IL NUOVO CIMENTO Vol. 32 C, N. 3-4 Maggio-Agosto 2009
DOI 10.1393/ncc/i2009-10468-6

Colloquia: IFAE 2009

The primary cosmic rays spectrum at knee energies. Experimental results and future developments

A. Chiavassa
Università di Torino - Torino, Italy

(ricevuto il 19 Settembre 2009; pubblicato online il 23 Novembre 2009)

Summary. — In this contribution I briefly review the most recent results obtained by experiments studying the primary cosmic rays spectrum at energies around the knee, *i.e.* the change of the slope observed at $E_0 \sim 3 \times 10^{15}$ eV. The contribution is completed discussing the arguments that still remain controversial, the measurements that will allow to clarify them and the experiments actually operating.

PACS `96.50.sb` – Composition, energy spectra and interactions.
PACS `96.50.sd` – Extensive air showers.

1. – Introduction

The primary cosmic rays energy spectrum has been measured in a very large energy range, from $\sim 10^{12}$ to $\sim 10^{20}$ eV. Its shape is very regular and can be described by a power law with a nearly constant slope (γ). Two main features have been detected: at $E_0 \sim 3 \times 10^{15}$ eV, the so-called knee with γ steepening from ~ 2.7 to ~ 3.0, and at $E_0 \sim 5 \times 10^{18}$ eV, where γ returns to ~ 2.8 (the so-called ankle). A recent review of experimental results, taken from [1], is shown in fig. 1 (for the single experiments see references therein).

The knee was first detected, with an array measuring the electromagnetic component of the extensive air showers (EAS, *i.e.* the cascade generated by the interaction of the primaries at the top of the atmosphere) almost fifty years ago [2], but the mechanism originating it is not yet completely understood. In the last decade experiments sampling, for all events, several EAS components (mainly, but not only, CASA-MIA [3], EAS-TOP [4] and KASCADE [5]) obtained high-precision results constraining the hypothesis proposed to explain the knee.

In the following section I review the main results obtained in the recent past, discussing their consequences on the different hypotheses proposed to explain the knee. The contribution is then concluded discussing the measurements that could give important information about the knee, and the experiments that are performing them.

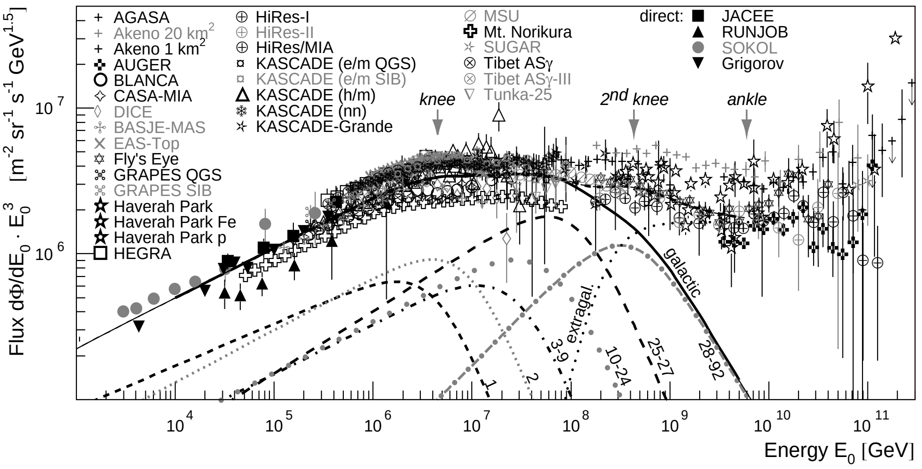

Fig. 1. – Review of measurements of the primary cosmic rays spectrum.

2. – Experimental results about the knee

Due to the low fluxes the energy range around the knee has to be studied with large area experiments operating at earth, thus measuring the secondary components of the EAS. The characteristics of the primaries must then be indirectly inferred using complete simulations of the EAS development in the atmosphere.

