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Cosmic Rays and Particle Physics

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Abstract. The study of high energy cosmic rays is a diversified field of observational and phenomenological physics addressing questions ranging from shock acceleration of charged particles in various astrophysical objects, via transport properties through galactic and extragalactic space, to questions of dark matter, and even to those of particle physics beyond the Standard Model including processes taking place in the earliest moments of our Universe. After decades of mostly independent evolution of nuclear-, particle- and high energy cosmic ray physics we find ourselves entering a symbiotic era of these fields of research. Some examples of interrelations will be given from the perspective of modern Particle-Astrophysics and new major experiments will briefly be sketched.

1. Introduction

Cosmic rays (CRs) were discovered in 1911 by Victor Hess through a series of balloon flights in which he carried electrometers to over 5000 m [1]. Originally being thought of as penetrating γ-radiation, in the late twenties Compton and others realized that CRs mainly consist of charged particles. By performing coincidence measurements in 1938 using Geiger counters at mountain altitudes and later also at sea level in Paris, Pierre Auger discovered the phenomenon of “extensive air showers”; A high energy CR entering the atmosphere initiates a cascade of secondary particles which is large enough and sufficiently penetrating to reach ground level. From his observations, Pierre Auger already concluded that primary particles up to energies of 10^{15} eV are found in CRs, and speculations were raised how to generate particles of such high energy. Present day simulations predict that, e.g. a single 10^{15} eV CR particle produces about 10^6 secondary particles at sea level, mainly photons and electrons plus some muons and hadrons being spread out over about a hectare. Indeed, the present particle physics has taken origin from the observations and measurements of CRs performed in the first half of our century, starting from the discovery of the positron in 1932, muons in 1937, to that of pions and strange particles (Λ and K) in 1947,

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Ξ^- and Σ^+ in 1952-53, and possibly even to the discovery of charm in 1971 [2]. On the other hand, nuclear and particle physics have also provided important input to CR physics. For example, data of nuclear spallation cross sections measured at accelerators turned out to be a key for understanding the propagation of CRs in our galaxy. Also, phenomenological prescriptions of high energy p+p, p+A and A+A interactions and the modelling of a Quark-Gluon Plasma state enter directly into Monte Carlo simulations of extensive air showers. Now, when the physics of accelerators is starting to fight against both technological and financial limitations, we see that new interest is flowing back to the origins [3]. In fact, many fundamental and unresolved questions are still presented to us by the cosmic radiation, and this is particularly true for the extremely high energies.

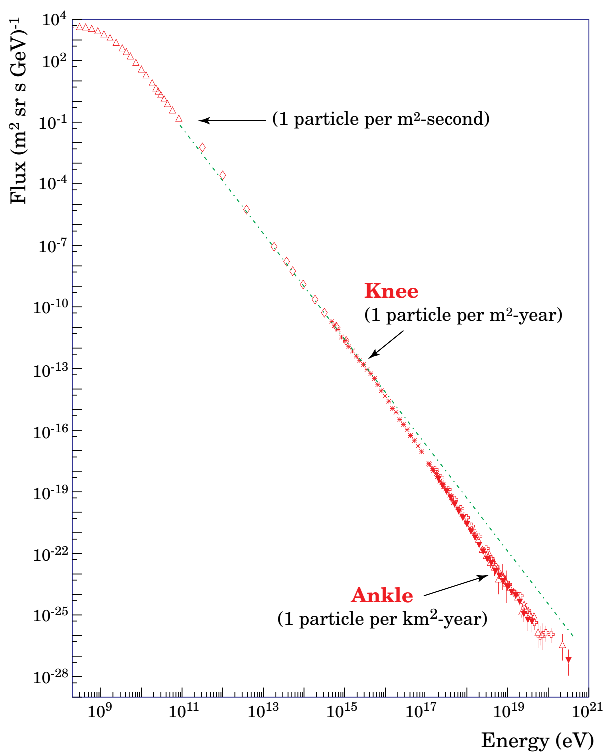

Fig. 1. The cosmic ray all particle spectrum (adapted from Ref. [4]). Approximate integral fluxes are indicated.

