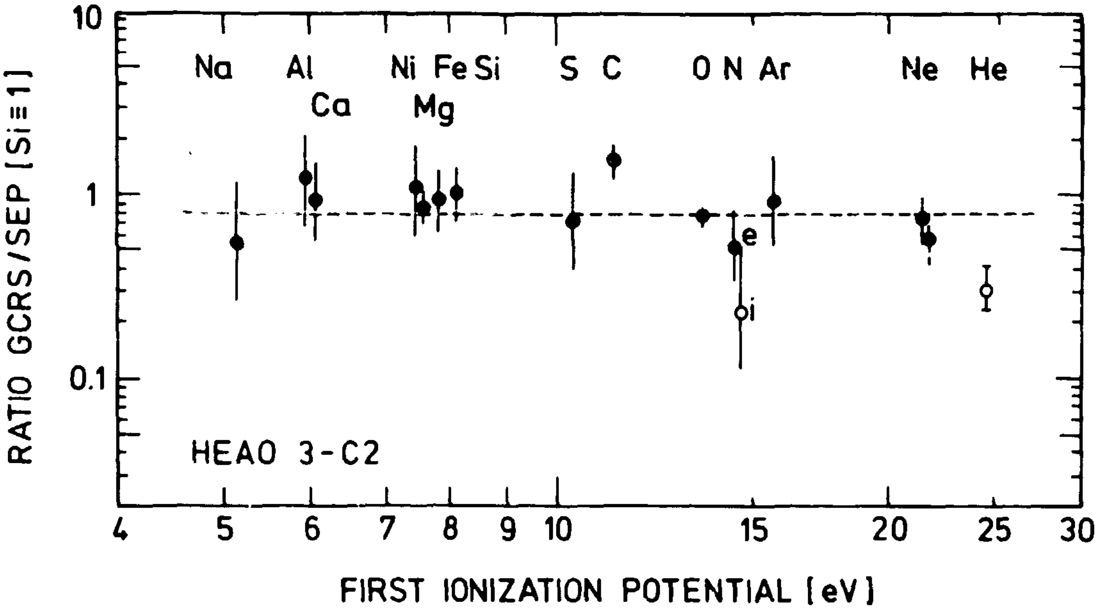

Fig. 6. The ratio between Galactic Cosmic Ray Source and Solar (Flare) Energetic Particles as a function of the First Ionization Potential. For N, see caption of Fig. 1. (From [22]).

the Solar System data. The composition of the injected matter is thus dependent on whether the particles of a given element are ionized or neutral at the injection site temperature.

There is a striking similarity between the GCRS and the SEP abundances as shown in Fig. 6. It is obvious that the same biasing effects are present in the selection of both galactic cosmic rays and the particles in Solar Flares. It can then be concluded that there is conclusive evidence that the elemental GCRS composition is similar to that of the Solar System, and that the selection mechanism cannot differ considerably from that operating in Solar Flares. Particles with FIP $\leq$ 9 eV are preferably selected and accelerated to subrelativistic energies.

It must be possible for the mechanism responsible for the acceleration of the cosmic-ray particles to relativistic energies, to give the observed single power-law spectra for all elements. This indicates that there exists a dominant mechanism giving the correct energies in a time which is short compared with the time spent by the cosmic rays in the interstellar medium. This has been verified experimentally since energy spectra for the secondaries are steeper than the spectra for the primary particles [21]. A continuous acceleration mechanism should produce a secondary spectrum flatter than that for the primaries.

The acceleration in itself is not believed to be selective. It should be noted that the injection and the acceleration are close in time because otherwise the energy loss by ionization (proportional to Z^2) of the low energy particles would change the composition.

The most probable mechanism accelerating the particles is by shock-waves from expanding supernova remnants. It is an efficient mechanism and the supernova rate of 0.03-0.1 supernovae per year in the Galaxy is sufficient to provide the necessary power. The shock-wave acceleration can also reproduce power-law energy spectra [24,25].

