For the Antarctic Journal of the United States

Cosmic Ray Hydrogen and Helium Energy Spectra up to the Supernova Shock Limit

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Abstract

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The galactic cosmic ray spectrum spans a tremendous energy range, obeying one power law below about 10^{15} electron-Volts (eV), and another above 10^{16} eV. The region of change in between is called the "knee," and suggests a change in the acceleration mechanism. Below the knee, the mechanism is understood, and theories agree with experiment. Less is known above the knee, and more experiments are needed to understand the mechanism. Five Antarctic balloon flights have allowed the Japanese American Cooperative Emulsion Experiment (JACEE) to extend direct measurements toward this critical region.

Cosmic rays originate outside our solar system. They consist of ionizing particles such as electrons, and atomic nuclei and non-ionizing particles such as gamma rays (photons), and neutrinos. Nuclei from every element and nearly every isotope are found. The most common of these are hydrogen (protons), and helium nuclei. Those nuclei formed in stars, such as carbon through iron, are the next most abundant. Galactic cosmic rays have been found over a tremendous energy range, from below 10^{7} eV, up to 10^{21} eV (about 50 joules), the highest energy cosmic ray yet recorded.

The flux of cosmic ray nuclei is proportional to $1/E^{\alpha}$, where α is the power law index and E is the cosmic ray's energy. From about 10^{10} eV through about 10^{16} eV, α is constant for each element[1]. But in the knee region the index of the All-Particle Spectrum abruptly increases (Figure 1). The steeper spectral slope means the fluxes diminish even more rapidly with increasing energy.

Below the knee, acceleration of ions by magnetohydrodynamic shocks from supernova remnants can explain the cosmic ray energy spectra. This type of acceleration, but on a much smaller scale, has been seen to accelerate energetic particles from the sun (Longair). This theory is well understood, and matches the data below the knee quite well. But it also predicts an acceleration limit, corresponding roughly to the knee.

Many different theories try to explain cosmic rays in the region above the knee through 10^{19} eV (Axford). These include:

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[1] Neglecting propagation effects that can change the slope at different energies for different elements.

1) an increased acceleration limit, due to high magnetic fields in the progenitor star's stellar winds acting on the magnetohydronamic shock,
2) an increased acceleration limit, due to a more favorable acceleration geometry,
3) reacceleration of the cosmic rays during their travel through the galaxy, possibly by an intersteller wind or by other supernovas,
4) an entirely different galactic source for these cosmic rays, such as pulsars,
5) an extra-galactic source.

Any of the above could be made to match the data as known to date. The last has long been the favored explanation (Waddington) but now the first is the leading candidate (Axford, Bierman). This is because the first is the most compatible with the processes happening below the knee. But more precise measurements are needed to differentiate among the possibilities.

At energies above 10^{19} eV no object in our galaxy could produce these cosmic rays (Hillas), nor could the galaxy's magnetic field confine them, as it does the less energetic particles. Therefore, the most energetic cosmic rays are thought to originate outside our galaxy where more exotic sources of acceleration may be found, such as quasars and jets associated with massive black holes.

Since cosmic ray nuclei are charged particles, their path through space is deflected by galactic magnetic fields. The net effect is that cosmic rays diffuse randomly through our galaxy as they encounter regions of varying magnetic field strength and direction. Therefore, it is not possible to infer the source of cosmic rays by their direction observed at Earth. Instead we must learn about their source from their elemental and isotopic abundances and from their energy spectra.

At energies above the knee the low flux means that detectors with very large area and large angular acceptance are required to detect these cosmic rays. Ground-based air-shower arrays detect cosmic rays by using the entire sky above them as part of the instrument. As cosmic ray nuclei impinge on our atmosphere they interact, breaking up into lighter nuclei and producing many short-lived particles that eventually decay to the electrons, photons, protons, muons, and neutrinos observed at ground level. It is this shower of particles that is detected by extensive air shower detectors such as the 20 km^2 Akeno array (Sokolsky) and the South Pole Air Shower Experiment (Gaisser).

Since our atmosphere has the equivalent stopping power of one meter of lead, essentially all cosmic rays will interact in the atmosphere, and only the highest energy cosmic rays will lead to an appreciable number of particles detectable on the ground. Therefore, ground-based detectors must infer information about the original cosmic ray from its shower of particles measured at the bottom of our atmosphere. Consequently they are unable to obtain direct information about cosmic ray composition.

