Proceedings of ICRC 2001: 792 © Copernicus Gesellschaft 2001

ICRC 2001

KASCADE-Grande: a conclusive experiment on the knee

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Abstract. We present the status and capabilities of the Extensive Air Shower experiment (KASCADE-Grande) which is being realized at Forschungszentrum Karlsruhe through a large collecting area (0.5 km^2) electromagnetic array (Grande) that will operate jointly with the existing KASCADE detectors. KASCADE-Grande will cover the primary energy range 10^{16} eV $< E_0 < 10^{18}$ eV, overlapping with KASCADE around 10^{16} eV, thus providing a continuous information from $3 \cdot 10^{14}$ eV to 10^{18} eV. The main task of the experiment is the observation of the "iron knee" in the cosmic ray spectrum that is expected at $E_k^{Fe} \approx 10^{17}$ eV. This is expected following the increasing mass of the primaries observed between 10^{15} and 10^{16} eV (knee region for the light component), and the rigidity dependent breaks for the spectra of different primaries from the conventional acceleration models. Its observation will provide a definite proof of the knee structure.

1 Introduction

One of the main results so far obtained by the KASCADE (Glasstetter et al. (1999) ; Roth et al. (1999) ; Hörandel et al. (1999) and Weber et al. (1999)) and EAS-TOP (Aglietta et al. , 1999) experiments, is a picture of an increasingly heavier composition above the knee largely caused by a break in the spectrum of the light component. A change towards a heavier composition above the knee is expected in conventional acceleration models, where the knee is supposed to be rigidity dependent. A convincing verification of this type of model would be the observation of the knee in the heavy component in the primary energy region around $E_0 = Z_{Fe} \times E_k \approx 10^{17}$ eV. Such an uncovering requires the extension of the high quality data obtained in the energy range 10^{15} - 10^{16} eV by KASCADE and EAS-TOP, without loosing accuracy, significantly above E_0. For such purpose, a new Extensive Air Shower array (KASCADE-Grande) is being realized at the Forschungszentrum Karlsruhe (8^o E, 49^o N, 110 m a.s.l.) by means of 37 stations of 10 m^2 each of scintillator counters at a mutual distance of about 130 m and covering globally an area of about 0.5 km^2, next to the KASCADE site in order to operate jointly with the existing KASCADE detectors. In this configuration KASCADE-Grande will cover the primary energy range $10^{16}\mathrm{eV} < \mathrm{E}_0 < 10^{18}\mathrm{eV}$. The superposition with KASCADE will guarantee the cross calibration of the detectors, and provide a full coverage from $3 \cdot 10^{14}$ to 10^{18} eV. The detector will start operation in January 2002, and will reach its full statistics in 3-4 years of data taking. The present status of the array, its resolutions and capabilities in the reconstruction of average primary composition, and verification of the hadronic interaction models used for the analysis, in the energy range of operation, are discussed.

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2 The experiment

The basic layout of KASCADE-Grande is reported in fig. 1. It consists of three different arrays: KASCADE, Grande, and Piccolo.

The KASCADE experiment (Klages et al. , 1997) is made by three major components: an array of electron and muon detectors, a central detector mainly for hadron measurements but with substantial muon detection areas, and a tunnel with streamer tube muon telescopes. The e/γ and μ detectors cover an area of about 200 × 200 m^2 and consist of 252 detector stations located on a square grid of 13 m separation providing in total about 490 m^2 of e/γ and 622 m^2 of μ coverage. The detection thresholds for vertical incidence are $E_e > 5$ MeV and $E_\mu > 230$ MeV. The central detector system (320 m^2) consists of a highly-segmented hadronic

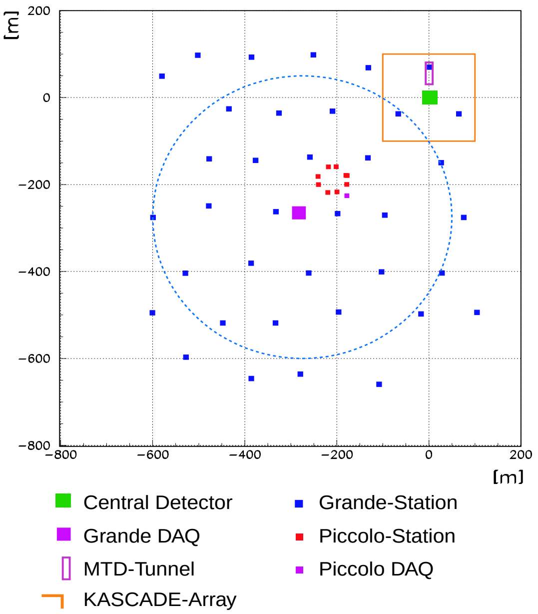

Fig. 1. Layout of KASCADE-Grande.

