

# Direct Measurements of Cosmic Rays

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**Abstract.** An overview is presented of the scientific implications of direct measurements of cosmic rays in terms of the origins and history of these particles. Within the last several years important constraints have been placed on the possible origins of cosmic rays in the GeV energy range by the analysis of isotopic composition. At higher energies new magnet experiments to measure elemental composition have supported the notion that all nuclei should have similar behaviour with magnetic rigidity. At still higher energies, into the cosmic ray "knee", there are some disagreements between measurements, suggesting that there are various issues which remain to be resolved in this region. We also emphasize the important role played by measurements of spallation-produced nuclei in cosmic-rays. These hold the key to our understanding of cosmic ray source spectra at high energies.

## 1. Direct Measurements of Isotopes

In the study of cosmic rays the most revealing aspect is their composition. Ideally we should know the isotopic composition of various nuclei and its variation with energy. This is an experimental challenge, particularly for high masses where the relative shift in the dynamics properties of nuclei between adjacent isotopes becomes smaller. By far the most successful measurement of isotopic properties to date has come from the ACE (Advanced Composition Explorer) satellite, a NASA Explorer mission launched in 1997[1]. An instrument on this satellite determines the energy loss rate and total energy deposited by particles in silicon detectors. This provides a determination of the nuclear isotopes up to elements with nuclear charge  $Z \sim 30$  in the energy range up to  $\sim 300 \text{ MeV/n}$ . The high resolution of these measurements has provided a number of key scientific observations of cosmic rays. These provide a significant part of our detailed knowledge about these particles. The following provides a summary of some of the most important observations, which in some cases were also previously determined with lower accuracy by other satellite measurements.

- *Comparison of cosmic-ray source and local galactic abundance:* The isotopic composition of the cosmic-ray source is in general very similar to the local galaxy, but there are some interesting differences. This similarity has led various authors to suggest that the nuclei that become cosmic rays originate from normal stellar outflows. The differences that do exist are explained by being characteristic of the contributions from stars with very large outflows (e.g. Wolf-Rayet stars), which consequently are overrepresented in the interstellar medium.
- *Cosmic-ray lifetime:* Various radioactive nuclei produced by spallation reactions with nuclei in the interstellar medium can be used to trace the lifetime of cosmic rays confined in the galaxy: if these nuclei are absent in observations the cosmic ray lifetime is long compared to their half-lives. A measurement of the lifetime can be made for nuclei whose

characteristic decay time is of a similar size to the lifetime. The measurements of  $^{10}\text{Be}$ ,  $^{26}\text{Al}$ ,  $^{36}\text{Cl}$ , and  $^{54}\text{Mn}$  made by ACE have consistently established the cosmic-ray confinement time in our galaxy at  $15.0 \pm 1.6$  Myr. These measurements also show the average density of hydrogen in the interstellar medium to be  $0.34 \pm 0.04$  atoms  $\text{cm}^{-3}$ .

- *Delay between nucleosynthesis and acceleration:* The measurement of the relative abundance of  $^{59}\text{Ni}$  and  $^{59}\text{Co}$  can be used to make an elegant estimate of the timescale during which the cosmic ray material is at relatively low energies. Since  $^{59}\text{Ni}$  decays by electron capture to  $^{59}\text{Co}$ , the relative abundances of these isotopes can be used to study the length of time this nucleus had orbital electrons. These will be absent for a nucleus with any appreciable energy. This isotopic ratio can be used to show the cosmic ray nuclei have spent at least  $\sim 100,000$  years at low energies. This means that for example the nuclei created during a supernova explosion are not predominantly accelerated by the same event. This fits in with a general picture of supernovae accelerating material from the surrounding medium to form cosmic rays.

## 2. Direct Measurements of Elements

The measurement of isotopes is at present limited to the region below  $\sim 1\text{GeV}/n$  because of the experimental challenges involved. However, the knowledge of elemental composition at higher energy has been significantly improved in recent years by improved measurements with magnets. In the case of the BESS balloon payload these have been extended to a maximum detectable rigidity of  $\sim 1\text{TV}$ . The following summarizes some measurements made with BESS[2] CAPRICE[3], and AMS1[4] on the Space Shuttle in the last few years.

Figure 1 shows a compilation of the measurements of the fluxes of protons and helium nuclei made by these three experiments. In this figure the flux values have been multiplied by a factor of  $(\text{Energy})^{2.75}$  to emphasize differences in the

measurements. Since these were made at slightly different periods of solar modulation, the values below a few  $\text{GeV}/n$  diverge somewhat. The impressive thing about this set of measurements is the agreement in both slope and absolute value at high energy, the estimated systematic error in flux measurements from these data seems to be on the order  $\sim 10\%$ . In addition the spectral slope of these values seems to be the same and essentially constant at high energy, near  $\sim 2.75$ . The direct measurements from magnet spectrometers now extend to  $\sim 400\text{GeV}$  for protons.