To avoid such indirect measurements, detectors must be above as much of the atmosphere as possible. Therefore, the detectors are unfortunately much smaller. At energies much lower than the knee, the flux is high enough such that small balloon or space based detectors like HEAO (Engelmann) and CRN (Müller) can be used.

In an attempt to understand the mechanisms producing the important "knee" region, the JACEE collaboration launched a series of experiments using some of the largest area, largest angular acceptance detectors, flown for the longest possible times (Table 1). Our instrument is well suited to the Antarctic environment because it is rugged, relying on passive photographic materials rather than active electronics.

The Antarctic campaigns have allowed us to fly for longer periods and with larger payloads than elsewhere in the world. This is due to the steady wind patterns found at flight altitude, the constant sunlight and albedo, and lack of political boundaries and areas of high population density to cross. The winds, which tend to follow lines of latitude, make recovery of the instrument easier, because we can wait for it to return near the launch site after a 7-14 day flight (Figure 2). The constant sun and albedo allow longer flights and heavier payloads because less ballast needs to be carried to counteract heating and cooling of the balloon. The lack of political boundaries and population centers expands our recovery options.

The only drawbacks when compared to other launch sites are the added expense of the logistics, the need to retrieve the instrument without heavy machinery, and the presence of the south magnetic pole which increases the number of low energy background cosmic ray tracks (Wilkes). Despite the risks, JACEE has recovered all but one of its gondolas. Since the major expense of time and money is in analyzing the data, the loss of a payload is not a serious setback. This would not be the case for spacecraft where the cost of the instrument and launch is far greater.

Table 1.
JACEE Balloon Flights

Flight	Launch Date	Launch Site	Altitude (g/cm^2)	Duration (hrs)	Units (cm × cm)	Cumulative Exposure (m^2-hrs)
JACEE 0	6/79	Sanriku, Japan	8.0	29.0	1 (40 × 50)	6
JACEE 1	9/79	Palestine, TX	3.7	25.2	4 (40 × 50)	26
JACEE 2	10/80	Palestine, TX	4.0	29.6	4 (40 × 50)	50
JACEE 3	6/82	Greenville, SC	5.0	39.0	1 (50 × 50)	59
JACEE 4	9/83	Palestine, TX	5.0	59.5	4 (40 × 50)	107
JACEE 5	10/84	Palestine, TX	5.0	15.0	4 (40 × 50)	119
JACEE 6	5/86	Palestine, TX	4.0	30.0	4 (40 × 50)	143
JACEE 7	1/87	Alice Springs, Australia	5.5	150.0	3 (40 × 50)	233
JACEE 8	2/88	Alice Springs	5.0	120.0	3 (40 × 50)	305
JACEE 9	10/90	Ft. Sumner NM	4.0	44.0	4 (40 × 50)	340

JACEE 10	12/90	Mc Murdo, Antarctica	3.5	204.0	2 (30×40)	389
JACEE 11	12/93	Mc Murdo	4.5	217.0	6 (40×50)	*
JACEE 12	7/94	Mc Murdo	5.0	212.0	6 (40×50)	644
JACEE 13	12/94	Mc Murdo	5.0	310.0	6 (40×50)	1016
JACEE 14	12/95	Mc Murdo	5.0	350.0	6 (40×50)	1436

* JACEE 11 was lost in the ocean due to a malfunction at cut-down after a successful nine-day flight.

The series of flights spans almost twenty years, each representing the longest duration flight available at the time. (Table 1). We typically fly at 35,000 meters where the atmospheric overburden is approximately 5 grams per square centimeter or less. At normal incidence, fewer than 6% of protons and 37% of iron nuclei interact traversing this amount of material.

A typical JACEE emulsion module is shown in figure 3. At the top is a region of many nuclear emulsion plates, used to determine the elemental species of the cosmic ray. These emulsions are sensitive to the charge of particles passing through them, but not their energy. In the middle is a target region designed to maximize the probability of the cosmic ray making a nuclear interaction, while still allowing us to follow its path and its shower of particles through the detector stack. At the bottom is a thin lead sampling calorimeter, used to determine the energy of the cosmic rays and the starting point for finding the interactions (Asakimori).