We know that the CR energy spectrum extends from below 1 GeV to above 10^{20} eV. The bulk of CRs up to at least an energy of some PeV (10^{15} eV) is believed to originate within our galaxy. Above that energy, which is associated with the so called "knee", the differential energy spectrum of particles steepens from a power law $E^{-2.7}$ to about $E^{-3.2}$. Above the so called "ankle" at $E \simeq 5 \cdot 10^{18}$ eV, the spectrum flattens again to about $E^{-2.8}$. This feature is often interpreted as the cross-over from a steeper galactic to a harder extra-galactic component. Figure 1 shows the measured CR spectrum.

Up to energies of some 10^{14} eV the flux of particles is sufficiently high so that their elemental distributions can be studied by high flying balloon or satellite experiments. Such measurements have provided important implications for the origin and transport properties of CRs in the interstellar medium. Two prominent examples are ratios of secondary to primary elements, such as the B/C-ratio, which are used to extract the average amount of matter CR-particles have traversed from their sources to the solar system (5 - 10 g/cm^2), or are radioactive isotopes, e.g. ^{10}Be or ^{26}Al, which carry information about the average 'age' of cosmic rays ($1 - 2 \cdot 10^7$ a).

Above a few times 10^{15} eV the flux has dropped to only one particle per m^2 and year. This excludes any type of 'direct observation' even in the near future, at least if high statistics is required. Ironically, one of the most prominent features of the CR energy spectrum, the knee, is at an energy just above some 10^{15} eV. It was observed already in 1956 [5] but it still remains unclear as to what is the cause of this spectral steepening. In the standard model of CR acceleration the knee is attributed to the maximum energy of galactic accelerators mostly believed to be supernova remnants in the Sedov phase.

The other target of great interest is the energy range around the Greisen-Zatsepin-Kuzmin (GZK) effect at $E \simeq 5 \cdot 10^{19}$ eV. Data currently exist, though with very poor statistics, up to $3 \cdot 10^{20}$ eV and there seems to be no end to the energy spectrum [6, 7]. Explanation of these particles requires the existence of extremely powerful sources within a distance of approximately 50-100 Mpc. Hot spots of radio galaxy lobes – if close enough – or topological defects from early epochs of the universe would be potential candidates.

Obviously, the topic of cosmic rays is very wide and deeply related to many fields of physics, ranging from hydrodynamics and astronomy via nuclear- and elementary particle physics to questions of cosmology. Experimentally, the topics addressed by cosmic rays are closely related to TeV γ- and ν-astronomy, and to some aspects of dark matter searches, all of which became known as "Particle-Astrophysics". Since the limited length of this paper excludes giving a comprehensive review about all of these many interesting facets, we shall pick only a few examples from different cosmic ray energy ranges and discuss some experimental aspects.

2. The Question of Dark- and Antimatter

The questions for dark matter as a major contributor to the energy density of the Universe or the Universe being a patchwork consisting of distinct regions of matter and antimatter are among the most fundamental ones in cosmology. Both of them are related to CR measurements in different regions of energy. In this section, we will discuss examples of direct observations on balloons and satellites.

A representative detector of this type is the Japanese BESS spectrometer. The main parameters and components of this detector are the 1 Tesla magnetic field produced by a thin (4 g/cm^2) superconducting coil filling a tracking volume equipped with drift chambers providing up to 28 hits per track with an acceptance of 0.3 m^2 sr. In addition, two hodoscopes provide dE/dx and time-of-flight measurements. A series of flights performed between 1993 and 1998 yielded at total 848 $\bar{p}$'s in the energy range 0.18 - 4.2 GeV. Their energy spectrum is shown in figure 2 [8]. The observed peak around 2 GeV is a generic feature of secondary $\bar{p}$'s which are produced by the interaction of galactic high energy cosmic rays with the interstellar medium. Both the shape of the energy spectrum and the absolute flux is well reproduced by several theoretical calculations [9, 10] using $\bar{p}$-production cross sections from nuclear physics experiments [11]. However, there remains some diversity about the calculations in the low energy region. The indication of an excess of antiprotons below 0.5 GeV has received growing attention since its first observation by BESS in 1993. Possible sources are the annihilation of neutralinos at the galactic centre or the evaporation of primordial black holes (PBH). The latter may have been formed with arbitrarily small masses during virulent conditions in the early Universe [12], e.g., by the collapse of large density perturbations [13, 14]. Data constraining PBH abundances will thus yield constraints on the density fluctuation spectrum in the early Universe, an important ingredient to structure formation theories. For $M_{PBH} \lesssim 4 \cdot 10^{13}$ g (typical mass of mountain) the evaporation process will result in relativistic quarks and gluons which may produce antiprotons during hadronisation. The expectation for the flux of antiprotons from this process is a spectrum increasing towards lower kinetic energies down to $\sim$0.2 GeV [15]. Another strategy to look for dark matter particles is via annihilation of neutralinos at the galactic centre; $\chi\chi \rightarrow \ell^+\ell^-, q\overline{q} \rightarrow \overline{p}, e^+, \gamma, \nu$. The $\overline{p}$ flux from this source is characterized by a significant flux below 1 GeV [16]. The uncertainty of the expected secondary flux due to the uncertainty of CR propagation in the Galaxy, however, is at present still of the same order of magnitude as the signal expected from these ‘primary’ sources.

