The Observed Mean Free Path and The p-Air Inelastic Cross Section of Proton Primaries at $E_0 = (2 \div 4)10^{15}$ eV.

EAS-TOP Collaboration

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Abstract

The mean free path of proton primaries and the p-air inelastic cross section are studied at energies $E_0 = (2 \div 4)10^{15}$ eV using the EAS-TOP array data. Proton initiated Extensive Air Showers, in such energy range and near maximum development, are selected from their $N_\mu(E_\mu > 1\,\mathrm{GeV})$ and N_e sizes. The observed mean free path Λ_{obs} is compared with $\Lambda^{\mathrm{sim}}_{\mathrm{obs}}$ obtained from simulations, including the full detector response, based on different interaction models (HDPM, VENUS, DPMJET, QGSJET and SIBYLL) in the frame of CORSIKA code. The proton-air inelastic cross section is also inferred by using the factor $k = \Lambda^{\mathrm{sim}}_{\mathrm{obs}}/\lambda^{\mathrm{sim}}_{p-\mathrm{air}}$ obtained from each interaction model.

1 Introduction:

It is well known that the study of cosmic ray primaries through Extensive Air Showers depends on the HE interaction models used for the analysis. On the other hand EAS technique provides some tools to check the general features of interaction models leading thus to information on high energy hadron physics. One of such observables is the proton interaction mean free path in the atmosphere which can be directly compared with expectation of theoretical models. Furthermore the p-air inelastic cross section ($\sigma^{p-\mathrm{air}}_{\mathrm{in}}$) can be derived at energies well beyond the p-nucleus fixed target experiments and , in our case, comparable with the $p\bar{p}$ collider measurements. Different techniques (Honda et al.,1993, Baltrusaitis et al.,1993) have been used to get such information from cosmic ray data. The present method (Honda et al.,1993, Aglietta et al.,1997) is based on the selection of showers with given primary energy ($E_1 < E_0 < E_2$) from the detected muon number ($N^1_\mu < N_\mu(E_0, r, E_\mu > 1\,\mathrm{GeV}) < N^2_\mu$). Primary proton showers near maximum development are then selected requiring large electron shower sizes (N_e). The mean free path of p-primaries in atmosphere (Λ_{obs}) is measured from the frequency attenuation rate at different zenith angles.

Extensive Air Showers are simulated (including full detectors' responses) in the frame of CORSIKA code (Knapp and Heck,1993) using different hadronic interaction and propagation models : HDPM (Capdevielle, 1989), VENUS (Werner, 1993), DPMJET (Ranft, 1995), QGSJET (Kalmykov et al., 1995) and SIBYLL (Fletcher et al., 1994).

The interaction models can thus be verified comparing experimental and simulated data. Furthermore, the factor $k = \Lambda^{\mathrm{sim}}_{\mathrm{obs}}/\lambda^{\mathrm{sim}}_{p-\mathrm{air}}$ is calculated for each interaction model and $\lambda_{p-\mathrm{air}} = \Lambda_{\mathrm{obs}}/k$ (*i.e.* $\sigma^{p-\mathrm{air}}_{\mathrm{in}}$) is inferred.

Table 1: Values of the parameters in (1) computed fitting the data from simulation with different interaction models.

Interaction Model	N_0	$r_0(m)$	a	b
HDPM	1.82×10^{-3}	312	1.97	0.89
VENUS	1.91×10^{-3}	306	2.20	0.88
DPMJET	1.52×10^{-3}	382	2.43	0.88
QGSJET	2.45×10^{-3}	297	2.20	0.86
SIBYLL	2.40×10^{-3}	277	2.01	0.85

Table 2: Fraction of vertical events ($\%$) selected with different cuts (N_e^i) in the given range of N_μ.

$\log N_e^i$	5.9	6.0	6.1	6.2	6.3
Exp.	13.8	7.3	3.3	1.4	0.6
HDPM	42.8	27.5	14.3	6.4	2.6
VENUS	36.8	21.5	11.6	5.2	1.9
DPMJET	30.5	18.2	9.5	4.2	2.0
QGSJET	33.0	20.1	11.1	5.5	2.3
SIBYLL	40.7	26.8	15.2	7.9	3.5

2 The detector and the simulation:

EAS-TOP (Aglietta et al., 1993, 1995) is an Extensive Air Shower array located at Campo Imperatore (National Gran Sasso Laboratories, 2005 m a.s.l., $x_0 = 820$ g/cm^2). The e.m. detector is made of 35 scintillator modules, 10 m^2 each, distributed over an area of $\approx 10^5$ m^2.