It has also been proposed that the supernova remnants should be responsible for the injection of the nuclei. Many complicated models have been developed for the nucleosynthesis and the evolution in these stars up to the point where the nucleus of the star collapses and the star explodes. These models do, however, have difficulties in giving the appropriate GCRS composition; some elements are correct within a factor of two while others clearly disagree. The models are not able to reproduce Fe and the elements in the CNO-group simultaneously.

It is thus likely that the selection of particles is related to atomic properties, such as FIP, but less probable that different isotopes of a given element will be influenced differently. A small difference in the mass-to-charge ratio for different isotopes cannot considerably affect the isotopic composition for the heavy component of the cosmic rays. This means that the elemental composition is to be interpreted with the atomic properties as a basis, while any isotopic anomalies will give us ideas about the nucleosynthetic processes that are involved and therefore the clues to the nuclear origin of the cosmic-ray nuclei.

If we compare the isotopic composition of the GCRS with that of the Solar System, there is no doubt that Ne, Mg and Si are "anomalous". The ratio ^{22}Ne/^{20}Ne is approximately a factor of 4 larger in the GCRS and the corresponding factor for the ratios ^{25}Mg/^{24}Mg, ^{26}Mg/^{24}Mg, ^{29}Si/^{28}Si and ^{30}Si/^{28}Si respectively, is ≈ 1.7 [26,27].

It is not possible to explain the similar enhancement factors for the neutron-rich Mg- and Si-isotopes by specific nucleosynthetic processes. One could imagine that this anomaly is due to evolutionary effects in the isotopic composition of the interstellar medium. This composition has gradually changed since the time of the birth of the Sun, some $4.6 \cdot 10^9$ years ago, while the GCRS reflects the situation in the source ≈ 10^7 years ago, a time which is obtained from measurements of the abundance of the "clocks" ^{10}Be and ^{26}Al.

The galactic evolution cannot alone explain the much higher proportion of the neutron-rich neon isotopes in the GCRS. An interesting theory which might explain this anomaly is that ^{22}Ne should origin from another source [28]. Such possible objects present in the Galaxy are carbon-rich Wolf-Rayet stars which have masses of the order of 10-50 solar masses. W-R stars seem to be a normal stage in the evolution of heavy ($M \geq 20M_\odot$) O-stars (very hot and luminous stars): O-star → red supergiant → nitrogen-rich WR-star (WN) → carbon-rich WR-star (WC) → supernova explosion. For the WC-stage it has been estimated that in such stars both ^{12}C and ^{22}Ne would be considerably enhanced. If ≈ 2 % of the cosmic rays come from WC-stars it is enough to explain the observed enhancement of ^{22}Ne in GCRS as compared to the Solar System. In addition this would also explain the fact that carbon is overabundant by a factor of 2 in the source, see Fig. 6.

8. Propagation Models

A number of models have been developed to explain the experimental data on energy spectra, composition and anisotropy. Up to now neither of these has succeeded in explaining all data, but since these are still uncertain and in some cases contradictory it has not been possible to definitely reject them either. Generally it is assumed that the Galaxy contains cosmic-ray sources in some number and with some distribution in space and that the nuclei which are emitted have a power-law energy spectrum. Below follows a short description of the model which is used most frequently, the leaky-box model [29]. A review of propagation models is given in [30].

Leaky-Box Model

The cosmic rays are trapped within reflecting boundaries which surround the Galaxy and have a finite probability of escape into extragalactic space. The cosmic-ray density is assumed to be uniform throughout the confinement volume.

