

# RECENT RESULTS FROM KASCADE-GRANDE

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## Abstract

KASCADE-Grande is a new extensive air shower experiment co-located to the KASCADE site at Forschungszentrum Karlsruhe. The multi-detector system allows to investigate the energy spectrum, composition, and anisotropies of cosmic rays with unprecedented precision in the energy range from  $10^{14}$ - $10^{18}$  eV. The primary goals besides investigating the origin of the knee at  $E \simeq 3 \cdot 10^{15}$  eV, are to verify the existence of the second knee at  $E \sim 10^{17}$  eV and to measure the composition in the expected transition region of galactic to extragalactic cosmic rays. The performance of the apparatus and shower reconstruction methods will be discussed on the basis of detailed Monte Carlo simulations and first data. First results based on slightly more than a year of data taking are presented.

## 1 Introduction

Despite intense research over several decades and measuring an impressive set of cosmic ray (CR) data, the origin of non-solar CRs remains unknown. As an example about the available data, Fig. 1 shows the so called *all-particle* spectrum. It has become standard practice to present the spectral data as the flux  $dJ/dE$  times a power of the energy  $E$ , so that the visibility of spectral features is emphasized. The most prominent feature in the spectrum is the *knee* at about  $3 \cdot 10^{15}$  eV where the index  $\gamma$  of the power law spectrum  $dJ/dE \propto E^{-\gamma}$  changes from  $\gamma \simeq 2.75$  to  $\simeq 3.1$ . The origin of this phenomenon is still unknown, but it is generally attributed to either the limiting energy of galactic CR accelerators and/or to the onset of strong diffusion losses of particles out of our Galaxy. Also, particle physics explanations have been put forward, either assuming the onset of a new interaction mechanism above the knee energy so that part of the CR-energy remains invisible to experiments or by considering propagation effects between the sources and the solar system. Generally, supernova remnants (SNR) are conceived to be the major sources for CRs up to the knee with the acceleration taking place by the first order Fermi mechanism. Based on simple dimensional arguments, the maximum energy would then be given by  $E_{\max} \propto Z \cdot R \cdot B$ , with  $Z$  being the charge of the CR particle and  $R$  and  $B$  being the size and magnetic field of the source, respectively. As a consequence, the knee position for different CR primaries would be expected to scale with their atomic number  $Z$ . Similarly, diffusion losses out of the Galaxy would result in a  $Z$  dependence of the knee position, since magnetic confinement is the underlying process. For a recent review on astrophysical models, the reader is referred to [1]

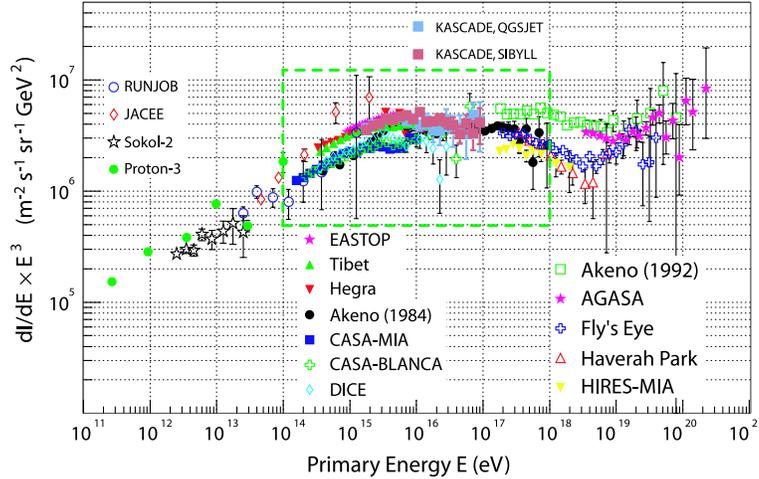


Figure 1: The all-particle CR energy spectrum weighted by  $E^3$  showing the knee at  $3 \cdot 10^{15}$  eV, a possible second knee at  $\sim 10^{17}$  eV, and the ankle at about  $3 \cdot 10^{18}$  eV. The energy range covered by KASCADE-Grande is indicated by the dashed box.

and references therein. Particle physics models generally predict a scaling of the knee energy with the atomic mass  $A$ , since the reaction mechanism at high energies is governed by the energy per nucleon rather than by the total energy of the CR particles. More recently, the cannonball (CB) model was suggested to explain the origin of all non-solar CRs [2]. It predicts a scaling of the knee position with  $A$  rather than with  $Z$ , because of deflections of CRs at the relativistically moving CBs. In any of the astrophysical models, light particles drop out of the acceleration and/or confinement region first – this is what should cause the knee – so that the composition is expected to change from light to heavy when crossing the knee energy.