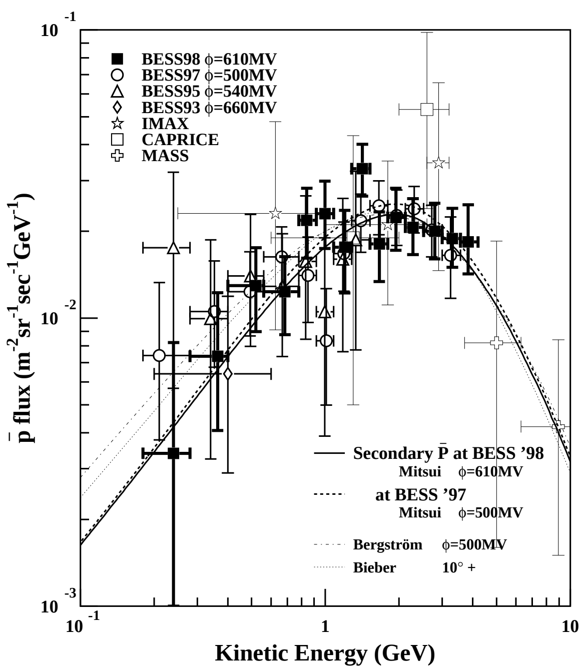

Fig. 2. The BESS 1998 antiproton fluxes measured at the top of the atmosphere. The thick solid curve represents the expected spectrum for secondary $\overline{p}$ at the 1998 flight. Also shown are other previously existing data and calculations [16, 10] for secondary $\overline{p}$ at solar minimum. From Ref. [8].

Measurements of antiparticles are directly linked also to the search for primordial antimatter. The laws of physics treat matter and antimatter almost symmetrically, and yet the stars, dust and gas in our celestial neighbourhood consist exclusively of matter. The absence of annihilation radiation from the Virgo cluster shows that little antimatter is found within typical sizes of galactic clusters and many cosmologists assume that the local dominance of matter persists throughout the entire visible universe. However, observational evidence for a universal baryon asymmetry is weak.

As most of the $\overline{p}$'s originate from CR interactions with the interstellar medium, the search for signatures of antimatter mostly concentrates on antinuclei with $|Z| \geq 2$. Although $\overline{He}$ might in principle also be produced in high energy cosmic ray interactions, their contribution to the $\overline{He}^4/He^4$ ratio is expected to be much smaller than 10^{-12}. From the absence of any candidate event, the BESS team [17] deduced an upper limit on $\overline{He}^4/He^4$ of 10^{-6} at rigidities between 1 and 16 GV/c. Similar values have been quoted from a test flight of the Alpha Magnetic Spectrometer (AMS) on the Space Shuttle [18]. These results provide the best evidence for the Galaxy and nearby Universe being made up solely of matter. Future experiments of BESS or AMS on the space station aim at at limit of $\overline{H}e^4/He^4 \leq 10^{-8}$ probing the antimatter contents of the Universe to more than 150 Mpc.

Finally, absolute fluxes of proton, helium, and atmospheric muons are important also for the derivation of the neutrino oscillation parameters e.g. from Super-Kamiokande [19], since the atmospheric neutrino flux is proportional to the normalization of the dominating CR proton and helium fluxes. Presently, new balloon borne experiments are in preparation to reduce particularly the uncertainties of the muon flux at different atmospheric depths. This is of great importance also for upcoming long-baseline neutrino experiments and is a good example of the interconnection between cosmic ray and particle physics.