calorimeter read out by 55,000 channels of warm liquid ionization chambers, a layer of scintillation counters above the shielding, a trigger plane of scintillation counters in the third layer and, at the very bottom, 2 layers of positional sensitive MWPC's, and a streamer tube layer with pad read-out for muon tracking at $E_\mu \geq 2.4$ GeV. The muon tracking detector (Zabierowski et al. , 2001) is located in a $44 \times 5.4 \times 2.4$ m^3 tunnel, close to the central detector. It houses three horizontal and two vertical layers of positional sensitive limited streamer tubes for muon tracking at $E_\mu \geq 0.8$ GeV. The accuracy in reconstructing the μ direction is $\sigma \approx 0.35^o$.

Grande consists of 37 stations of 10 m^2 each of scintillator counters - basically the electromagnetic detector of EAS-TOP (Aglietta et al. , 1989) - at a mutual distance of about 130 m and covering globally an area of about 0.5 km^2 next to the KASCADE site. Each of the 10 m^2 station is split into 16 individual scintillators (NE102A, 80×80 cm^2 area, 4 cm thick). Each scintillator is viewed by a photomultiplier XP3462B for timing and particle density measurements from $n_p \approx 0.3$ to ≈ 750 /10 m^{-2} (HG ch). The four central scintillators are equipped with an additional similar PM but with a maximum linearity divider, for large particle density measurements: from $n_p \approx 12$ to ≈ 30000 /10 m^{-2} (LG ch).

Piccolo consists of an array of 8 huts (10 m^2 each) equipped with 12 scintillator plates each, placed towards the center of Grande array. The main aim of Piccolo is to provide an external trigger to Grande and KASCADE for coincidence events allowing the recording of data from all the detectors of KASCADE-Grande. A triggering condition of ≈ 1 Hz will provide an efficiency $\epsilon > 0.6$ at 10^{16} eV, becoming $\epsilon \approx 1$ at $5 \cdot 10^{16}$ eV for all primaries in the fiducial area of 300 m radius around Piccolo (from CORSIKA-QGSJET).

A summary of the detector components together with their most relevant parameters is given in Table 1.

Piccolo, Grande and the cross triggering electronics are under construction, and the full array will start common data taking in January 2002.

3 Analysis.

The energy range of interest is shown in fig. 2. With three

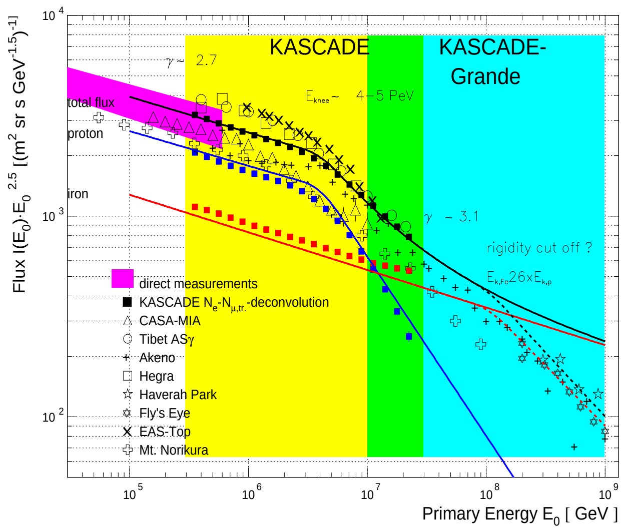

Fig. 2. Differential energy spectrum of CRs. The knee of the light component, the expectation for the heavy one, and the energy region covered by the KASCADE and KASCADE-Grande arrays are shown. The darker area represents the region of superposition of the two detectors.

years data taking, and collecting area $A \simeq 0.5$ km^2, the total exposure of KASCADE-Grande will be: $\Gamma \simeq 10^{14}$m^{2}srs. This will correspond to a collected number of events (including the trigger efficiency of Piccolo): $n(> 10^{16}eV) \simeq 1.7 \cdot 10^6$, $n(> 3 \cdot 10^{16}eV) \simeq 2.8 \cdot 10^5$, $n(> 10^{17}eV) \simeq 2.5 \cdot 10^4$, $n(> 3 \cdot 10^{17}eV) \simeq 2.8 \cdot 10^3$, $n(> 10^{18}eV) \simeq 250$.
Up to about 10^{18} eV KASCADE-Grande will thus provide statistically significant physical information.