We have completed the analysis of the hydrogen and helium cosmic ray energy spectra through JACEE flight 12. We now have 25 hydrogen events above 90×10^{12} eV and 37 helium events above 25×10^{12} eV per nucleon. The energy spectra for hydrogen and helium are shown in figure 4, with the results from other experiments. The large circular points with error bars are from the JACEE experiments.

Figure 5 shows the integral flux of hydrogen and helium as measured by the JACEE collaboration. Here the highest energy points represent the flux associated with the highest energy hydrogen and helium measurement. The next highest energy point represents the sum of the previous point and the next highest energy measurement, and so on. The waviness at high energy is a result of the low counting statistics. These distributions are well described by a single power law of the form

$$N(>E)\big|_{hydrogen} = \left(6.2^{+0.5}_{-0.3}\right)\times10^{-2}\left(\frac{E}{10^{12}\ eV}\right)^{-1.80\pm0.04}\ (\mathrm{m}^2\text{-sr-s-}10^{12}\mathrm{eV})^{-1}$$

for hydrogen and

$$N(>E)\big|_{helium} = (4.7\pm0.1)\times10^{-3}\left(\frac{E}{10^{12}\ eV}\right)^{-1.68^{+0.04}_{-0.06}}\ (\mathrm{m}^2\text{-sr-s-}10^{12}\mathrm{eV\ per\ nucleon})^{-1}$$

for helium. No evidence of the knee is found in either spectrum up to 10^{14} eV per nucleon (Asakimori).

The acceleration limit of cosmic rays is expected to be proportional to the charge of the cosmic ray nuclei Z, where Z is the charge in units of the proton charge. This is true for any form of acceleration by an electromagnetic field. If we make a toy model where we assume this cutoff to be at $Z\times10^{15}$ eV, then sum the hydrogen and helium energy spectra with some preliminary spectra of heavier cosmic rays (Takahashi) we obtain the result shown in figure 6. To make it easier to plot and to see small effects in the energy distributions, it is customary to multiply the energy spectra by $E^{2.5}$ or $E^{2.75}$ and to use a log-log scale. In figure 6 is also shown the “All-Particle Spectrum” from a number of different experiments along with the summed spectrum from JACEE. The summed spectrum is remarkably similar to the All Particle Spectrum up to about 10^{16} eV. Depending on the details of the cutoff in acceleration by supernova remnants, the cosmic ray spectra could be explained above the knee, removing the need to introduce an extragalactic cosmic ray component until still higher energies.

With these new results, JACEE is beginning to determine the composition approaching 10^{15} eV. With the analysis of JACEE flights 13 and 14 we will either find a change in the power law index in the cosmic ray spectra or push the position of the knee up to still higher energies.

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Asakimori, K. *et al. Astrophysical Journal* **502** (1998). pp. 278-283.

Axford, W. I. *Astrophysical Journal Supplement* **90** (1994). pp. 937-944.

Biermann, P. L. *et al. Phys Rev.D* **51 (**1995), pp. 3450-3454.

Cherry, M. L. *Proc. Sixth Conference on the Intersections of Particle and Nuclear Physics*, Big Sky, Montana, AIP Conference Proc. **412,** 1022 (1997).

Engelmann, J.J., *et al., Astron. Astrophys.* **233** (1990). p. 96.

Gaisser, T.K. *et al. Proceedings of the 24th International Cosmic Ray Conference* (Rome), **1**:938.

Hillas, A. M. *Ann. Rev. Astron. Astrophys.,* **22** (1984). p. 425.

Müller, D. *et al. Astrophysical Journal* **374** (1990). p. 356.

Longair, Malcolm S. **High Energy Astrophysics, V1,** Cambridge University press, 1992, pp. 279-330, 396-399.

Sokolsky, Pierre. **Introduction to Ultrahigh Energy Cosmic Ray Physics,** Addison-Wesley, 1989, pp. 36-49.

Takahashi, Y., *Proc. IInd Rencontres du Vietnam*, "The Sun and Beyond", Oct. 21-28, 1995, Ho chi-Minh City, (World Scientific 1996)

Waddington, C. J. and Working Group. 1992, GOAL, NASA Report.

Wilkes, R. J. *Proceedings of the 24th International Cosmic Ray Conference,* **V3.** p 615.