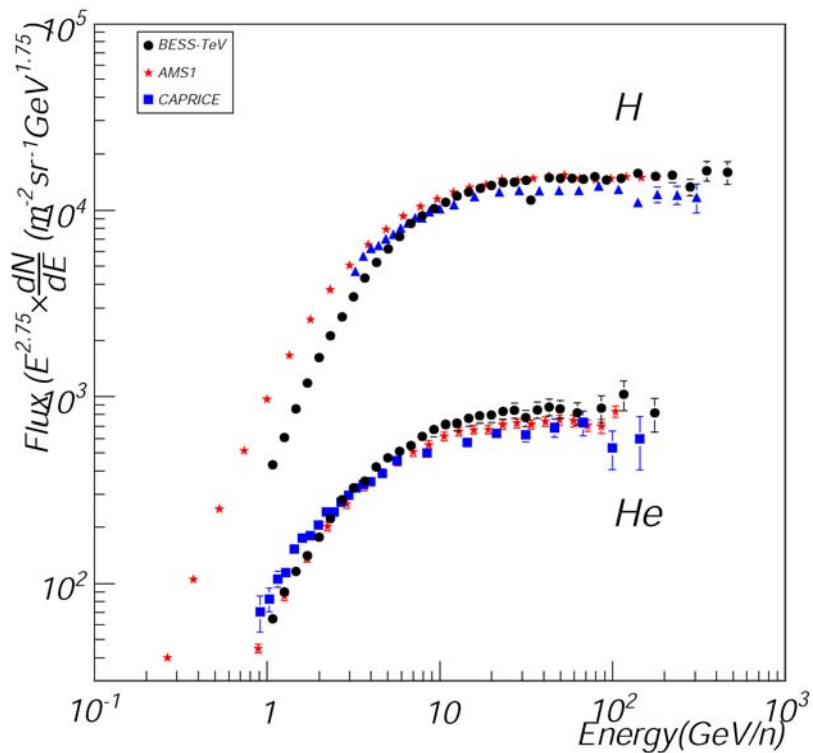


Figure 1. A compilation of recent magnet spectrometer fluxes for protons and helium.

A great advantage of magnet spectrometers from an experimental point of view is that the determination of particle momentum per unit mass (and consequently particle Lorentz factor) is essentially independent of particle charge. This is not the case for other methods which are used at still higher energies; transition radiation and thin calorimetry. In the case of transition radiation mis-identification of particle charge can have a significant effect on the assigned lorentz factor and for calorimetry there are similar caveats. However even calorimetry can have a larger collection aperture than magnets. Transition radiation measurements have the distinct advantage that they can be used in the largest detectors above the atmosphere for direct detection of cosmic rays.

Figure 2 shows an extension of the compilation of Figure 1 to higher energy using the data from three calorimetry experiments, JACEE[5], ATIC[6], and RUNJOB[7]. There are clearly significant discrepancies here at the higher energies between the different experiments. A continuation of the observed spectrum with a slope close to  $\sim 2.75$  would seem to be consistent with the RUNJOB results.

This would be probably the easiest to understand since this would suggest a constant magnetic rigidity spectrum over this energy interval. A little more unexpected is JACEE, where protons and helium appear to have differing spectral slopes above 1TeV/n, producing a significant increase in the abundance ratio of He/H. ATIC seems to show this difference to an even larger extent.

Since protons and helium are the dominant nuclear species in cosmic rays an estimate of the "mean mass" at a given total particle energy shows a similar trend with energy to those data in Figure 2. This mean logarithmic mass quantity is extremely useful for the connection to air shower indirect measurements, which start to become

useable near  $\sim 100$ TeV in total particle energy. The data for mean mass is shown in Figure 3, where the measurements for JACEE and RUNJOB are compared into the energy region of the "knee" of  $\sim 1$ PeV per particle. These data show that the mean logarithmic mass determined by RUNJOB is essentially constant into this region, similar to the value at lower energy of  $\sim 1.5$ . On the other hand JACEE shows this value as increasing into this energy range, climbing up to a value near  $\sim 2.7$ . These are significant differences in mass which will have a significant impact on the interpretation of indirect measurements of air showers, which are the only way to extend these measurements to higher energies. At present the situation seems unresolved as to which of these values is more correct.