3. Extensive Air Showers and High Energy Interactions

Cosmic ray measurements at energies above some 10^{14} eV are performed by large area air shower experiments. An extensive air shower (EAS) is a cascade of particles generated by the interaction of a single high energy primary cosmic ray nucleus or nucleon near the top of the atmosphere. The secondary particles produced in each collision, mostly charged and neutral pions and kaons, may either decay or interact with another nucleus, thereby multiplying the number of particles within an EAS. After reaching a maximum in the number of secondary particles, the shower attenuates as more and more particles fall below the threshold for further particle production. A disk of relativistic particles extended over an area with a diameter of some tens of metres at 10^{14} eV to several kilometres at 10^{20} eV can then be observed at ground. This magnifying effect of the earth atmosphere allows to instrument only a very small portion of the EAS area and to still reconstruct the major properties of the primary particles. It is a lucky coincidence that at the energy where direct detection of CRs rays becomes impractical, the resulting air showers become big enough to be easily detectable at ground level. Due to the nature of the involved hadronic and electromagnetic interactions and the different decay properties of particles, an EAS has three components, electromagnetic, muonic, and hadronic. Extracting the primary energy and mass from such measurements is not straightforward and a model must be adopted to relate the observed EAS parameters (total number of electrons, muons, hadrons, shapes of their lateral density distributions, reconstructed height of the shower maximum, etc.) to the properties of the primary particle [20]. A large body of experimental data from heavy-ion collisions studied at CERN and Brookhaven and from pp-collisions studied at the CERN SPS and Fermilab Tevatron is available and has been used to constrain the phenomenological QCD-inspired models entering EAS simulations. However, CR interactions above the knee are already beyond the maximum CMS-energy of the Tevatron. Furthermore, the very forward kinematic region being mostly relevant to the propagation of air showers is basically uncovered by collider experiments. Finally, effects of possible quark-gluon plasma formation may affect EAS observables [21]. Testing air shower simulations and thereby hadronic interaction models by means of EAS data thus is of interest for particle and CR physics.

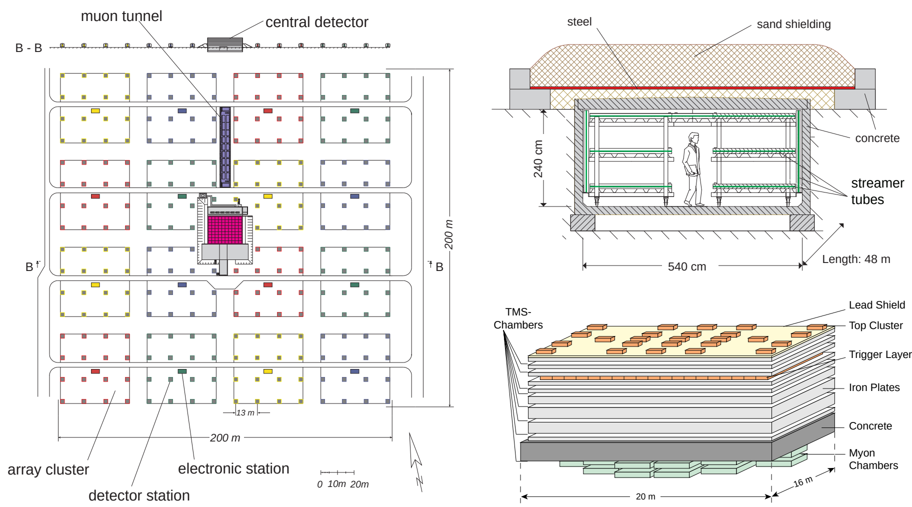

Fig. 3. Schematic layout of the KASCADE experiment (left), with its streamer tube tracking system (top right) and central detector (bottom right) [22].