A naïve extrapolation of this idea suggests that the putative second knee would mark the position of the Fe-knee. No consensus on a preferred accelerator site or mechanism exists for the energies between the (second) knee and ankle. It has long been argued that CRs above the ankle are of extragalactic origin, as they cannot be isotropized by the Galactic magnetic fields, but their arrival directions are surprisingly isotropic. At the highest energies, above  $5 \cdot 10^{19}$  eV, the GZK<sup>1</sup> cut-off is expected. Because of the low flux involved, such energies cannot be measured with KASCADE-Grande. This is the domain of the Pierre Auger Observatory [3].

<sup>1</sup>Greisen, and Zatsepin & Kuzmin

## 2 The KASCADE-Grande Experiment

The multi-detector system KASCADE-Grande (KARlsruhe Shower Core and Array DETector and Grande array) is optimized for the energy range  $10^{14}$  -  $10^{18}$  eV and addresses the questions of the previous section by measuring as much as possible from each single air-shower event [4, 5]. The main detector components of KASCADE-Grande are the KASCADE array, the Grande array, the Central Detector, and the Muon Tracking Detector.

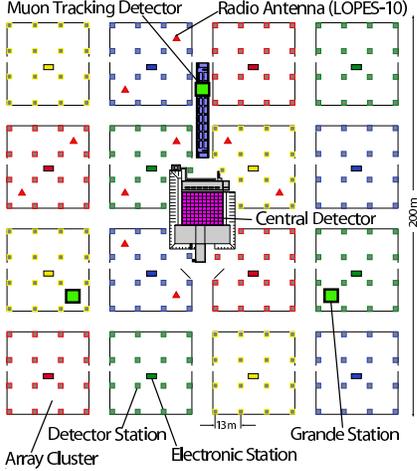


Figure 2: The main detector components of the KASCADE experiment: (the 16 clusters of) Field Array, Muon Tracking Detector and Central Detector. The location of 10 radio antennas is also displayed, as well as three stations of the Grande array.

The KASCADE array (Fig. 2) measures the total electron and muon numbers ( $E_\mu > 230$  MeV) of the shower by using an array of 252 detector stations containing both shielded and unshielded detectors located on a grid of  $200 \times 200$  m<sup>2</sup> [6]. The excellent timing resolution of these detectors allows also investigations of the arrival directions of the showers in searching for large scale anisotropies [7] as well as for cosmic ray point sources [8]. The KASCADE array is optimized to measure extensive air showers (EAS) in the energy range of  $10^{14}$  eV to  $8 \cdot 10^{16}$  eV and has provided for the first time energy spectra of CR mass groups [9]. The Muon Tracking Detector ( $128$  m<sup>2</sup>) measures the incidence angles of muons ( $E_\mu > 800$  MeV) relative to the shower arrival direction [10]. These measurements provide a sensitivity

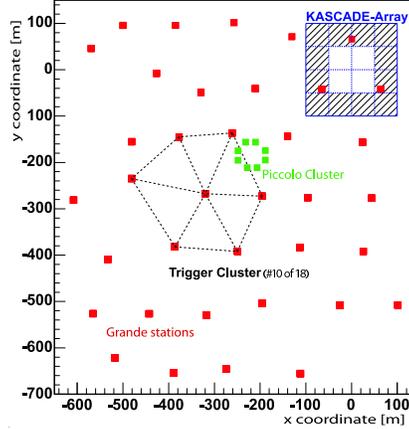


Figure 3: Layout of the KASCADE-Grande experiment with its 37 Grande and 8 Piccolo stations. One of the 18 Grande trigger hexagons is also shown.

to the longitudinal development of the showers.

Muons with energies above 2.4 GeV are measured in the 300 m<sup>2</sup> large central detector by a multiwire proportional chambers (MWPC) and limited streamer tubes (LST).

