A Measurement Technique of p-Air Inelastic Cross-Section above 10^{18} eV

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Abstract

A method of determining the proton-air inelastic cross-section from the distribution of air shower maxima (X_{max}) measured by HiRes stereo fluorescence detector is described. Fitting an empirical function to the X_{max} distribution we directly obtain proton-air mean free path (λ_{p-air}). This method has been tested on simulated air showers using QGSJET model for proton. The systematic uncertainties associated with this method have been discussed.

1. Introduction

The HiRes stereo fluorescence detector started operation in 1999. More than 3000 ultra high energy particle induced air showers are collected in stereo mode. The fluorescence technique allows us to measure the air shower longitudinal development profile therefore the shower maximum depth X_{max} and the shower energy. The stereoscopic detector provides high resolution X_{max} and energy. It is possible to measure the proton to atmosphere nucleon (p-air) inelastic cross-section using the X_{max} distribution. To establish a relationship between the X_{max} distribution and proton mean free path in the air, we developed a fitting procedure which allows us to fit X_{max} distribution and directly obtain the proton mean free path in the air. This procedure has been tested using air showers simulated by Corsika with QGSJET interaction model.

2. Detector

The HiRes stereo fluorescence detector is located in Utah West Desert and consist of two fluorescence detector stations HiRes1 and HiRes2 separated by 12.6 km. HiRes1 is a 20 mirror detector with sample and hold type electronics. HiRes2 is a 42 mirror detector with FADC type electronics. The UV sensitive camera of each mirror holds 256 photomultiplier tubes, which provide a field of view of about 13 x 16 degrees. The details of the detector can be found elsewhere [1].

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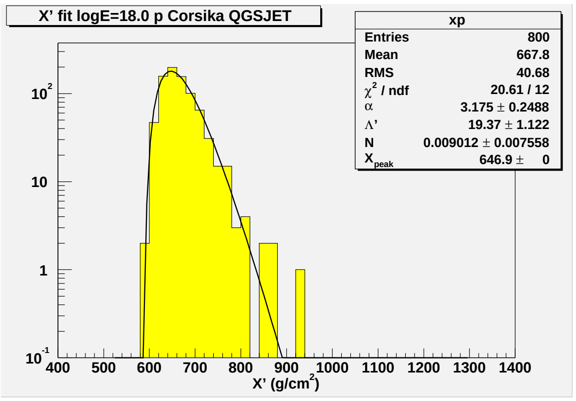

Fig. 1. x'_m distribution. p QGSJET $E = 10^{18}$ eV.

3. The Fitting Procedure

Traditionally, the exponential index of the deep part of the X_{max} distribution was related to the proton mean free path in the air as $\lambda_{p-air} = k\Lambda_{p-air}$, where λ_{p-air} is the proton mean free path in the air and Λ_{p-air} is the fitted exponential index of the X_{max} distribution [2]. Both λ_{p-air} and Λ_{p-air} are in g/cm^2. There are two uncertainties associated with this method however: the nature of the coefficient k is not well understood and the strong dependance of Λ_{p-air} on which part of the X_{max} distribution is used for fitting. To overcome these difficulties we suggest another approach to this problem.

The probability of the first interaction of a proton at a slant depth between x_1 and $x_1 + dx_1$ depends on the p-air inelastic cross-section. The probability density is:

$$p(x_1) = \frac{1}{\Lambda_1} e^{-\frac{x_1}{\Lambda_1}}, \tag{1}$$

where Λ_1 is the proton mean free path in the air in g/cm^2.

The probability for a shower to reach a maximum between x'_m and $x'_m + dx'_m$ after the first interaction at x_1, depends on the shower cascading properties in the air. The probability density for this process can be approximated by an empirical function:

$$P(x'_m) \propto [\frac{x'_m - x_{peak} + \alpha\Lambda'_m}{e}]^{\alpha} e^{-\frac{x'_m - x_{peak}}{\Lambda'_m}}, \tag{2}$$

where $x'_m = X_{max} - x_1$, x_{peak}, α and Λ'_m are three parameters obtained as a function of energy by fitting to x'_m distribution generated from the shower development simulation. A fit result is shown on Fig. 1 as a solid curve with $\chi^2 = 1.7$. The best fitting returns $x_{peak} = -310.9 + 53.21\log(E)$, $\alpha = 5.628 - 0.1689\log(E)$ and $\Lambda'_m = 22.2 g/cm^2$.