The mean free path for escape, λ_e, has proven to be dependent on the particle energy. The evidence for this is that the ratio between the secondaries and the primaries decreases as the particle energy increases. The most energetic particles have in the mean traversed a smaller amount of matter. Data from the HEAO 3-satellite have given the following energy dependence for the mean escape length:

$$\lambda_e = \begin{cases} (22 \pm 2)\ R^{-0.60 \pm 0.04} & \text{g cm}^{-2}, \quad R > 5.5 \text{ GV} \\ 7.9 \pm 0.7 & \text{g cm}^{-2}, \quad R \leq 5.5 \text{ GV} \end{cases}$$

where R is the magnetic rigidity of the particle.

Low energy ($\approx$ 50-300 MeV/n) data on the radio-nuclides ^{10}Be and ^{26}Al give a confinement time of $\approx 8 \cdot 10^6$ years and a density of $\langle n_H \rangle \approx 0.3$ cm^{-3} [31,32]. The mean density in the neighbourhood of the Sun is on the average 1-2 cm^{-3}. The interpretation of this difference may be that the cosmic-ray particles are confined in a low density volume, a halo, at least 3 times wider than the galactic disk which has a thickness of about 200 to 400 pc (1 parsec = $3.1 \cdot 10^{16}$ m = 3.3 light years).

9. Future Work

It is evident that although much progress has been made in the field of cosmic radiation during the last 35 years, there still remains work to be done. The main issues have been known since the discovery of the heavy component in 1948, but with the extension of the measurements to higher energies and the continuous development of the detection technique, it has become clear that more data are still needed to reveal the true nature of the radiation.

Even though the elemental composition is well known in the multi-GeV range it is of interest to extend the measurements into the TeV-range. In that way it could be ascertained whether the source energy spectra are the same for all elements, implying a common origin for the elements. If some element partly comes from an additional source with a different energy spectrum, this could be revealed in such an investigation.

The elemental composition of the cosmic radiation is very similar to that of the Solar System with only a few exceptions. This is not true for the isotopic composition of the cosmic rays where several "anomalous" abundances have been found as compared to the Solar System. In fact, all isotopic abundances of the GCRS measured with an accuracy better than 30 % differ from the Solar System value [33]. To be able to put restrictions on the possible models for the nucleosynthesis it is important to have detailed knowledge about the isotopic composition also for the heaviest elements, at least up to $Z = 30$. There is a need for more accurate isotopic measurements, especially on rare isotopes to establish if they are present in the source. This also includes the radio-nuclides which may give important information about time-scales and the density of the confinement volume. The measurements of these "cosmic-ray clocks" should preferably be performed at high energies where a larger fraction of them survives.

It is, however, very difficult to make isotopic measurements in the multi-GeV region. If it would be possible to launch super-conducting magnets in space, for instance in the planned Space Platform, one would be able to make accurate measurements between 0.1 and 100 GeV/n with today's technique [33]. To get a sufficient flux even for the rarest isotopes, this would require exposure times of 1-2 years.

The new and extended measurements on the composition must also be followed up with new and accurate cross-section measurements, more reliable semi-empiric formulae and a better understanding of the solar modulation. It would then, ideally, be the uncertainties in the composition measurements that is predominant and not the additional uncertainties introduced in the corrections for solar modulation and propagation. This would indeed make it more easy to interpret the high-quality cosmic-ray data.

10. Summary of the Publications

Paper I

The Cosmic Ray Boron and Carbon Isotopic Composition Measured in Nuclear Emulsions

C Bjarle, N-Y Herrström, G Jönsson and K Kristiansson
Z Physik A291 (1979) 383.

In this paper a measurement of the isotopic composition of the cosmic-ray boron and carbon is described. The measurement of the boron isotopes is the first ever made in nuclear emulsion. Since boron is completely produced during propagation the composition mainly reflects the differences in cross-sections for the boron isotopes.

The carbon measurement made it possible to substantially improve the statistical accuracy in the determination of the abundance of ^{13}C as compared to an earlier measurement using the same technique.

The method of measurement and the correction procedure are shortly described. The mass determinations are based on measurements of the relation between track width and residual range and have been made with a nuclear track photometer.