The EAS arrival direction is obtained using the time of flight technique. From the fit to NKG lateral distribution function, the shower size (N_e) and core location (x_c, y_c) are derived.

For $N_e \geq 2.10^5$ the shower size, core location and arrival direction are measured with accuracies, respectively: $\frac{\sigma(N_e)}{N_e} \approx 10\%$, $\sigma_r \approx 5$ m and $\sigma_\theta \approx 0.5°$.

The muon number N_μ is obtained by means of a tracking detector (144 m^2 area) made of 9 double layers of streamer tubes interleaved by 9 layers of iron absorber (13 cm thick). The readout is performed on orthogonal x (wires) and y (strips) views. A muon track is defined by the alignment of at least 6 hits in different layers of the muon tracking system. The energy threshold for vertical incidence is $E_\mu^{th} \approx 1$ GeV. The muon number is correctly measured up to $N_\mu \geq 30$.

Proton initiated EAS are simulated by means of the CORSIKA code using NKG option to describe the e.m.

Table 3: Measured and simulated mean free path $\Lambda_{\rm obs}(\rm g/cm^2)$. Different accuracies in the simulations are due to different statistics.

$\log N_e^i$	5.9	6.0	6.1	6.2	6.3
Exp. Data	79 ± 5	75 ± 5	76 ± 6	75 ± 7	77 ± 10
He correction	91 ± 6	84 ± 6	83 ± 7	80 ± 8	80 ± 10
HDPM	105 ± 8	90 ± 7	81 ± 7	78 ± 8	85 ± 11
VENUS	84 ± 5	74 ± 5	68 ± 5	68 ± 6	67 ± 8
DPMJET	73 ± 4	66 ± 4	64 ± 5	62 ± 6	60 ± 8
QGSJET	79 ± 5	70 ± 5	62 ± 5	61 ± 6	49 ± 7
SIBYLL	92 ± 6	80 ± 6	73 ± 6	65 ± 6	68 ± 8

Table 4: $k = \Lambda^{\rm sim}_{\rm obs}/\lambda^{\rm sim}_{p-{\rm air}}$ for different N_e^i cuts and models.

$\log N_e^i$	5.9	6.0	6.1	6.2	6.3
HDPM	$1.64 \pm .12$	$1.40 \pm .10$	$1.26 \pm .10$	$1.22 \pm .12$	$1.32 \pm .17$
VENUS	$1.29 \pm .08$	$1.14 \pm .08$	$1.04 \pm .08$	$1.04 \pm .10$	$1.02 \pm .12$
DPMJET	$1.23 \pm .08$	$1.11 \pm .07$	$1.08 \pm .08$	$1.04 \pm .10$	$1.02 \pm .13$
QGSJET	$1.32 \pm .09$	$1.18 \pm .08$	$1.05 \pm .08$	$1.03 \pm .11$	$0.82 \pm .11$
SIBYLL	$1.50 \pm .10$	$1.30 \pm .09$	$1.19 \pm .09$	$1.06 \pm .09$	$1.10 \pm .13$

cascade. Shower particle interaction with our detectors is described by means of GEANT for the muon detector and of an EGS based ad hoc simulation for the electromagnetic detector modules. Experimental fluctuations in individual scintillator modules, trigger generation and event reconstruction have been included. The selection on primary energy (E_0) is made using the detected muon number $N_\mu(E_0, r, E_\mu > 1\,{\rm GeV})$. The relationship between these quantities, established with a multi parameter fit of simulated data, is:

$$N_\mu(E_0, r, E_\mu > 1\,{\rm GeV}) = N_0 \times \cos^a\theta \times E_0^b \times r^{-0.75} \times (1 + r/r_0)^{-2.5}. \tag{1}$$

The values of N_0, r_0, a and b for different interaction models are reported in Table 1.

Expression (1) holds for energies $10^6\,{\rm GeV} < E_0 < 10^7$ GeV, core distance $50\,{\rm m} < r < 150\,{\rm m}$ and zenith angle $\theta < 45°$.

Table 5: Values of $\sigma_{\rm in}^{p-{\rm air}}({\rm mb})$ inferred from experimental data using k factors derived from different interaction models. Accounting for He contamination, all values should be divided by the α correction factor corresponding to each N_e^i cut.