The basic observables will be: the muon density at core distance between 300 and 600 m (providing, together with the observed muon lateral distribution, the muon density at 600 m, $D_{\mu 600}$), their reconstructed production heights (h_μ) from the tracking modules (including timing information for the muons in the KASCADE central detector), and the shower size (N_e) and lateral electron density profile from the extended electromagnetic (e.m.) array.

For what concerns the reconstruction accuracies of the Grande array, the resolutions reported in table 2 have been estimated through a simulation based on CORSIKA-QGSJET model for near vertical events ($1.00 < \sec\theta < 1.05$) - left - and inclined showers ($1.15 < \sec\theta < 1.30$) - right. A good performance of the array is expected in all the simulated conditions (and that will be verified, at the lower energies, by the coincident data with the e/γ detector of KASCADE). Concerning the μ detectors, the same simulation gives a density

Detector	Channels	Separation(m)	Total area (m^2)	Threshold E_{kin}	Particle
Array e/γ	252	13	490	5 MeV	e
Array μ	192	13	622	230 MeV $\times \sec\theta$	μ
Trigger	456	-	208	490 MeV $\times \sec\theta$	μ
MWPCs	26080	-	129	2.4 GeV $\times \sec\theta$	μ
Calorimeter	44000	-	304	50 GeV	Hadrons
Muon Tunnel	24576	-	128	800 MeV	μ
Grande	74	$<$130$>$	370	3 MeV	e,μ
Piccolo	16	$<$25$>$	80	5 MeV	e,μ

Table 1. Most relevant parameters of detector components. Detection thresholds refer to the particle energies above the absorber material of the detectors.

	$1.00 < sec\theta < 1.05$				$1.15 < sec\theta < 1.30$			
	p		Fe		p		Fe	
	$10^{16}\ eV$	$10^{17}\ eV$	$10^{16}\ eV$	$10^{17}\ eV$	$10^{16}\ eV$	$10^{17}\ eV$	$10^{16}\ eV$	$10^{17}\ eV$
$Log(Ne)$	6.15	7.26	5.85	7.08	5.73	6.82	5.42	6.65
ϵ	0.99 ± 0.02	1.00 ± 0.02	0.99 ± 0.02	1.00 ± 0.02	0.98 ± 0.02	1.00 ± 0.02	0.94 ± 0.02	1.00 ± 0.02
$\Delta\ x$	$-0.07\ (m)$	$0.06\ (m)$	$-0.04\ (m)$	$0.01\ (m)$	$-0.04\ (m)$	$0.02\ (m)$	$-0.14\ (m)$	-0.16
$\sigma(x)$	$9.08\ (m)$	$5.32\ (m)$	$11.2\ (m)$	5.39	$9.08\ (m)$	$5.32\ (m)$	$11.2\ (m)$	5.39
$\Delta\ y$	$0.14\ (m)$	$0.04\ (m)$	$-0.09\ (m)$	$0.04\ (m)$	$-0.05\ (m)$	$-0.05\ (m)$	$-0.19\ (m)$	0.02
$\sigma(y)$	$6.1\ (m)$	$4.69\ (m)$	$7.13\ (m)$	$4.54\ (m)$	$8.60\ (m)$	$5.27\ (m)$	$10.6\ (m)$	5.23
$\Delta\ s$	-0.10	-0.03	-0.14	-0.04	-0.13	-0.04	-0.18	-0.05
$\sigma(s)$	0.09	0.07	0.10	0.08	0.10	0.07	0.11	0.07
$\Delta\ Ne\%$	0.6	1.3	-1.8	2.7	-13.1	-1.0	-28.4	-0.03
$\sigma(Ne\%)$	12.2	12.9	12.0	14.2	17.8	10.9	26.1	12.1

Table 2. Simulated reconstruction resolution (based on QGSJET) of the Grande array for near vertical events ($1.00 < \sec\theta < 1.05$) on the left and for inclined showers of $1.15 < \sec\theta < 1.30$ on the right. Numbers labelled Δ represent the average of (extracted - reconstructed) values. ϵ = efficiency, x and y = coordinates, s = age parameter and Ne = e.m. size.

of μ at 600 m from the core ($D_{\mu600}$) of about 0.1 m^{-2} for a $E_0 = 10^{17}$eV proton. Considering a detection area of about 800 m^2 it implies an average of 80 μ detected on a event by event basis meaning a statistical fluctuation of about 12%.