The 37 stations of the Grande Array (Fig. 3) extend the cosmic ray measurements up to primary energies of 1 EeV. The Grande stations, 10 m<sup>2</sup> of plastic scintillator detectors each, are positioned at an average mutual distance of approx. 130 m covering a total area of  $\sim 0.5$  km<sup>2</sup>. There are 16 scintillator sheets in a station read out by 16 high gain photomultipliers; 4 of the scintillators are read out also by 4 low gain PMs. The covered dynamic range is up to 3000 mips/m<sup>2</sup>. A trigger signal is build when 7 stations in a hexagon (trigger cluster, see Fig. 3) are fired. Therefore, the Grande array consists of 18 hexagons with a total trigger rate of 0.5 Hz.

Additionally to the Grande Array a compact array, named Piccolo, has been build in order to provide a fast trigger to KASCADE ensuring joint measurements for showers with cores located far from the KASCADE array. The Piccolo array consists of 8 stations with 11 m<sup>2</sup> plastic scintillator each, distributed over an area of 360 m<sup>2</sup>. One station contains 12 plastic scintillators organized in 6 modules; 3 modules form a so-called electronic station providing ADC and TDC signals. A Piccolo trigger is built and sent to KASCADE and Grande when at least 7 out of the 48 modules of Piccolo are fired. Such a logical condition leads to a trigger rate of 0.3 Hz.

The trigger and reconstruction efficiency of KASCADE-Grande is depicted in Fig. 4 [11]. Full efficiency is reached already at around 10<sup>16</sup> eV so that a significant region of overlap for cross-checks is attained with KASCADE.

Presently, a self-triggering, dead-time free FADC-based DAQ system is being implemented in order to record the full time evolution of energy deposits in the Grande stations at an effective sampling rate of 250 MHz and high resolution of 12 bits in two gain ranges [13]. This system runs in parallel to the present data acquisition system and will allow for an intrinsic electron-muon separation by the time traces measured in the Grande stations.

The whole KASCADE-Grande setup is read out if a certain multiplicity of the KASCADE, Piccolo, or the Grande array detector stations is firing, leading to a total trigger rate of  $\approx 4.5$  Hz.

The redundant information of the showers measured by the Central Detector and the Muon Tracking Detector is predominantly being used for tests and improvements of the hadronic interaction models underlying the analyses [14].

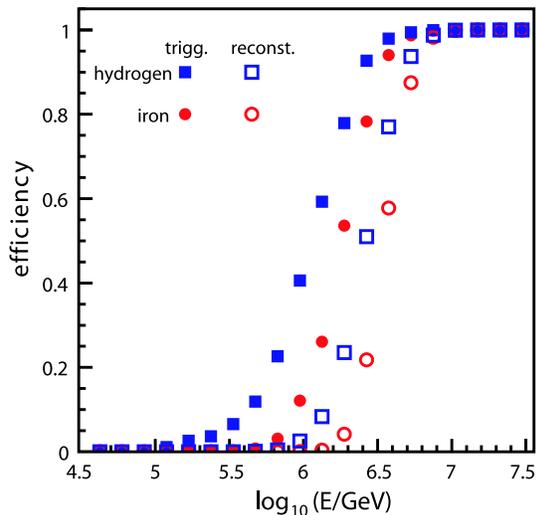


Figure 4: Trigger and reconstruction efficiency for Hydrogen and Iron induced EAS (zenith angles  $< 18^\circ$ ) as function of primary energy.

For the calibration of the radio signal emitted by the air shower in the atmosphere an array of first 10 and meanwhile 30 dipole antennas (LOPES) is set up on the site of the KASCADE-Grande experiment [15, 16].