One improvement as compared to earlier measurements for carbon is that all tracks have been measured by two different persons. This has made it possible to study the errors in the mass determination which originate from the measuring procedure. The results are consistent with several other experiments including recent satellite data with excellent mass resolution.

Paper II

A Method to Study the Atmospheric Influence on the Isotopic Composition of Primary Cosmic Rays Applied to the Elements Carbon and Oxygen

C Bjarle, N-Y Herrström and G Jönsson
Physica Scripta 22 (1981) 551.

In this paper an experimental method of studying the atmospheric influence on the isotopic composition of primary cosmic radiation is described. Mass-spectra of cosmic-ray carbon and oxygen in different zenith angle intervals are compared with spectra based on extrapolation calculations using estimated nucleus-nucleus cross-sections.

In this way it is possible to get a rough estimate of the goodness of the semi-empiric cross-sections involved. The calculations predict almost the same spectra as are observed experimentally.

Paper III

Photometric Measurements on Fragments from Heavy Ion Interactions in Nuclear Emulsions

N-Y Herrström and R Kullberg
Lund University Internal Report LUIP 8204 (1984).

In this paper a charge measurement of multiply charged fragments from oxygen-induced interactions in nuclear emulsion is presented. The method of measurement is essentially the same as in [I]. However, since the emulsions have been irradiated by an accelerator beam, there is a large number of calibration tracks. The accelerator exposure gives numerous parallel tracks which introduce disturbances in the measurements.

The investigation includes measurements and identification of particles stopping in the emulsions as well as of particles leaving the stack. To determine the charges of the non-stopping fragments it was necessary to select stopping non-interacting particles with high energies of all charges, including p, d and t, for calibration measurements. These tracks were measured at a number of different residual ranges. It was thereby easy to distinguish between slow target H and non-stopping projectile He. For multiply charged fragments, photometric measurements are more reliable and faster than other methods.

The purpose of this investigation was to make definite charge assignments on all fragments, thus enabling exclusive event-by-event studies of the interactions. The result of those studies have been published elsewhere [34,35].

Paper IV

The Isotopic Composition of Cosmic-Ray Ne at 2.4 and 6.3 GeV/n as Measured on HEAO-3

N-Y Herrström, B Byrnak, N Lund, B Peters, I L Rasmussen, M Rotenberg,
N J Westergaard, P Ferrando, P Goret, L Koch-Miramond, N Petrou and
and A Soutoul
Lund University Internal Report LUIP 8501 (1985).

In this paper a measurement of the isotopic composition of cosmic-ray neon is described. The investigation is the first ever made in the multi-GeV region where the measurements are much more difficult than at MeV-energies. On the other hand, the radiation in this region is less sensitive to solar modulation effects and the propagation calculation is more straight-forward since all cross-sections are energy independent.

The rigidity-dependent filtering of the cosmic rays by the magnetic field of the Earth has been used. The technique is non-trivial and is discussed in some detail. The data have been taken from the Danish-French cosmic-ray experiment on the HEAO-3 satellite.

The measurement has confirmed that neutron-rich isotopes are present in the cosmic radiation, also at higher energies. The cosmic-ray abundance of ^{22}Ne is enhanced by a factor of 3-4 as compared to the Solar System abundance. This implies a different history for at least a part of the cosmic-ray neon. It has been proposed that matter from additional sources enriched in ^{22}Ne is mixed with matter from "normal" cosmic-ray sources. Only a small contribution from these peculiar sources would then be needed to account for the observed ^{22}Ne abundance. This theory is discussed with the observed energy-dependence of the ^{22}Ne/^{20}Ne ratio as a basis.

