A Measurement of the Energy Spectrum of Unaccompanied Hadrons

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Abstract

The energy spectrum of unaccompanied hadrons is measured with the large hadron calorimeter of the KASCADE experiment. From the measured flux at detector level the primary proton spectrum at the top of the atmosphere has been derived. The flux obtained is well compatible with results of direct measurements.

1. Introduction

Unaccompanied hadrons are cosmic-ray induced events for which only one hadron has been registered at ground level. They offer a possibility to study details of hadronic interactions in the atmosphere and the primary proton spectrum in the energy range from 100 GeV up to 5 PeV.

Different definitions of an unaccompanied hadron are used in the literature. For the present investigations an unaccompanied hadron is defined as follows: Only one hadron with an energy of at least 50 GeV is reconstructed and the zenith angle is smaller than 30°.

2. Experimental Set-up and Simulations

The measurements have been carried out with the KASCADE air shower experiment [1]. It consists of a 200×200 m^2 scintillator array, equipped with 252

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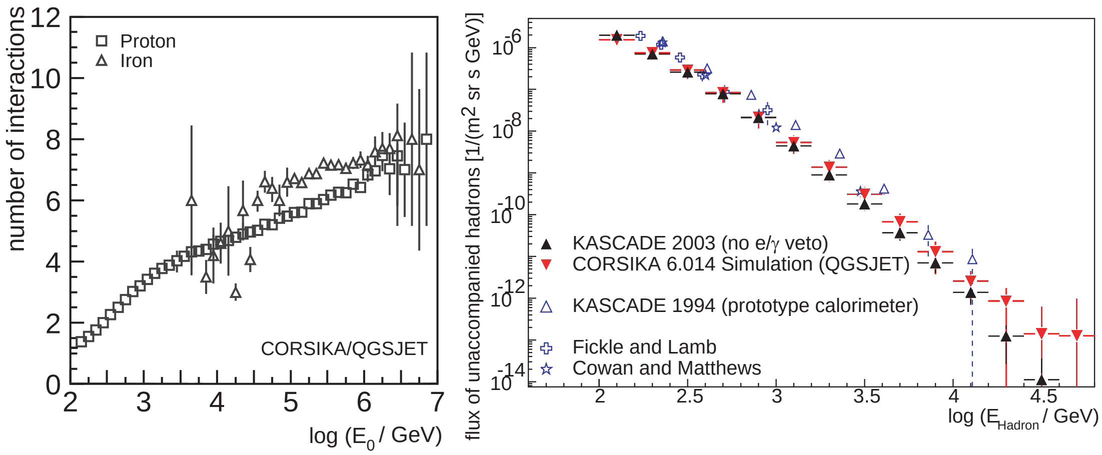

Fig. 1. Left: Number of interactions versus hadron energy at ground level. Right: Flux of unaccompanied hadrons at ground level.

stations to measure the electromagnetic and muonic shower components and a 16×20 m^2 hadron calorimeter [3]. With the calorimeter the energy, as well as the point and angle of incidence of individual hadrons are measured. Between October 1996 and October 2001 more than $3 \cdot 10^8$ events have been recorded with at least one reconstructed hadron in the calorimeter.

Accompanying simulations have been carried out using CORSIKA 6.014 with the GHEISHA and QGSJET01 hadronic interaction codes. In total about $2 \cdot 10^{10}$ events have been simulated in the energy range from 10^2 to $3 \cdot 10^6$ GeV for proton, helium, oxygen and iron induced air showers, using flux values of direct measurements according to a recent compilation [6]. All secondary particles reaching ground level have been treated with a GEANT-based detector simulation program.

3. Results

The average number of interactions in the atmosphere for unaccompanied hadrons registered in the calorimeter is plotted in Fig. 1. (left) versus their energy at ground level according to the CORSIKA simulations. As expected, the unaccompanied hadrons interact only a few times in the 11 interaction length thick atmosphere before they reach the detection level. Integrated over all relevant energies, the average number of interactions is 3.6 ± 1.9 for proton and 6.6 ± 2.3 for iron induced showers. Both values are smaller than the corresponding numbers for all air showers, i.e. 6.4 ± 1.8 for primary protons and 7.6 ± 2.2 for iron induced showers.

The measured flux of unaccompanied hadrons is presented in Fig. 1. (right) as function of energy. It is compared to simulations taking into account the flux values of direct measurements, as mentioned above. The measured and simulated flux values agree reasonable well. An interesting result, since the unaccompanied