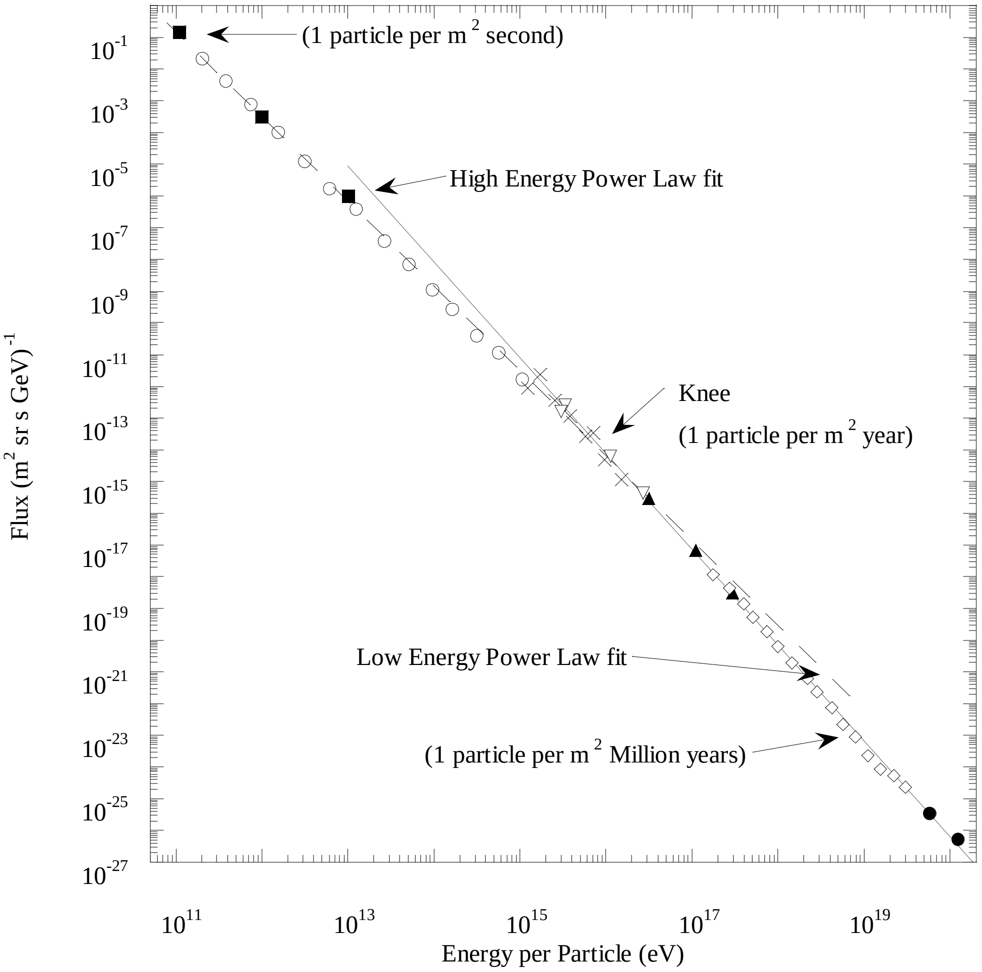

Figure 1. Energy dependence of cosmic rays. At very low energies the flux of cosmic rays is obscured and distorted by the solar wind. Otherwise the spectrum is well represented by a power law with an increase in slope above the knee region. Reproduced with permission from the author M. L. Cherry.