The change of slope has been observed in the spectra of all EAS components (electromagnetic [6-8], muonic [9, 10] and hadronic [11]) and at different stages of the shower development, both with experiments operating at different altitudes above see level and with each array measuring in different intervals of zenith angle. In fig. 2 a compilation of spectra of the electromagnetic component, taken from [12], is shown. It can be seen as all of them show the change of slope and that the shower size at the knee (N_e, *i.e.* the number of electrons at observation level) decreases with atmospheric depth. The attenuation of the shower size at the knee is compatible with what we expect for EAS development.

Moreover the characteristics of the observed change of slopes of the spectra of different components, namely the integral fluxes above the knee and the number of electrons and muons at the knee, agree with the expectations of shower development in the atmosphere [9].

All these measurements lead to the conclusion that the knee is a characteristic of the primary cosmic ray spectrum and it is not due to a change in the interaction mechanism (affecting the EAS development).

The EAS-TOP [9] and CASA-MIA [13] experiments have measured, correlating the mean values of electrons and muons in EAS, that the primary chemical composition becomes heavier at energies crossing the knee.

Using a more refined analysis the KASCADE experiment shows that: the knee is due to the light component of cosmic rays [10] and that the spectra of single elements show knees at energies increasing with the primary atomic number [14]. A similar result has been obtained by the EAS-TOP Collaboration correlating the shower size both with GeV [9] and TeV [15] muons. The resolution reached (by both experiments) does not allow to discriminate between a Z or A dependence.

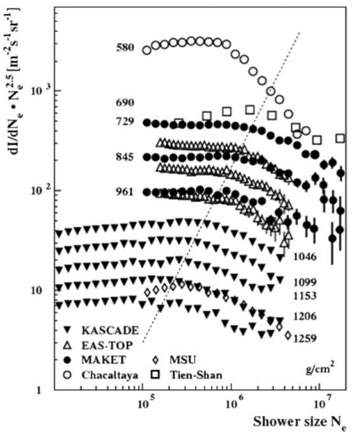

Fig. 2. – Shower size (N_e) spectra measured by different experiments at different atmospheric depths. The dashed line is simply a reference to guide the eye over the N_e values where the change of slope is observed.

All these analyses concerning the primary chemical composition heavily depend (at least for the quantitative aspects) on EAS simulation, thus being affected by the lack of knowledge of primary interactions at the energies under investigation. Moreover at colliders the forward region of the interactions (the one relevant for the EAS development) is not studied.

We can conclude that the favored scenario to explain the knee deals with astrophysical mechanisms: either the acceleration or the propagation of galactic cosmic rays. In both scenarios a change of the slope of the spectra of single elements is expected at an energy scaling with the charge Z, thus we expect the iron knee at an energy equal to $Z_{\mathrm{Fe}}E_{\mathrm{knee}} \sim 10^{17}\,\mathrm{eV}$. Its detection would be a conclusive argument in favor of an astrophysical mechanism. It is thus necessary to extend the measurements in the 10^{16} to 10^{18} eV energy range with high-resolution experiments allowing a separation between different elements or at least between light and heavy components.

This lead to the start of new experimental projects. Most of them are in the construction phase: ICE-TOP [16], TUNKA-133 [17], the low-energy extensions of the Pierre Auger Observatory [18] and of the Telescope Array [19]. The only experiment that is nowadays taking data in the full configuration is KASCADE-Grande [20].

3. – The KASCADE-Grande experiment

The KASCADE-Grande experiment [20] is a multi-detector set-up consisting of the KASCADE [5] experiment, the trigger array Piccolo and the scintillator detector array Grande. Additionally, KASCADE-Grande includes an array of digitally read out dipole antennas (LOPES) to study the radio emission in air showers at $E > 10^{16}\,\mathrm{eV}$ [21]. The KASCADE experiment is itself a multiple detector set-up and its major parts are an array of 252 scintillator detector stations, a streamer tube Muon Tracking Detector ($E_\mu >$ 800 MeV) [22], and a multiwire proportional chamber muon detector ($E_\mu > 2.4\,\mathrm{GeV}$). The Grande array is formed by 37 stations of plastic scintillator detectors, $10\,\mathrm{m}^2$ each (divided into 16 individual scintillators) spread on a $0.5\,\mathrm{km}^2$ surface, with an average grid size of 137 m.