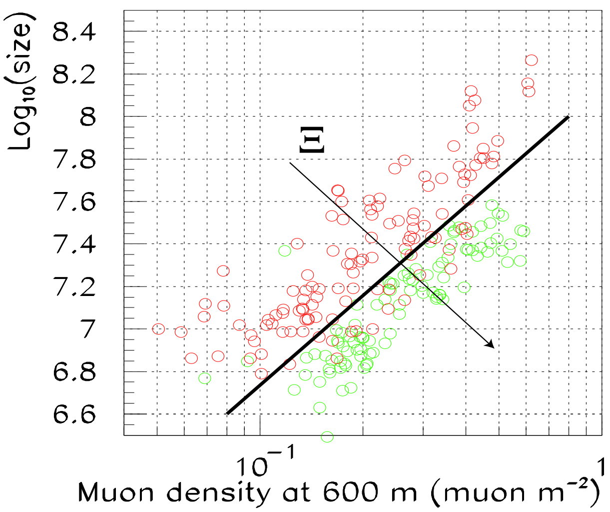

Fig. 3. QGSJET Simulations of proton and iron primaries in the energy range of $2 \cdot 10^{16} \leq E \leq 5 \cdot 10^{17}$ eV. The light symbols represent iron and the dark ones proton simulations. Both, shower fluctuations and experimental uncertainties are taken into account. The Ξ line is used as a guideline for the Ξ mass axis.

A Monte Carlo simulation, using the CORSIKA package, has been performed in order to check the experiment capabilities for testing the hadronic interaction models and reconstructing the mass of primary CRs through the three observables N_e, $D_{\mu600}$, and h_μ. An example is presented in fig.3. Here, the primary composition is defined in terms of the mass parameter Ξ, whose definition through N_e and $D_{\mu600}$ is shown in the same figure, in which N_e vs $D_{\mu600}$ scatter plots obtained for protons and iron primaries obtained from QGSJET simulations are shown. The line separating p and Fe primaries best is indicated in the figure. The mass axis, Ξ is thus shown orthogonal to this line. $D_{\mu600}$ is, as first approximation, used as energy estimator. The "iron knee" is identified as the saturation point ($D^{sat}_{\mu600}$) of the mass parameter Ξ vs $D_{\mu600}$, while the saturation level Ξ^{sat} depends on the low energy composition and the change in the spectrum of the individual components at the knee ($\Delta\gamma$). In figs. 4 and 5 the evolution of the mass parameter (Ξ) vs. primary energy ($D_{\mu600}$) is shown for different interaction models (QGSJET and HDPM), for $\Delta\gamma = 0.5$ and $\Delta\gamma = 0.7$ (that are realistic values obtained from the interpretation of the data in the $10^{15} - 10^{16}$ eV energy range, assumed equal for all primaries) and a rigidity dependent knee (at $5 \cdot 10^{15}$ eV for primary protons). The statistic and reconstruction accuracies are sufficient to obtain the quoted measurements with uncertainties $< 20\%$.

Concerning hadronic interaction models, their significant differences lead to different longitudinal developments. The average relation between h_μ and $D_{\mu600}$ for the interaction models used (HDPM and QGSJET) are shown in Fig. 6.

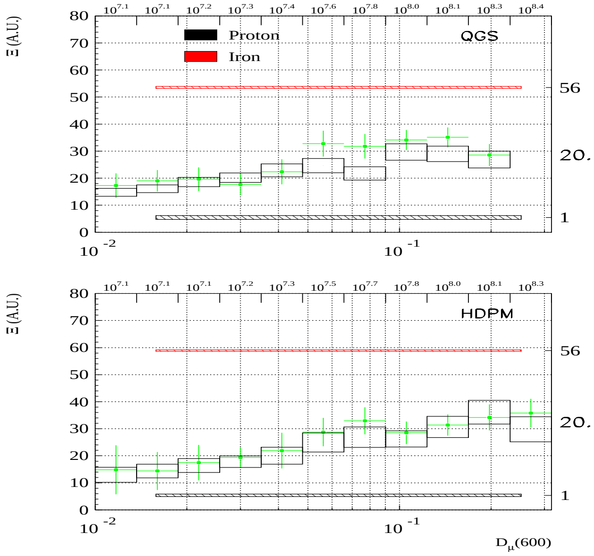

Fig. 4. Ξ vs μ density for a CMC composition model with a $\Delta\gamma$ = 0.5. Cross and boxes represent the input and reconstructed values. The top scale is expressed in GeV, while the bottom one in m^{-2}.