### 3 Shower Reconstruction

The key observables for reconstruction the primary energy and mass of CRs are given by the electron and muon numbers at ground. The KASCADE detector stations allow for a separation of electrons and muons because of a 20 radiation lengths shielding used above the muon counters. In case of the KASCADE-Grande stations such shielding was not available, so that at present only numbers of *charged particles* can be obtained. This will change in the future with the availability of the FADC readout system [13]. For the time being, the muon numbers are obtained relatively locally from the KASCADE array. The shower geometry of EAS landing within the fiducial area of Grande are reconstructed by the particle densities and timing information of the Grande stations and the muons are extracted from the muon densities measured in KASCADE. An important step in such an analysis is the determination of the lateral density distributions (LDF) of electrons and muons. In hadronic induced air showers especially at large core distances a

slightly modified NKG<sup>2</sup>-function is used for the electrons:

$$\rho_e = N_e \cdot C(s) \cdot \left(\frac{r}{r_0}\right)^{s-\alpha} \left(1 + \frac{r}{r_0}\right)^{s-\beta}, \quad (1)$$

with the normalization factor  $C(s) = \Gamma(\beta - s)/\Gamma(s - \alpha + 2)/\Gamma(\alpha + \beta - 2s - 2)/(2\pi r_0^2)$ , the shower size  $N_e$ , and the so-called shower age  $s$ . Performing CORSIKA [17] simulations and taking into account the experimental response of the Grande array, the parameters  $\alpha = 1.5$ ,  $\beta = 3.6$ , and  $r_0 = 40$  m were found to describe the lateral distribution function best [18]. The same set of parameters also provides a better description of the high precision KASCADE data, as was pointed out recently [19]. Such a deviation is not surprising, since the traditional NKG-formula with  $\alpha = 2$ ,  $\beta = 4.5$  and  $r_0 = 89$  m has been derived analytically for the case of pure  $e/\gamma$ -showers.

To describe the average arrival time  $\bar{t}$  and the time spread  $\sigma_t$  of the shower electrons, a Linsley-function has been adapted to the time distributions of pure CORSIKA simulations [18]:

$$\bar{t} = 2.43 \cdot \left(1 + \frac{r}{30 \text{ m}}\right)^{1.55} \quad \text{and} \quad \sigma_t = 1.43 \cdot \left(1 + \frac{r}{30 \text{ m}}\right)^{1.39}$$

The parameters were found to depend only weakly on the primary particle properties. To first order approximation the measured arrival time of the first out  $N$  of particles inside a detector is given by  $\bar{t}_{1.\text{of } N} = \bar{t}/\sqrt{N}$ .

Since the functions above are coupled via the particle number and the core distance in shower disc coordinates, they are fitted simultaneously to the data in a combined neg.-log-likelihood/ $\chi^2$  minimization. For the calculation of the expected particle density in a Grande station a contribution from the previously reconstructed muon lateral distribution function is taken into account. Thus, the free 7 parameters of the global fit are the core position and shower direction (incl. a global time offset), as well as the electron number ( $E_{kin} > 3$  MeV) and shower age. For the muon LDF a parametrization similar to [20] has been used:

$$\rho_\mu = N_\mu \cdot \frac{0.28}{r_0^2} \left(\frac{r}{r_0}\right)^{p1} \cdot \left(1 + \frac{r}{r_0}\right)^{p2} \cdot \left(1 + \left(\frac{r}{10 \cdot r_0}\right)^2\right)^{p3} \quad (2)$$

with  $r_0 = 320$ m and  $p1 = -0.69$ ,  $p2 = -2.39$ ,  $p3 = -1.0$  when averaging the fits to the LDF in the energy range  $10^{16}$  eV -  $10^{17}$  eV [12, 11]. The result of  $\rho_e + \rho_\mu$  fitted to the data by eqns. 1 and 2 is shown Fig. 5.

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<sup>2</sup>NKG = Nishimura, Kamata, Greisen

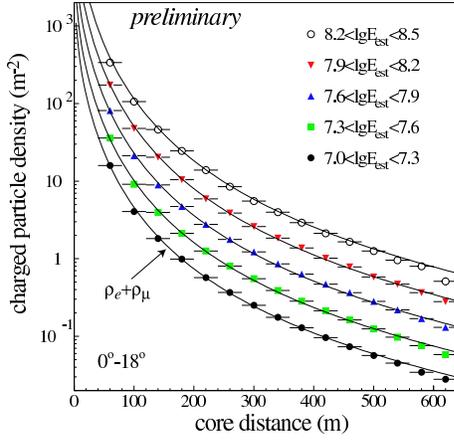


Figure 5: Measured lateral distribution of the charged particle component for five estimated energy intervals [18]. The lines represent the sum of the LDFs of eqn. 1 and 2 fitted to the data.