$\log N_e^i$	5.9	6.0	6.1	6.2	6.3
HDPM	503 ± 47	449 ± 44	398 ± 45	393 ± 54	414 ± 74
VENUS	394 ± 34	366 ± 35	329 ± 36	336 ± 45	320 ± 55
DPMJET	376 ± 31	356 ± 33	341 ± 38	337 ± 46	319 ± 57
QGSJET	404 ± 35	380 ± 37	331 ± 37	332 ± 47	257 ± 48
SIBYLL	461 ± 41	417 ± 40	377 ± 42	343 ± 45	346 ± 60

3 Analysis and results:

Events with primary energy $2.10^6\,{\rm GeV} < E_0 < 4.10^6$ GeV are selected using expression (1), given their core distance (r), zenith angle (θ) and detected muon number (N_μ).

In order to select proton initiated showers near maximum development, events belonging to the uppermost few percent of the shower size distributions are used. Five cuts ($\log N_e^i = 5.9 \div 6.2$) are performed, to verify the stability and the convergence of the measurement. The corresponding percentage of selected vertical events (i.e. $\sec(\theta) < 1.05$) is shown in Table 2.

The fraction of selected events in the experimental data is lower than in the simulated ones, because they include heavier primary nuclei which produce, for fixed muon number, smaller electron size showers.

The frequency attenuation length in the atmosphere $\Lambda_{\rm obs}$ is obtained by fitting the rate of selected events, grouped in 8 angular bins ($1 + .05 \times (n-1) < \sec(\theta) < 1 + .05 \times n$, $n = 1, 8$) with the following expression:

$$f(\theta) = \Gamma(\theta) f(0) \exp[-x_0(\sec\theta - 1)/\Lambda_{\rm obs}], \tag{2}$$

where $\Gamma(\theta)$ is the calculated acceptance. Experimental values are stable for different cuts as shown in Table 3.

Possible contamination from heavier nuclei is essentially due to helium primaries. Superimposing an helium flux of the same intensity as the proton one, a correction factor α has been found such as $\Lambda^p_{\rm obs} = \alpha \times \Lambda^{p+{\rm He}}_{\rm obs}$ (with α=1.16, 1.12, 1.09, 1.07, 1.04 respectively for the five $\log N_e^i$ cuts). Experimental results multiplied for correspondent α factors to take in account the possible heavier nuclei contamination are reported in the second row of Table 3.

For each interaction model, $\Lambda_{\rm obs}^{\rm sim}$ is compared to the interaction mean free path $\lambda_{p-{\rm air}}^{\rm sim}$ providing the factor k = $\Lambda_{\rm obs}^{\rm sim}/\lambda_{p-{\rm air}}^{\rm sim}$. This factor includes shower fluctuations, detectors' response and some features of the interaction model. The values of k are similar and stable for all considered models and ≈ 1.1 for N_e^i cut high enough to select p-showers near maximum (*i.e.* $N_e = 10^{5.9} - 10^{6.3}$, see Table 4).

The experimental value of $\lambda_{p-{\rm air}}$ and consequently of $\sigma_{\rm in}^{p-{\rm air}}({\rm mb}) = 2.41 \times 10^4/\lambda_{p-{\rm air}}$ is obtained from $\lambda_{p-{\rm air}} = \Lambda_{\rm obs}/k$. Results are reported in Table 5, where the $\log N_e^i = 6.2$ cut column has to be considered, due to the convergence of k values, smaller contamination of heavier nuclei and still good statistic.

4 Discussion and Conclusions:

- Concerning $\Lambda_{\rm obs}$, the obtained experimental value ($\Lambda_{\rm obs} = 75 \pm 7\,{\rm g/cm^2}$ for $\log N_e^i = 6.2$, possibly to be increased of about $(5 \div 10)\%$ in case of heavier nuclei contamination as shown in Table 3) is in better agreement with models predicting longer absorption lengths such as HDPM and VENUS.

- Concerning the value of $\sigma_{\rm in}^{p-{\rm air}}$, four interaction models (VENUS, DPMJET, QGSJET and SIBYLL) provide consistent results : $\sigma_{\rm in}^{p-{\rm air}} = (332 \div 343) \pm 47$ mb. The result obtained using HDPM is larger but not inconsistent with such range of values. The reported value of $\sigma_{\rm in}^{p-{\rm air}}$ is therefore rather independent from the hadronic interaction models used in our simulations and lower then previously reported in literature (Knapp,1997). An helium contamination (considering equal p and He fluxes at $E_0 \approx 10^{15}$ eV) would result in a reduction of $\sigma_{\rm in}^{p-{\rm air}}$ by $\approx$(5 $\div 10)\%$.

We notice that the experimental values of $\Lambda_{\rm obs}$ are quite similar to the previously reported ones (Baltrusaitis et al., 1993, Honda et al., 1993); the difference in the $\sigma_{\rm in}^{p-{\rm air}}$ values arises from the different hadronic interaction models used in this analysis leading to different values of k parameter.

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