The KASCADE experiment at Forschungszentrum Karlsruhe (Germany), shown in Fig. 3, is a 200×200 m^2 multi-detector installation measuring all of the three EAS components simultaneously [22]. It comprises 252 detector stations housing electron-gamma and muon detectors, a 48×5.4 m^2 tunnel for muon tracking, and a 320 m^2 large central detector consisting of a finely segmented hadronic calorimeter (11 λ_I) with additional muon detection capabilities. The major goal of the experiment is to measure the energy spectrum and chemical composition of CRs in the energy range of the knee and to allow for tests of the aforementioned interactions models. High energy hadrons ($E \gtrsim 100$ GeV) observed at ground by means of the hadronic calorimeter are easily recognized to provide the best test bench for these models. To perform such tests, the KASCADE collaboration has followed different approaches. A sensitive test at primary energies around 10-100 TeV is provided by comparing experimental and simulated trigger rates in the central detector [23]. Feeding absolute CR fluxes as measured on balloons and satellites into the CORSIKA air shower simulation package [24] and subsequently into a GEANT-based detector simulation, allows to directly compare the expected trigger and hadron rates with experimental data. This test exhibits differences between interaction models by about a factor of two and proves to be sensitive to percentage changes of the total inelastic cross section or to the contribution of diffractive dissociation [25]. Another type of test has been performed by investigating distributions of high energy hadrons observed in the shower core, an example of which is given in Fig. 4 [26]. Clearly, the SIBYLL model [27] provides only a poor description of the experimental data and has been refined by know. At present, QGSJET [28] yields the best overall result and is used as the 'reference model' by most EAS experiments.

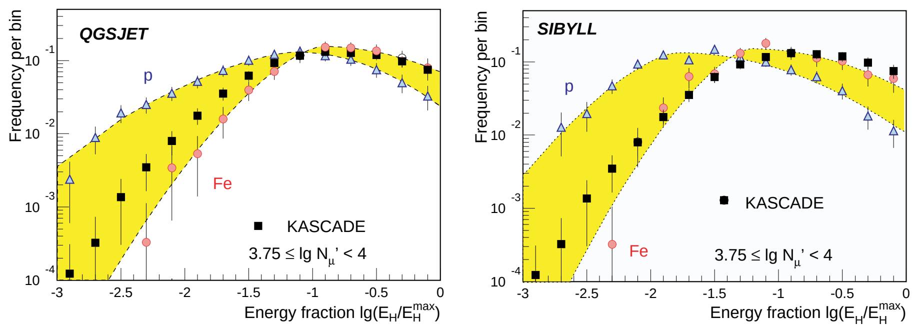

Fig. 4. Relative energy distribution of hadrons obtained by normalization to the most energetic hadron in a shower. The data are compared to QGSJET and SIBYLL simulations for primary protons (p) and iron nuclei (Fe). Shaded is the physically meaningful region as obtained from the simulations. The primary energy correspond to 2 PeV. From Ref. [26].

4. Mystery of the Knee

High energy cosmic rays do not only serve as test bench for hadronic interaction models or as input to atmospheric neutrino calculations, but are even more interesting in their own right. Their origin and acceleration mechanism have been subject to debate for several decades. Mainly for reasons of the required power the dominant acceleration sites are generally believed to be supernova remnants in the Sedov phase. Naturally, this leads to a power law spectrum as is observed experimentally. Detailed examination suggests that this process is limited to $E/Z \lesssim 10^{15}$ eV. Curiously, this coincides well with the knee at $E_{\rm knee} \cong 4 \cdot 10^{15}$ eV, indicating that the feature may be related to the upper limit of acceleration. The underlying picture of particle acceleration in magnetic field irregularities in the vicinity of strong shocks suggests the maximum energies of different elements to scale with their rigidity $R = pc/Ze$. This naturally would lead to an overabundance of heavy elements above the knee, a prediction to be proven by experiments. A change in the CR propagation with decreasing galactic containment at higher energies has also been considered. This rising leakage results in a steepening of the CR energy spectrum and again would lead to a similar scaling with the rigidity of particles but would in addition predict anisotropies in the arrival direction of CRs with respect to the galactic plane. Besides such kind of 'conventional' source and propagation models [29, 30], several other hypotheses have been discussed in the recent literature. These include an astrophysically motivated single source model [31], as well as several particle physics motivated scenarios which try to explain the knee due to different kinds of CR-interactions. For example, photodisintegration at the source [32], interactions with gravitationally bound massive neutrinos [33], or sudden changes in the character of high-energy hadronic interactions during the development of extensive air shower (EAS) [34] have been considered.