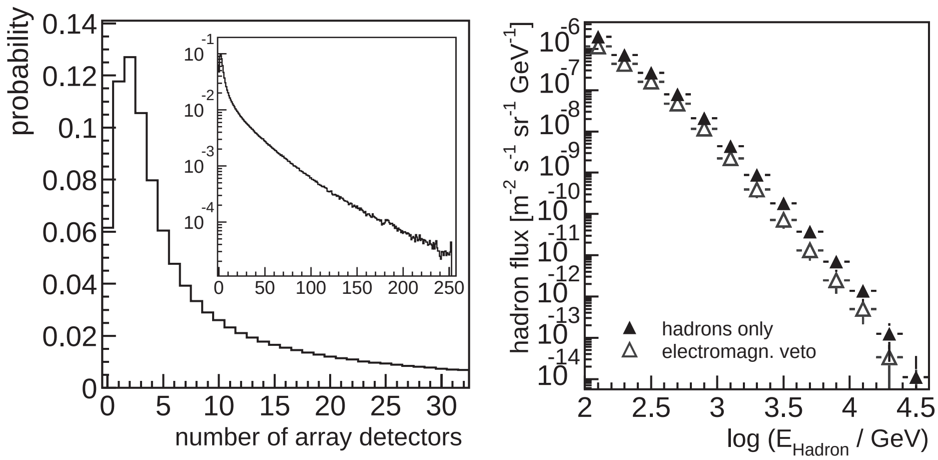

Fig. 2. Left: Number of electromagnetic detectors with $E_{dep} > 5$ MeV for unaccompanied hadrons. Right: Unaccompanied hadron spectrum including electromagnetic veto with $N_{e/\gamma}(E_{dep} > 5 \text{ MeV}) \leq 8$.

hadrons are a very special and untypical class of air shower events, sensitive to inelastic proton-air and pion-air cross-sections. The compatibility indicates that the interactions seem to be described correctly in the model QGSJET up to energies of 10^5 GeV. The flux obtained with the KASCADE prototype calorimeter [7] is somewhat larger as the present result due to the smaller surface of 6 m^2. The KASCADE calorimeter with 320 m^2 surface acts as efficient veto counter. Results from Fickle and Lamb [5] as well as Cowan and Matthews [2] exhibit a similar behavior, their flux values are slightly larger due to a smaller active area.

So far, unaccompanied hadrons were defined using the hadron calorimeter as veto counter against accompanying particles only. Additionally, the number $N_{e/\gamma}$ of electromagnetic detectors in the scintillator array with an energy deposit $E_{dep} > 5$ MeV can be used to identify accompanying particles. The measured probability distribution for $N_{e/\gamma}$ for events with one reconstructed hadron is depicted in Fig. 2. (left). In only 6% of the events no e/γ detector has a reasonable signal. For most of the "unaccompanied" hadrons, electrons are detected in the scintillator array, indicating that the definition of unaccompanied hadrons as one hadron only, as frequently used in the literature, is somehow arbitrary. The influence of the additional electromagnetic veto on the unaccompanied hadron spectrum is illustrated in Fig. 2. (right) for $N_{e/\gamma} \leq 8$. As expected, the absolute flux is reduced. The suppression is stronger for large hadron energies, originating from larger primary energies.

It is interesting to derive a primary energy spectrum form the measured flux of unaccompanied hadrons. The simulated number of events which initiate an unaccompanied hadron is shown in Fig. 3. (left) as function of primary energy for individual elemental groups. Up to 10^5 GeV unaccompanied hadrons originate mostly from primary protons. At larger energies the contamination with heavier

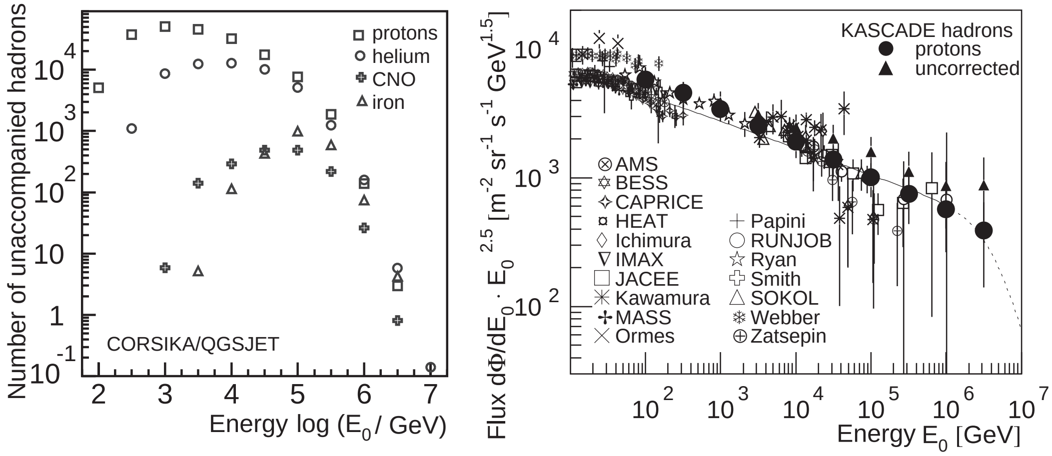

Fig. 3. Left: Number of unaccompanied hadrons versus primary energy for different elemental groups. Right: Primary proton flux reconstructed from unaccompanied hadrons compared to results of direct measurements, for references see [6]. The line represents a fit to the measurements [6].

elements is not negligible.

Based on the simulations the flux of unaccompanied hadrons has been converted to a primary flux at the top of the atmosphere. The result is shown in Fig. 3. (right) as filled triangles. The flux obtained should essentially coincide with direct measurements of the primary proton energy spectrum, shown in the figure as well. Subtracting the contribution of heavy elements, taking into account their abundances according to direct measurements, results in the filled circles, representing the flux of primary protons derived from unaccompanied hadrons. The correction amounts to less than 30%. No indication for a steepening in the proton spectrum between 10^4 and 10^5 GeV, as reported in the literature, can be seen from the derived flux. The derived proton spectrum agrees well with a parametrization of direct and indirect measurements [6], represented as solid and dotted lines. The agreement between the derived proton spectrum and the direct measurements seems to indicate that the underlying physics processes are reasonable well described in the simulation codes up to energies of 10^6 GeV.

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