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References

ICRC ≡ International Cosmic Ray Conference

1. V F Hess
   Phys Zeitschr 12 (1911) 998.
   Phys Zeitschr 13 (1912) 1084.

2. W Kolhörster
   Phys Zeitschr 14 (1913) 1153.
   Deutsch Phys Gesell Verh 16 (1914) 719.

3. J Clay
   Proc Roy Acad Amsterdam 30 (1927) 1115.

4. W Bothe and W Kolhörster
   Z Physik 56 (1929) 751.

5. C D Anderson
   Phys Rev 43 (1933) 491.

6. C Størmer
   Z Astrophysik 1 (1930) 237.

7. G Lemaître and M S Vallarta
   Phys Rev 43 (1933) 87.

8. A H Compton
   Phys Rev 41 (1932) 111.
   Phys Rev 41 (1932) 681.

9. T H Johnson
   Phys Rev 48 (1935) 287.

10. T H Johnson
    Rev Mod Phys 11 (1939) 208.

11. M Schein, W P Jesse and E O Wollan
Phys Rev 59 (1941) 615.

12. P S Freier, E F Lofgren, E P Ney, F Oppenheimer, H L Bradt and B Peters
Phys Rev 74 (1948) 213.

13. H L Bradt and B Peters
Phys Rev 80 (1950) 943.

14. M Garcia-Munoz and J A Simpson
16th ICRC, Kyoto 1, (1979) 270.

15. J A Simpson
Ann Rev Nucl Part Sci 33 (1983) 323.

16. A G W Cameron
in *Essays in Nuclear Astrophysics*, eds C A Barnes, D D Clayton and D N Schramm, Cambridge Univ Press, Cambridge (1982) 23.

17. J A Simpson
in *Composition and Origin of Cosmic Rays*, ed M M Shapiro, Reidel Publishing Comp, Dordrecht, Holland (1983) 1.

18. R B McKibben, K R Pyle and J A Simpson
Ap J (Letters) 254 (1982) L23.

19. R Silberberg and C H Tsao
Ap J Suppl 25 (1973) 315.
Ap J Suppl 25 (1973) 335.
J R Letaw, R Silberberg and C H Tsao
"Propagation of Heavy Cosmic Ray Nuclei"
Submitted to Ap J Suppl.

20. J J Engelmann, P Goret, E Julisson, L Koch-Miramond, N Lund, P Masse, I L Rasmussen and A Soutoul
Astron Astrophys (1985), in press.

21. N Lund
Adv Space Res 4 (1984) 5.

22. P Goret, J J Engelmann, L Koch-Miramond, J P Meyer, N Lund,
I L Rasmussen and C Perron
17th ICRC, Paris 9 (1981) 122.

23. J P Meyer
Ap J Suppl 57 (1985) 151.
Ap J Suppl 57 (1985) 173.

24. W I Axford
17th ICRC, Paris 12 (1981) 155.

25. W I Axford
in *Origin of Cosmic Rays*, eds G Setti, G Spada and A W Wolfendale,
Reidel Publishing Comp, Dordrecht, Holland (1981) 339.

26. M E Wiedenbeck and D E Greiner
Ap J (Letters) 247 (1981) L119.

27. M E Wiedenbeck and D E Greiner
Phys Rev Letters 46 (1981) 682.

28. M Cassé and J A Paul
Ap J 258 (1982) 860.

29. R Cowsik, Y Pal, S N Tandon and R P Varma
Phys Rev 158 (1967) 1238.

30. C J Cesarsky
Ann Rev Astron Astrophys 18 (1980) 289.

31. M E Wiedenbeck and D E Greiner
Ap J (Letters) 239 (1980) L139.

32. M E Wiedenbeck
18th ICRC, Bangalore 9 (1983) 147.

33. R A Mewaldt
in ***The Workshop on Cosmic Rays and High Energy Gamma Ray Experiments for the Space Era***, Lousiana State University, SRL84-6 (1984).

34. C Bjarle, N-Y Herrström, R Kullberg, A Oskarsson and I Otterlund
Nucl Phys A381 (1982) 544.

35. N-Y Herrström, R Kullberg, A Oskarsson and I Otterlund
Nucl Phys A392 (1983) 474.