To constrain the SN acceleration model from the other proposed mechanisms, precise measurements of the primary energy spectrum and particularly of the mass composition as

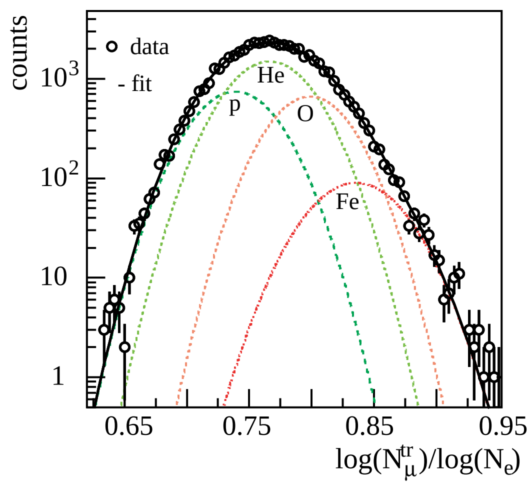

Fig. 5. Muon/Electron ratio from experimental data compared to simulations using different primary mas- ses at energies of about 1 PeV [35].

a function of energy are needed. A number of EAS observables has been identified to serve these purposes with only moderate model dependence [20]. Basically, one makes use of the fact that a heavy primary particle will – on average – experience its first interaction higher in the atmosphere as compared to a proton. One of the consequences is a stronger effect of absorption to electrons and photons in the atmosphere while the more penetrating muons reach ground mostly unaffected. Thus, the total number of muons provides a good measure of the primary energy while the muon/electron ratio is indicative for its mass. This is nicely illustrated in Fig. 5. The ratio, calculated on an event-by-event basis, is compared to CORSIKA simulations using different primary masses. Interestingly, the entire elemental spectrum between proton and iron is needed to describe the experimental data. Also, the left and right hand tails of the data are well described by the simulations, giving some confidence in the reliability of the EAS simulations. Repeating the analysis in different bins of energy finally yields the primary energy spectrum for different elemental groups. The result of a preliminary analysis is presented in Fig. 6 together with data from experiments other than KASCADE. The agreement appears reasonable and deviations are mostly explained by uncertainties in the energy scale by up to 25 %, e.g. CASA MIA data [36] were shifted upwards in energy by 20 % to yield a better agreement to the other data sets. This is likely to be explained by the outdated interaction model SIBYLL 1.6 [27] employed by the authors of Ref. [36]. The lines represent fits to the electron and muon size spectra of KASCADE assuming the all-particle spectrum to be described by a sum of proton and iron primaries [37]. Interestingly, a knee is only reconstructed for the light component and no indication of a break is seen in the heavy one up to $\sim 10^{17}$ eV. This important finding giving direct support to the picture of acceleration in magnetic fields (see above) will be target of future studies with improved experimental capabilities. For example, KASCADE and EAS-TOP have just started a common effort to install the EAS-TOP scintillators at the site of Forschungszentrum Karlsruhe providing a 12 times larger acceptance as compared to the original KASCADE experiment and still taking advantage of the multi-detector capabilities.

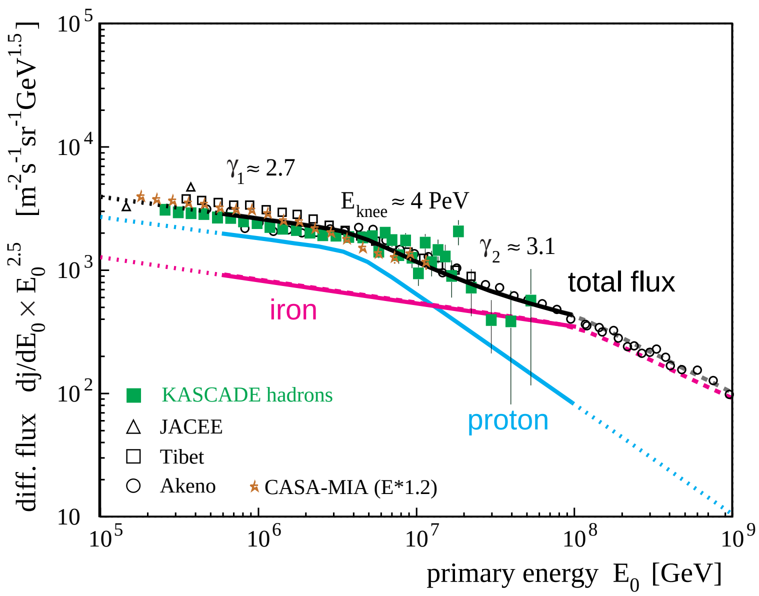

Fig. 6. Primary energy spectrum in the knee region as obtained from different experiments. The lines represent a preliminary deconvolution of the all-particle KASCADE spectrum into a light and heavy component [37].