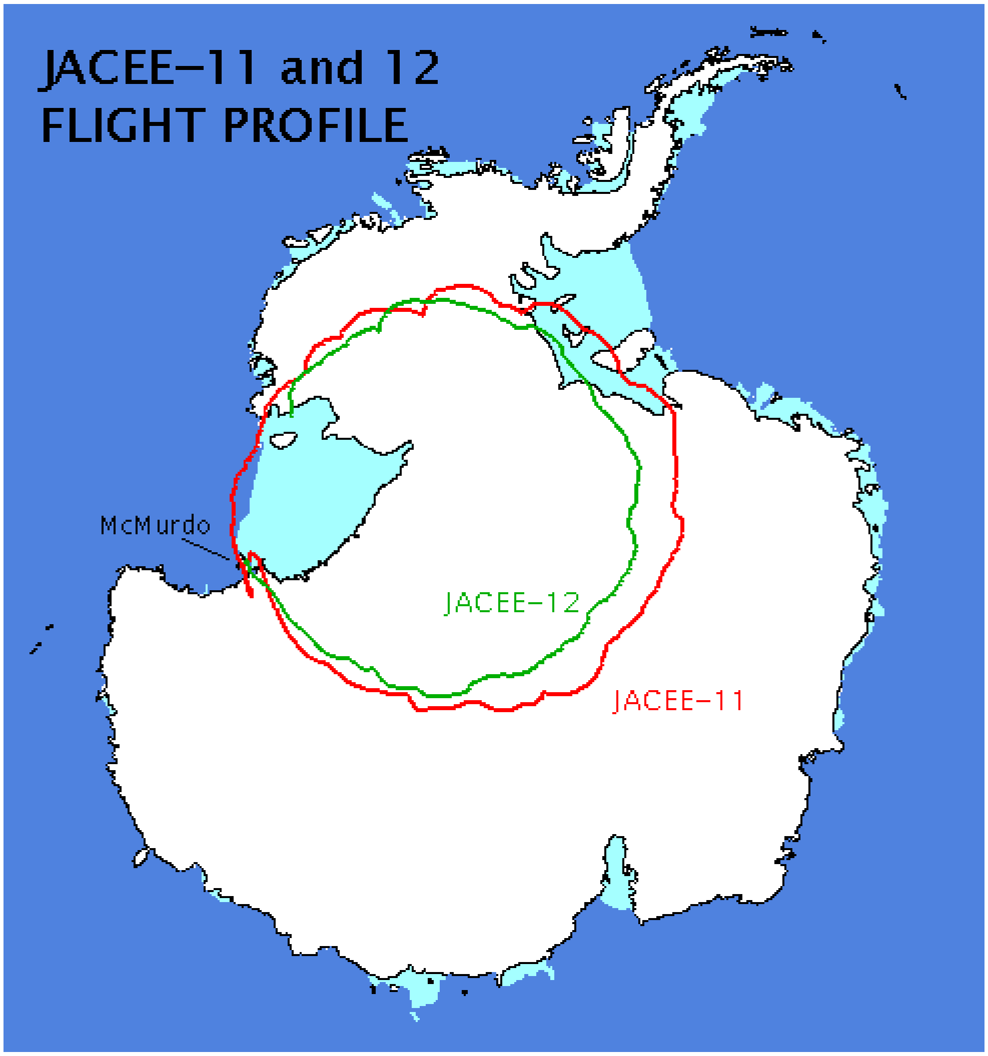

Figure 2. The flights of JACEE 11 and 12 over Antarctica.