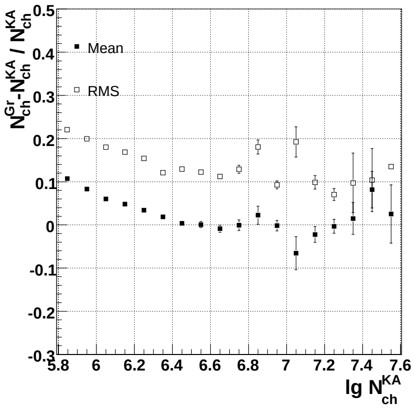

Fig. 3. – Mean value and RMS of the relative difference between the shower size values obtained by the KASCADE and the Grande arrays.

The arrival direction of the events is determined fitting the arrival time of the particles in the Grande detectors to a curved shower front [23]. The core position, the shower age and the shower size are obtained fitting the particles densities measured by the Grande stations with a NKG like function [23]. The total number of muons is then calculated using the core position determined by the Grande array and the muon densities measured by the KASCADE muon detectors [24].

The precisions obtained in the reconstruction of the shower parameters are evaluated exploiting the unique feature of the KASCADE-Grande experiment of having two independent samplings of the same event by the KASCADE and the Grande arrays. For events at energies greater than 10^{16} eV (threshold for 100% Grande detection efficiency) the measured resolutions are: better than 1° for the arrival direction; lower than 10 m for the core position and lower than 20% for N_e (see fig. 3 including also the systematic shift between the two measurements). Thus showing that the array performances are those required to perform the previously mentioned studies.

4. – Conclusions

The results recently obtained, by experiments studying the cosmic rays spectrum at knee energies, favor the astrophysical scenario, even if some details remain unclear. To solve them high-precision measurements in the energy range from 10^{16} to 10^{18} eV are required. As an example the performances of the KASCADE-Grande experiment have been described.

REFERENCES

[1] Hörandel J., *Adv. Space Res.*, **41** (2008) 442.
[2] Kulikov G. and Khristiansen G. B., *JEPT*, **35** (1958) 635.
[3] Borione A. *et al.*, *Nucl. Instrum. Methods A*, **346** (1994) 329.
[4] Aglietta M. *et al.*, *Nucl. Instrum. Methods A*, **336** (1993) 310.
[5] Antoni T. *et al.*, *Nucl. Instrum. Methods A*, **513** (2003) 490.

[6] Aglietta M. *et al.*, *Astropart. Phys.*, **10** (1999) 1.
[7] Antoni T. *et al.*, *Astropart. Phys.*, **19** (2003) 703.
[8] Glasmacher M. A. K. *et al.*, *Astropart. Phys.*, **10** (1999) 291.
[9] Aglietta M. *et al.*, *Astropart. Phys.*, **21** (2004) 583.
[10] Antoni T. *et al.*, *Astropart. Phys.*, **16** (2002) 373.
[11] Hörandel J. *et al.*, *Proc. of the 26th ICRC*, **1** (1999) 337.
[12] Haungs A. *et al.*, *Rep. Prog. Phys.*, **66** (2003) 1145.
[13] Glasmacher M. A. K. *et al.*, *Astropart. Phys.*, **12** (1999) 1.
[14] Antoni T. *et al.*, *Astropart. Phys.*, **24** (2005) 1.
[15] Aglietta M. *et al.*, *Astropart. Phys.*, **20** (2004) 641.
[16] Gaisser T. *et al.*, arXiv:0711.0353v1 (2007).
[17] Budnev N. M. *et al.*, arXiv:0801:3037 (2008).
[18] Klages H. O. *et al.*, *Proc. of the 30th ICRC*, **5** (2007) 849.
[19] `http://www.telescopearray.org`.
[20] Navarra G. *et al.*, *Nucl. Instrum. Methods A*, **518** (2004) 207.
[21] Falcke H. *et al.*, *Nature*, **435** (2005) 313.
[22] Doll P. *et al.*, *Nucl. Instrum. Methods A*, **488** (2002) 517.
[23] Di Pierro F. *et al.*, arXiv:0906.4007 (2009).
[24] Fuhrmann D. *et al.*, arXiv:0906.4007 (2009).