5. The Most Energetic Particles in the Universe

Cosmic rays with energies in excess of 10^{20} eV are very rare (about 1 particle per km^2 and century) but have been known for more than 30 years. There is continuing fascination in understanding their origin and the route by which they acquire their macroscopic energy up to 50 Joule or more [38, 7]. The Lamor radius of protons or nuclei at these energies is too large to allow for conventional acceleration in magnetized shocks within our galaxy. Searching the sky beyond our galaxy, hot spots at the termination shock of gigantic plasma jets streaming out from the central engines of active galactic nuclei (AGN) stand out as the most likely sites from which particles can be hurled at Earth with Joules of energy. Sufficiently powerful sources, however, are found only at distances much larger than 100 Mpc. This is a major problem if the CR particles are ordinary nucleons or nuclei, because soon after the discovery of the cosmic microwave background radiation it was realized that the universe would be opaque for protons with $E \geq 6 \cdot 10^{19}$ eV. This was become known as the Greisen-Zatsepin-Kuz'min (GZK) cut-off. The principal reaction is $p + \gamma_{2.7K} \rightarrow \Delta^+ \rightarrow n + \pi^+$ or $\rightarrow p + \pi^0$ with a mean free path of ~ 6 Mpc. Similarly, nuclei of mass A suffer from photodisintegration $A + \gamma_{2.7K} \rightarrow (A-1) + N, (A-2) + 2N$ occuring via giant resonances at about the same primary energy. This is another nice example of classical nuclear and particle physics processes giving rise to phenomena in the extreme high-energy Universe. Energy spectra of dis-

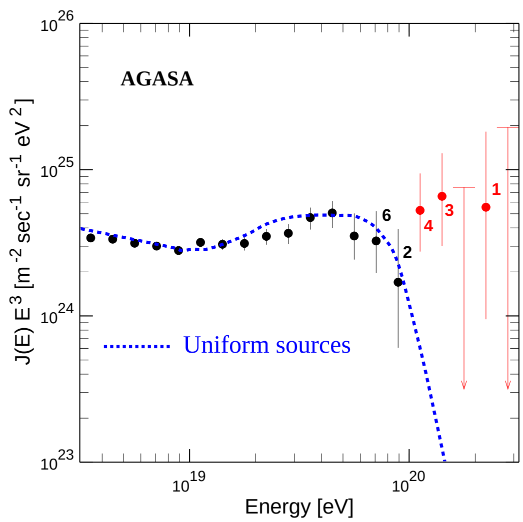

Fig. 7. Energy spectrum observed with AGASA [6]. The vertical axis is multiplied by E^3. The dashed curve represents the spectrum expected for extragalactic sources distributed uniformly in the Universe, taking account of the energy determination error.

tant sources thus should exhibit a cut-off as is indicated in Fig. 7. However, no such effect is seen in the experimental data. Presently, 16 events with energies above 10^{20} eV have been clearly identified with about half of the statistics originating from the Japanese AGASA experiment [6]. Do we have to conclude from this that the sources are very close, instead? If true, one expects to 'see' their sources in the arrival direction of the CRs, because known magnetic fields would deflect particles of such energies by one or two degrees at most. But again, no convincing astrophysical source can be identified beside some doublets and even one triplet of arrival directions. This has caused some debate of whether or not we start to see point sources of extremely energetic CRs.

The present situation on this fundamental problem appears rather curious; there is sufficiently convincing experimental material about the existence of the particles but the statistics is still too poor to allow for definitive conclusions about their origin! An enormous number of papers and large number of review articles have addressed the problem of solving the enigma, see e.g. [39, 7, 40]. Roughly, they can be grouped into models trying to circumvent the transport problems of hadrons thereby allowing for distant sources, or novel exotic sources are invented close by so that the GZK cut-off is irrelevant.