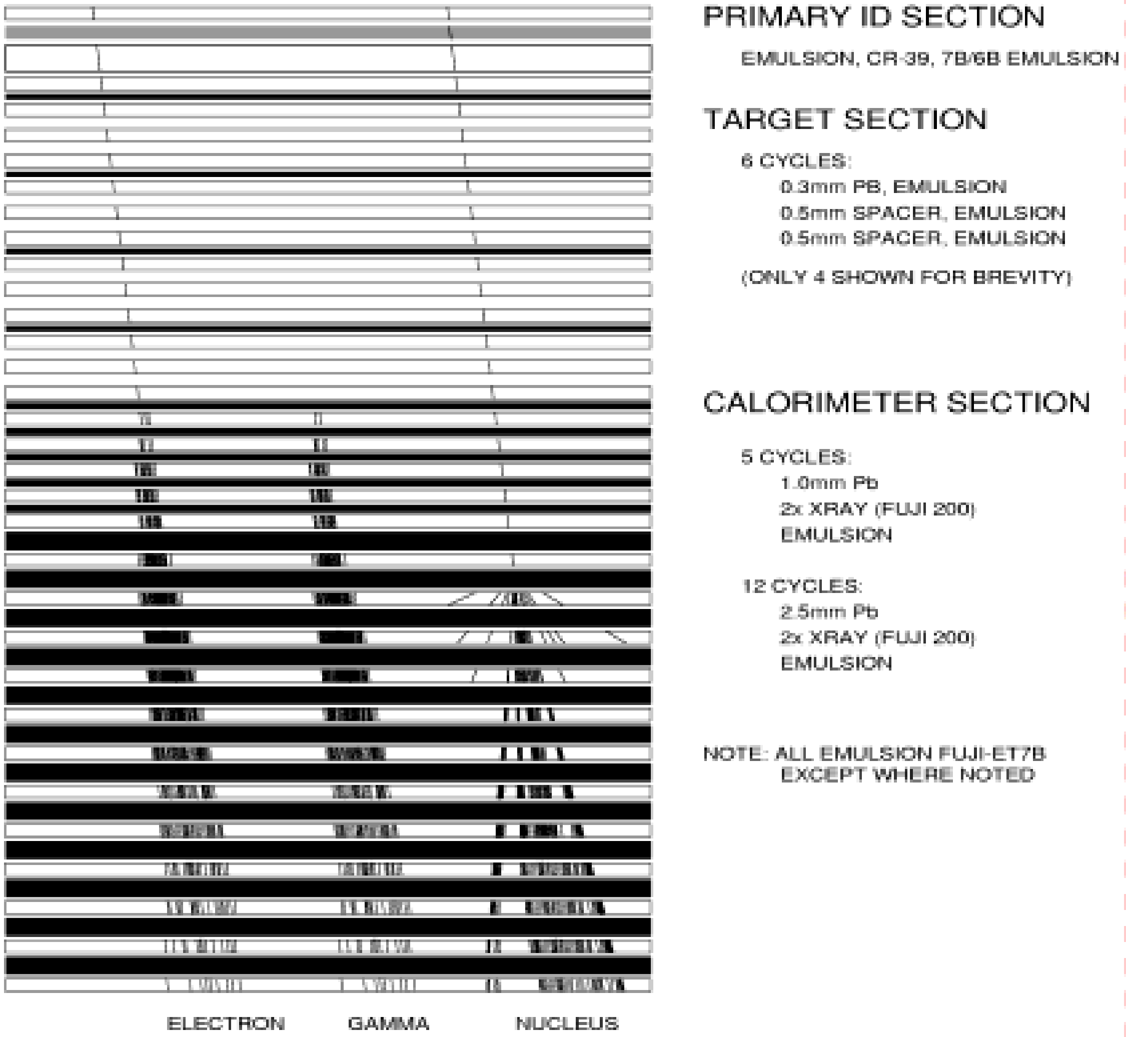

Figure 3. A typical emulsion box used in a JACEE flight.