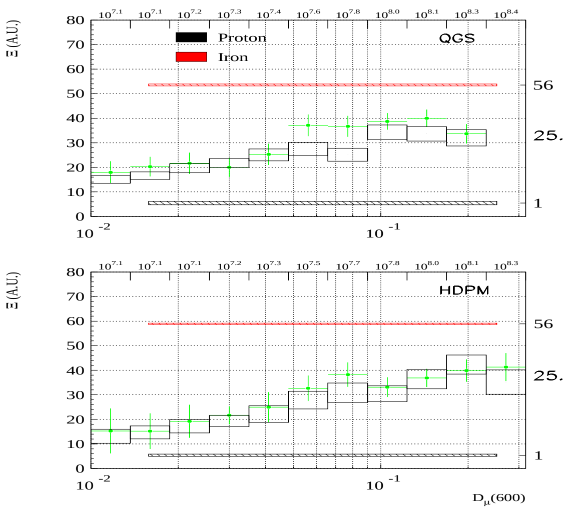

Fig. 5. Same as fig.4 but for $\Delta\gamma$ = 0.7.

At $D_{\mu600} \approx 0.1$ the accuracy $D_{\mu600}$ on individual events is $\approx 15\%$, and on $h_\mu < 100$ gcm^{-2}, thus a separation can be performed from the clustering of the events in the regions corresponding the two models for the different masses.

4 Conclusions

The main characteristics of a new experiment (KASCADE-Grande) that is being realized at the Forschungszentrum Karlsruhe as a joint application of the KASCADE and EAS-TOP detectors, by employing well understood and proven experimental techniques already applied at lower energies, are discussed. The apparatus will be completed in 2001, data taking is planned from 2002 to 2005. In three years of effective data taking it will accumulate sufficient statistics up to 10^{18} eV ($\approx 10^3$ events above $5 \cdot 10^{17}$ eV). This experiment will cover an energy range that is poorly known, essentially from old AKENO (Nagano et al. , 1984) and the lower tail of FLY'S EYE (Bird et al. , 1994) data. The task of the experiment is to give a conclusive answer on the structure of the knee, testing the rigidity dependent model up to the energies of the "iron" group. Moreover it will allow to test different hadronic models in an energy range not accessible to accelerators but important for CRs physics. Finally it will provide a bridge to the measurement and interpretation of CRs for experiments working at much higher energies like the Pierre Auger, HIRES or OWL-Airwatch Projects.

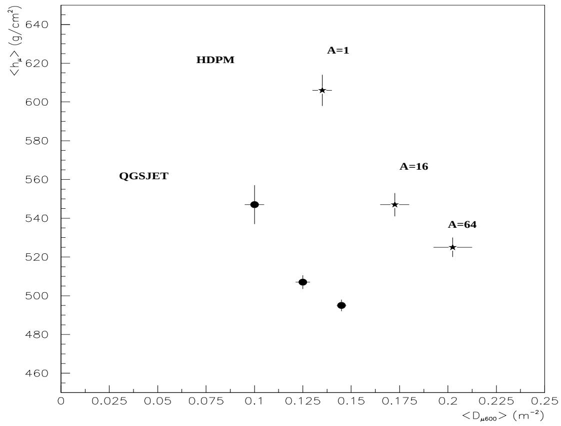

Fig. 6. Relation between $< h_\mu >$ and $D_{\mu600}$ for different interaction models and primary mass nuclei for primary energy $E_0 = (1-2) \cdot 10^{17}$ eV and 600 m from the EAS core.

Acknowledgements. The KASCADE-Grande experiment is supported by Forschungszentrum Karlsruhe and by collaborative WTZ projects in the frame of the scientific-technical cooperation between Germany and Romania (RUM 97/014) and Poland (POL 99/005). The Polish group (Soltan Institute and University of Lodz) aknowledges the support by the Polish State Committee for Scientific Research (grant No. 5 P03B 133 20). Special thanks are due to INFN for allowing the use of the EAS-TOP equipment to build the Grande array.

References

Aglietta M. et al, Nucl. Instr. Meth. A, 277, 23, 1989.
Aglietta et al, Proc. 26th ICRC, HE-2.2.05, 1999.
Bird D.J. et al., Astrophys. J., 424, 491, 1994.
Glasstetter R. et al, Proc. 26th ICRC, HE-2.2.03, 1999.
Hörandel J.R. et al, Proc. 26th ICRC, HE-2.2.41, 1999.
Klages H.O. et al, KASCADE Collaboration, Nucl. Phys. B, Proc. Suppl. 52B, 92, 1997.
Nagano M. et al., J. Phys. G, 10, 1295, 1984.
Roth M. et al, Proc. 26th ICRC, HE-2.2.40, 1999.
Weber J.H. et al, Proc. 26th ICRC, HE-2.2.42, 1999.
Zabierowski J. et al, KASCADE Collaboration, Proc. 27th ICRC, HE-1.8.32, 2001.