In the first of the two strategies, primary particles are proposed whose range is not limited by the CMB. Within the standard model the only candidate is the neutrino, whereas in supersymmetric extensions of the standard model, new neutral hadronic bound states of light gluinos, so called R-hadrons that are heavier than the nucleon have been suggested. They would shift the GZK cut-off to higher energies and thus allow for 10^{20} eV particles. The particles itself would be produced as secondaries in collisions of 'ordinary' $E \gtrsim 10^{21}$ eV particles within the powerful (AGN) accelerator. Another proposed solution of the transport problem would be possible small violations or modifications of fundamental tenets of physics, e.g. violations of Lorentz invariance. Indeed, such a violation is expected from models of quantum gravity. Since all of these examples require particles to be accelerated to extremely high energy within the accelerator, this group of models is often named *Bottom Up* approaches.

Top Down scenarios on the other hand involve the decay of X-particles of mass close to the Grand Unified Theory (GUT) scale ($\sim 10^{24}$ eV). Basically, they can be produced in two ways: if they are short lived, as expected in many GUT's, they have to be produced continuously. The only way this can be achieved is by emission from topological defects (cosmic strings, magnetic monopoles, domain walls, etc.) left over from cosmological phase transitions that may have occurred in the early Universe at temperatures close to GUT scale, possibly during reheating after inflation. Alternatively, X-particles may have been produced directly in the early Universe. Due to unknown symmetries they could have lifetimes comparable to the age of the Universe. In all of the pictures, such particles would contribute to the dark matter and their decays $X \to W, Z \to q\bar{q}, \gamma, \nu$ would account for the extremely energetic CR particles. In this case, the flux would be dominated by γ's and ν's with only 10-20 % nucleons.

Clearly, there is an urgent need to collect a sufficient amount of data in the GZK energy domain in order to discriminate such kind of models. The Pierre Auger Observatory [41], presently under construction, has been conceived to provide such data. The completed observatory will consist of two instruments, constructed in the northern and southern hemispheres, each covering an area of 3000 km^2. It will be a hybrid detector system with 1600 particle detectors and 4 eyes of atmospheric fluorescence telescopes. The particle detectors will be water Čherenkov tanks of 10 m^2 size and 1.2 depth arranged on a grid of 1.5 km. During clear moonless nights, the fluorescence detectors will record the light tracks generated by charged particles of EAS up to distances of 30 km. This will provide a very reliable energy (and mass) measurement of the CRs. First data are expected by late 2002.

There are also plans to launch a dedicated satellite or to instrument a flourescence camera on the ISS for observing extremely high energy CRs from space with much larger exposure [42] than expected for the Pierre Auger Observatory.

6. Summary and Conclusions

Cosmic ray physics is entering a renaissance of activity and has become the central pillar of what is known as Particle-Astrophysics. The other pillars are TeV γ-astronomy addressed by imaging atmospheric Čherenkov telescopes, TeV-PeV ν-astronomy studied deep underwater or in ice, and dark matter searches. It is fascinating to recognize the Universe as a laboratory for truly high energy physics and to observe traces of the high energy processes in each of these different observables. Due to sophisticated experimental techniques we are beginning to be able asking much more specific questions about CRs, νs and γs at all energies than have been possible a few years ago and we and may expect to obtain the answers within the next few years. A major potential is given also by synergistic effects combining particle, nuclear, and atomic physics with astrophysics and cosmology making an impact on fundamental physic questions. Examples were given on how the input from nuclear and particle physics has advanced the understanding of CRs and vice versa. Furthermore, extremely energetic CRs address fundamental questions of physics at energy scales of Grand Unified Theories, i.e. at an energy scale not accessible to man-made particle accelerators. All of this constitutes a challenge to basic science and the future appears very promising and exciting due to the advent of several large experiments.

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It is a pleasure to contribute to this volume commemorating Michael Danos. Mike's interests in science were widely oriented, he was always open minded and rightfully sceptical. I sincerely thank Walter Greiner and co-organizers for inviting me to this Symposium. Special thanks go my collaborators in KASCADE and AUGER. During the preparation of this talk I particularly benefited also from fruitful discussions with P. Biermann, G. Sigl, M. Simon, and many others.

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