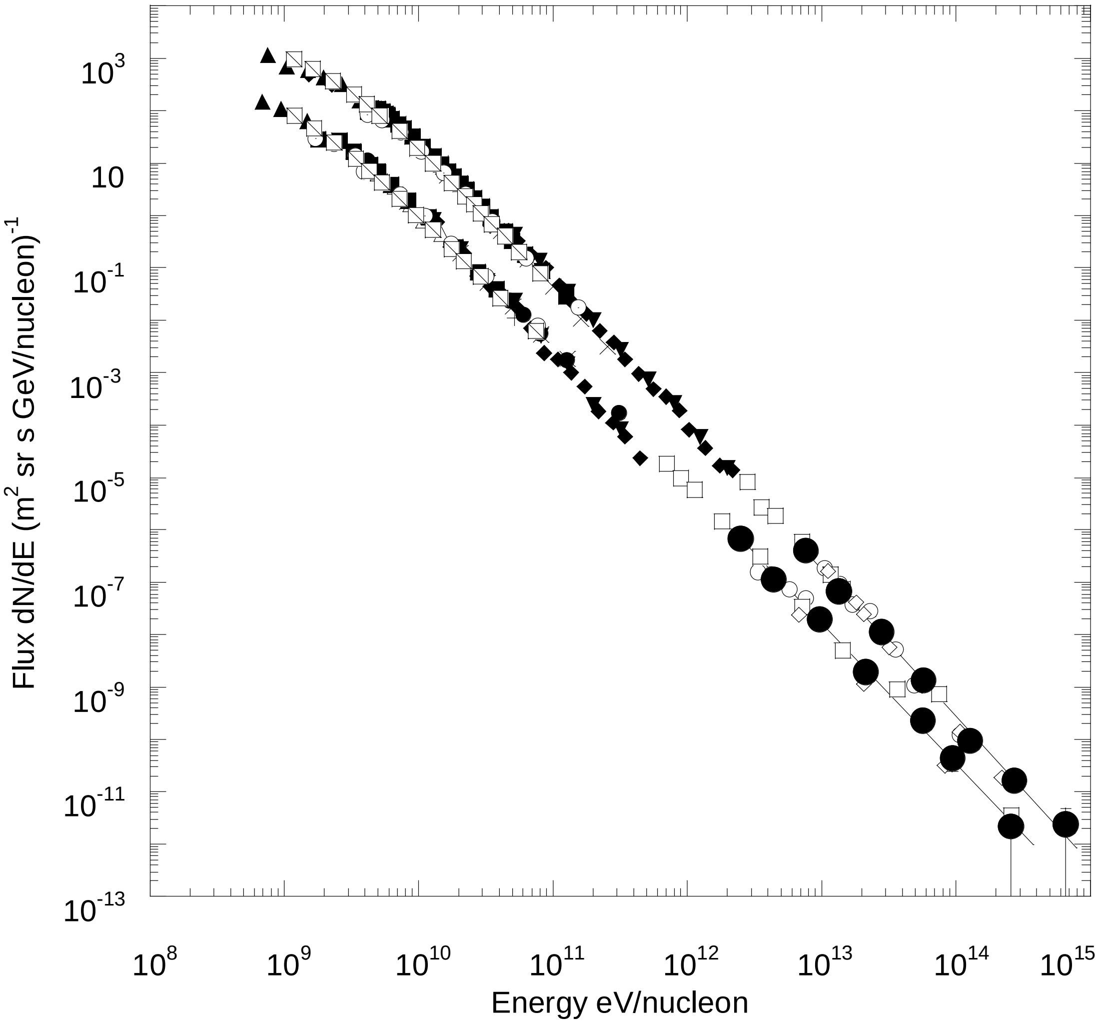

Figure 4. Differential energy spectra for hydrogen and helium nuclei found in the cosmic rays. The large circles are from the JACEE experiments. See Asakimori *et al*. for a list of the other experiments.

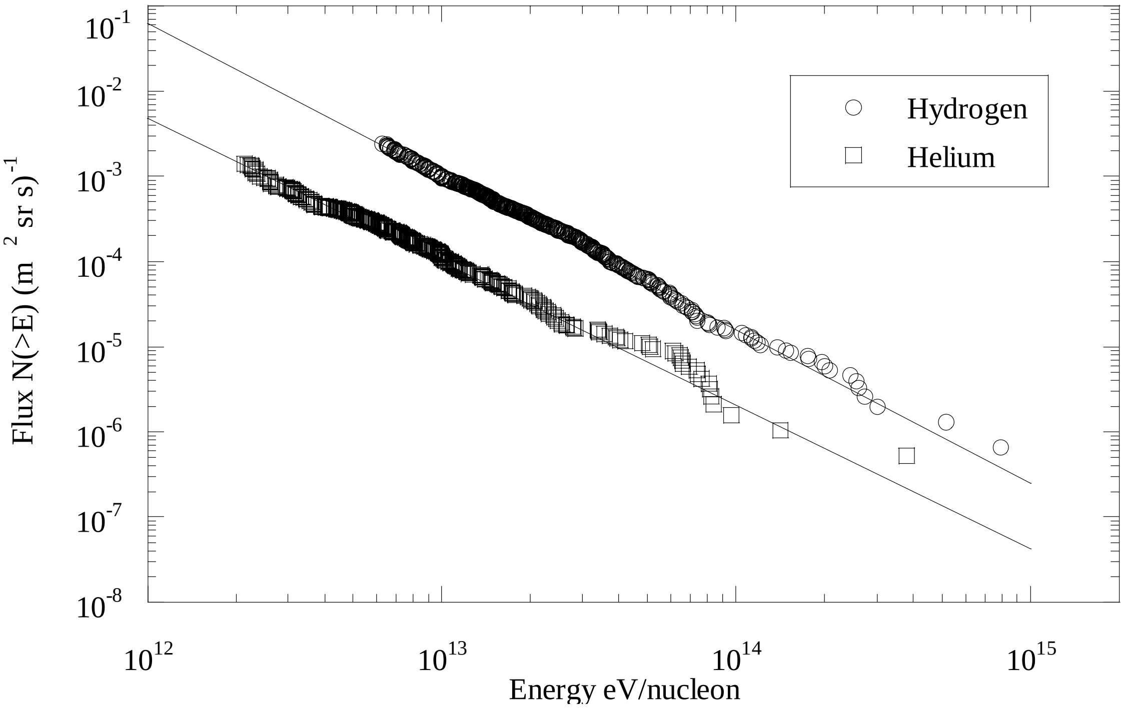

Figure 5. Integral energy spectra for hydrogen and helium nuclei as measured by the JACEE experiments.