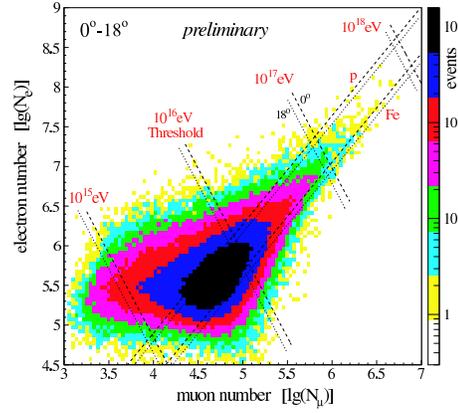


Figure 6: Reconstructed electron and muon numbers from KASCADE-Grande. The dashed line pairs indicate average lines of constant energy and mass derived from CORSIKA simulations for the extreme zenith angles.

The reconstruction quality has been studied extensively in Ref. [18]. Above a threshold of  $10^6$  electrons corresponding to 100% trigger efficiency the shower core and direction resolution is reconstructed to better than 12 m resp.  $0.6^\circ$  and they improve to better than 8 m resp.  $0.4^\circ$  at  $10^7$  electrons. At the same time, the statistical uncertainties of the electron and muon numbers are below  $\Delta \log N_{e,\mu} = 10\%$  and  $20\%$ , respectively. Systematic deviations are always well below the statistical accuracy of the experiment.

The resulting distribution of electron and muon numbers is presented in Fig. 6 for zenith angles below  $18^\circ$ . Even though full efficiency is only obtained at  $10^{16}$  eV, most events are recorded at lower energies which is due to the steeply falling energy spectrum of CRs. The dashed line pairs indicate energy and mass ranges as derived from CORSIKA simulations for zenith angles of  $0^\circ$  and  $18^\circ$  and using the relation presented in the next section.

## 4 First Data

The data presented in the following were taken from March 2004 to March 2006. Due to calibrations and tests at KASCADE-Grande still going on, this corresponds to an effective data taking time of 363 days when accepting only periods where both KASCADE and KASCADE-Grande were operating with all components and without failures. During this period approximately

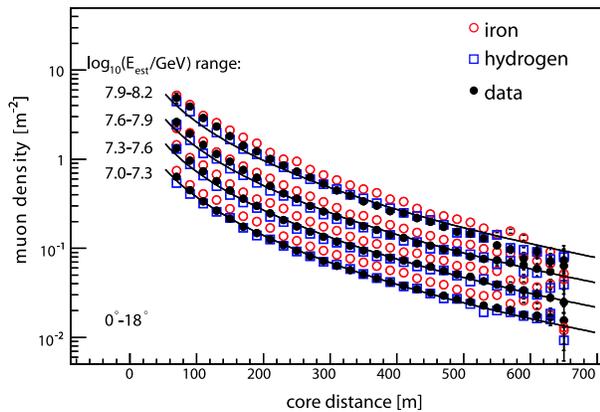


Figure 7: Measured and simulated muon density distribution for zenith angles  $0^\circ$ - $18^\circ$  and four estimated energy intervals [11]. The lines represent the LDF of eqn. 2.

15.1 million events have been registered by the Grande array. In order to be considered in this preliminary analysis, at least 20 Grande stations with measured energy deposits were requested with the reconstructed shower core to be within a circle of 250 m radius around the center of the Grande array. The reconstructed age parameter was restricted to  $0.4 < s < 1.4$ . These cuts are applied to reduce the effect of misreconstructed cores at the border of the array, especially from showers being originally outside the Grande array and to ensure good electron size reconstruction also at the trigger threshold. It has been verified by simulations that these cuts do not result in an increase of the energy threshold of the experiment. Still, 100 % efficiency is maintained both for proton and iron primaries at  $E \geq 10^{16}$  eV which provides a large region of overlap with the KASCADE data. However, the total number of events in the sample is reduced by these cuts to  $6.50 \cdot 10^4$  and  $4.67 \cdot 10^4$  for zenith angles  $0^\circ$ - $18^\circ$  and  $18^\circ$ - $25^\circ$ , respectively.