The X_{max} distribution then is a convolution of the two distributions and

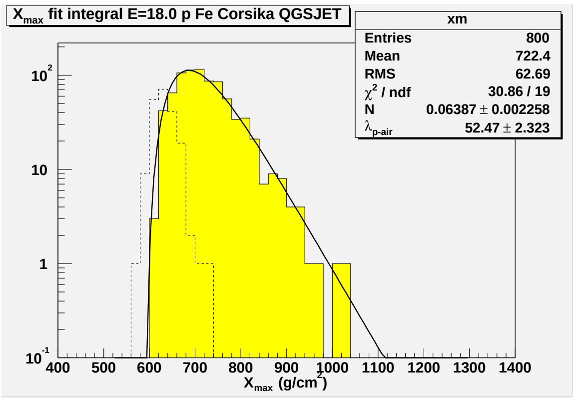

Fig. 2. X_{max} distribution for Iron (dashed line) and for proton (solid line) fit by function (3). Corsika QGSJET $E = 10^{18}$ eV.

can be written as:

$$f(x_m) = \int_0^{x_m - x_{peak} + \alpha\Lambda'_m} \frac{N}{\lambda_{p-air}} e^{-\frac{x_1}{\lambda_{p-air}}} [\frac{x_m - x_1 - x_{peak} + \alpha\Lambda'_m}{e}]^{\alpha} e^{-\frac{x_m - x_1 - x_{peak}}{\Lambda'_m}} dx_1 \tag{3}$$

where N is the normalization factor and λ_{p-air} is p-air mean free path. An example of this fit is shown on Fig. 2. The X_{max} distribution was generated by Corsika using QGSJET model.

Fig. 3 shows the result of applying this method for energies from 10^{17} to $3 \cdot 10^{20}$ eV. For the simulated showers λ_{p-air} is extracted directly from X_{max} distribution using function (3) while Λ_1 is the input into the shower cascade simulator. Within the error bars, these two sets of mean free paths are consistent with each other. This demonstrates that the method proposed in this paper is capable to extract the mean free path of proton in the atmosphere and thus, the inelastic scattering cross-section of the proton on the atmospheric nuclei directly from the measured X_{max} distribution by fitting only one parameter.

X_{max} is determined by fitting fluorescence light curve measured by HiRes detector. The resolution of this measurement is about 40 g/cm_2 with a small non gaussian tail. The effect of this resolution function on our measurement is being studied using a detector simulation program [3].

A part of our systematic error comes from the interaction model dependance. We will estimate this uncertainty by using several hadronic interaction models, such as QGSJET, SIBYLL2.1 and different shower cascade models, such as Corsika and Aries.

The composition of the cosmic rays is predominantly light above 5×10^{18}, mostly proton with a small portion of heavier nuclei [4-6]. Air showers caused by heavier nuclei develop faster in the atmosphere with significantly less fluctuations. The X_{max} distribution of Iron is shown on Fig. 2 as dashed line. The contamina-

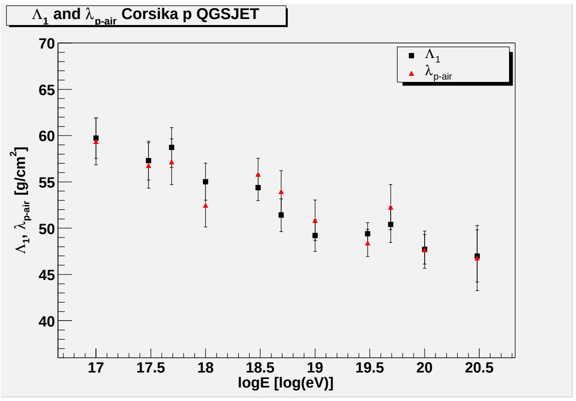

Fig. 3. λ_{p-air} and Λ_1 as a function of energy from X_{max} distribution fit and Corsika input for proton QGSJET

tion from heavier nuclei can be suppressed by using the data with X_{max} deeper than the contribution from heavier nuclei.

4. Conclusion

Applying the proposed fitting technique to the simulated data set we are able to measure the p-air inelastic cross-section at the energies above 10^{18} eV. We will discuss the model and composition induced systematic errors.

5. References

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