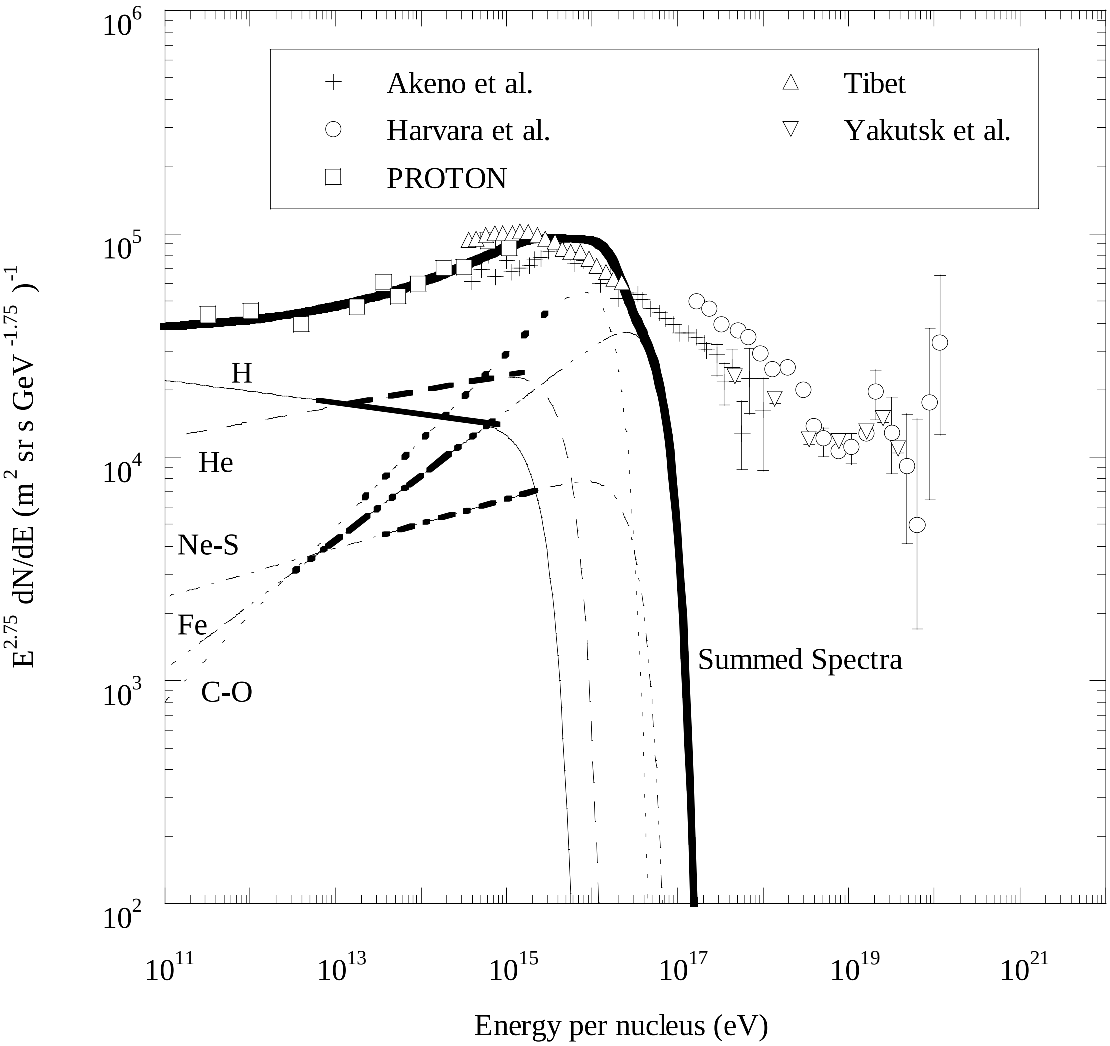

Figure 6. All Particle Spectrum determined from different ground-based extensive air shower experiments, the PROTON 4 satellite, and the energy spectrum based on the toy model determined by the JACEE experiments along with the sum of these spectra. The fluxes are multiplied by $E^{2.75}$