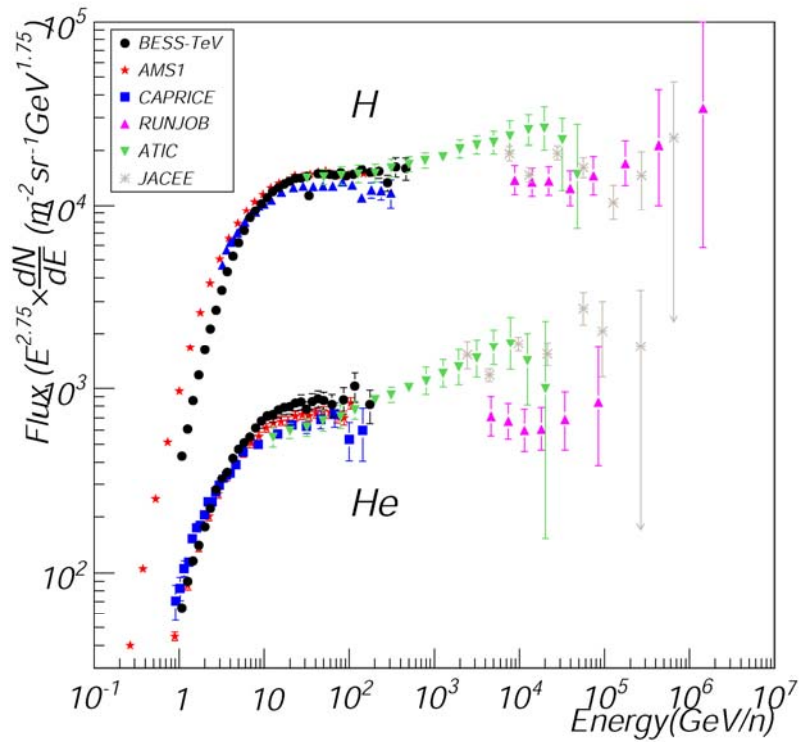


Figure 2. Compilation of direct measurements of protons and helium (see text for references)

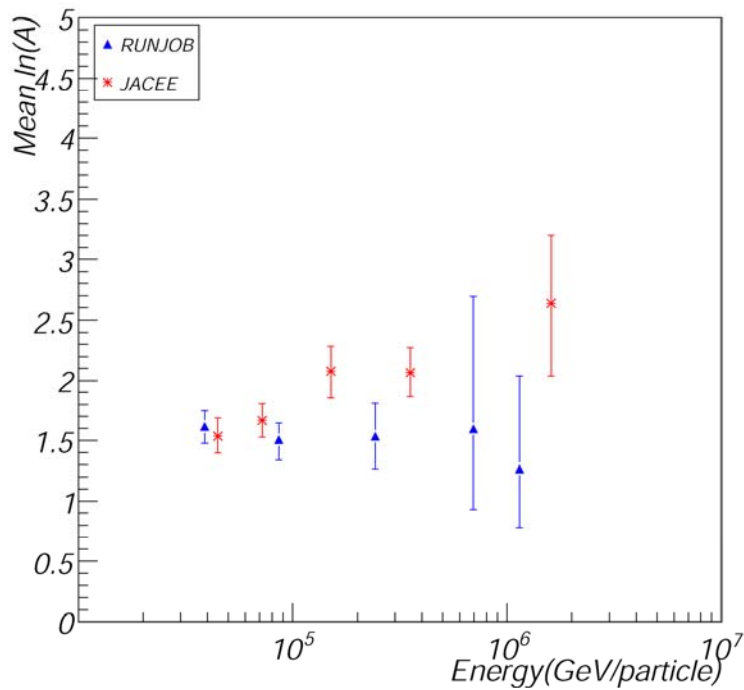


Figure 3: The mean logarithmic mass versus energy (see text)

### 3. Secondary Nuclei

The nuclei that are produced by spallation of particles in the interstellar medium can also provide some key scientific information about cosmic rays. It was discovered in the 1970s that the relative proportion of secondary nuclei decreases with increasing energy. This decrease scales approximately as  $\sim(\text{Energy})^{-0.6}$ , which has been interpreted as the energy dependence of the escape path-length in the galaxy. This naturally leads to the conclusion that the observed cosmic rays do not reflect the actual source spectrum of these particles. In the simplest picture this energy dependent escape implies the source spectral index of particles is closer to  $\sim 2.15$ . This is actually much closer to the predictions of strong shock acceleration than the observed local spectral index of  $\sim 2.75$ . At present these measurements of secondary particles only extend to  $\sim 100\text{GeV/n}$ . Recent results from RUNJOB have estimated the fraction of secondary nuclei above  $1\text{TeV/n}$  to be fairly large compared to this expected decline. The interpretation of these data is still being made, but it certainly looks like the fraction of secondary nuclei at high energy remains an important topic for the future. Knowledge of the proportion of secondary nuclei with energy is directly connected to our ability to determine the source spectrum.

### 4. Future Prospects

There are various long duration balloon experiments which promise to make significant contributions to the high energy composition over the next few years. A new technique, observation of direct Cerenkov radiation from the ground[8], may hold the most significant long term prospects for composition measurements in the knee region - because of known precision coupled with the possibility of large area detection via ground arrays.

### References

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