Figure 7 presents the measured muon LDFs for different primary energies in comparison to CORSIKA simulations for proton and iron primaries. The energy has been estimated from the electron and muon numbers by

$$\log_{10}(E_{\text{est}}/\text{GeV}) = 0.313 \cdot \log_{10} N_e + 0.666 \cdot \log_{10} N_\mu + 1.24/\cos\theta + 0.580.$$

Generally, the agreement between data and MC is very good with data being always contained between p and Fe simulations. The LDF (eq. 2) describes the data reasonable well up to  $\sim 10^{17}$  eV but appears somewhat too flat at higher energies.

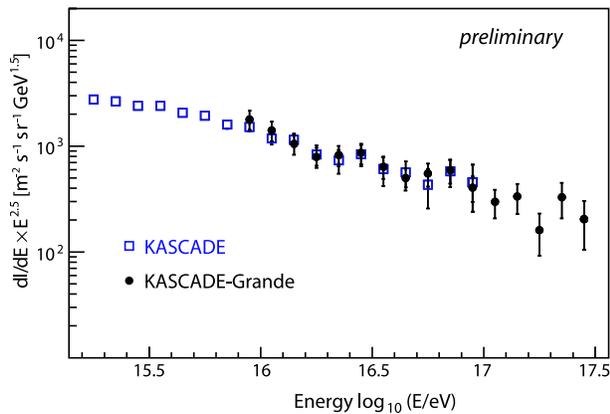


Figure 8: Unfolded all-particle energy spectrum of KASCADE-Grande compared to data of KASCADE from Ref. [9] for QGSJet based CORSIKA simulations and for zenith angles  $0^\circ \leq \theta \leq 18^\circ$ . The data correspond to one year of KASCADE-Grande and are of preliminary nature.

In Ref. [9] we have emphasized the importance of unfolding algorithms for the reconstruction of the energy and mass of cosmic rays. This is because of the large fluctuations of shower observables affecting any measurement in the presence of steeply falling spectra. Because of the preliminary nature of the data, we have not yet attempted a 2-dimensional unfolding of the electron and muon numbers such as in Ref. [9]. However, since the primary energy is mostly determined by the muon number with only a weak dependence on the primary mass, an unfolding of the muon size spectrum can be used as a first step to determine the CR energy spectrum at energies beyond the KASCADE range. Again, the iterative Gold algorithm was employed. As an example, Fig. 8 shows the results of unfolding for the zenith angle range  $0^\circ \leq \theta \leq 18^\circ$ . The error bars of the total spectrum indicate the total statistical error as squared sum of Poissonian statistics and those resulting from the unfolding. The results are compared with previous ones from KASCADE and are also based on the QGSjet assumption. One observes a very good overlap in the energy range of  $10^{16}$  eV to  $10^{17}$  eV. The KASCADE-Grande energy spectrum reaches up to an energy of  $3 \cdot 10^{17}$  eV. The statistics is still too poor to draw any conclusion about a second knee. The quality of the solution can be characterized by the  $\chi^2$  value, which is obtained by folding the solution with the response matrix and comparing the resulting vector with the original data vector. For the first and second zenith angle ranges one obtains  $\chi^2/\text{dof} = 2.59$  and  $2.25$  respectively, indicating the still imperfect description of the data. This is expected to improve with the

presently applied new calibration of the Grande stations.

## 5 Summary and Conclusions

KASCADE-Grande has started to take data. All components are working stable and perform well. The presently installed FADC system will extend its capabilities and provide detailed information about the longitudinal profile of the shower disk and allow for additional electron - muon separation. The LDFs of both electrons and muons are found to agree well with EAS simulations. From their obtained electron and muon numbers a first estimate of the primary energy spectrum could be derived. Within the overlap region with KASCADE, a good agreement is found. However, the statistics beyond  $3 \cdot 10^{17}$  eV is still too poor to allow conclusions about the second knee. This will change in the near future with more data becoming available. KASCADE-Grande keeps the multi-detector concept for tuning different interaction models at primary energies up to  $10^{18}$  eV. It also provides a perfect environment for detecting radio emission in extensive air showers, which is the aim of the LOPES project [16].

### Acknowledgments

KHK wishes to thank the organizers for their invitation to the Vulcano workshop conducted in a very pleasant and fruitful atmosphere. KASCADE-Grande is supported by the Ministry for Research and Education of Germany, the INFN of Italy, the Polish State Committee for Scientific Research (KBN grant for 2004-06) and the Romanian National Academy for Science, Research and Technology.

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