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Inelasticity in Proton-Air Collisions from Cosmic Ray Data

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Abstract

The total inelasticity in proton-air collisions has been estimated from cosmic ray extensive air shower data using the Bellandi et al formula at an energy equal to Tevatron collider experiment. The result obtained in the present approach is compared with the prediction of different theoretical models of high energy interactions developed on the basis of accelerator results.

1. Introduction:

Monte Carlo simulation of extensive air showers (EAS) requires high energy particle interaction characteristics as input. Any uncertainty in the characteristics of elementary interaction will intern produce uncertainty in the astrophysical informations extracted from cosmic ray EAS data. With the outcome of results on high energy interactions from collider experiments, particularly that from CERN and Tevatron experiments and with the emergence of a viable theory of high energy hadronic interactions (QCD) at present multiparticle production scenario at high energy regime is more complete and clear than few years ago. But in some features, which are mainly concerned with EAS, still interaction scenario is partially or even totally unknown. The main reason for this is that the detectors operating at present colliders can only detect particles produced in the central region whereas cosmic ray observation is mainly confined in the forward region. Inelasticity, in a given hadronic interaction which represents the fraction of total energy used for multiparticle production, is one important parameter of high energy interaction about which our knowledge is limited at present due to the geometrical limitations of detectors of the present colliders. Moreover prediction of different theoretical models regarding energy dependence of inelasticity are contradictory.

Solving nucleonic diffusion equation Bellandi et al (1992) put forward an expression relating absorption length of cosmic ray nucleonic flux with the interaction mean free path and average inelasticity. Recently absorption length of proton component of primary cosmic rays has been measured in EAS-TOP EAS experiment (Aglietta et al, 1997) at an energy equal ($\sqrt{s}$ ~1.8 TeV) of Tevatron collider experiment. At this energy total cross section of proton-proton collisions (σ_t^{p-p}) is known and one can estimate interaction mean free path of proton in air from σ_t^{p-p} using theoretical model .In Akeno experiment (Hara et al, 1983) also absorption length of proton component of primary cosmic rays has been measured at energies close to the energy of Tevatron collider experiment. Thus information on inelasticity can be extract from the mentioned EAS experimental data using the expression of Bellandi et al.

2. Formulations used:

We start with the expression of Bellandi et al (1992) which gives effective attenuation length (absorption length)(Λ) of cosmic ray nucleonic flux as a function of interaction mean free path (λ_{in}) and elasticity (x) as follows

$$\Lambda (E) = \lambda_{in} /(1-x^{\gamma})$$

In deducing the above expression primary particle spectrum has been assumed as power law I (E) ~ $E^{-(\gamma+ 1).}$
The above expression may be rewritten for elasticity as

$$x(E) = (1 - \lambda_{in} (E)/ \Lambda (E))^{\beta} \qquad ....(1)$$

Where $\beta = 1/\gamma$ .So studying evolution of the nucleonic component of cosmic rays in the atmosphere inelasticity in proton air collisions ($k^{p-air} = 1 - x^{p-air}$) can be estimate provided λ_{in}^{p-air} is known .The λ_{in}^{p-air} is inversely proportional to the inclusive proton-air collisions cross section

$$\lambda_{in}^{p-air} = 2.41 \times 10^4 / \sigma_{in}^{p-air} (mb) \quad gm\ cm^{-2}$$

Since no data on hadron-nucleus collisions are available at this high energy ($\sqrt{s}$ ~1.8 TeV) from collider experiments, $\sigma_{in}^{p\text{-}air}$ only can be estimate from $\sigma_t^{p\text{-}p}$ using theoretical model .Following Glauber model (1970), one can write

$$\sigma_{in}^{p\text{-}air} = \int d^2b \{ 1 - [1-(1/2A)\, \sigma_t^{p\text{-}p} \int \rho(b,z)dz]^{2A}\}$$
$$\approx \int d^2b \{ 1 - \exp[-\sigma_t^{p\text{-}p} \int \rho(b,z)dz]\} \qquad ....(2)$$

Where b is the impact parameter, A is the atomic weight of the nucleus and $\rho(r)$ is the nuclear density which is normalized in such a way that

$$\int \rho(r)d^3r = A$$

In the present work nuclear density $\rho(r)$ has been calculated using Durand-Pi (1988) parameterization. Thus knowing $\lambda_{in}^{p\text{-}air}$, $k^{p\text{-}air}$ can be estimate from the measured value of Λ (E) from eqn. 1. Inelasticity in proton-proton collisions ($k^{p\text{-}p}$) is related with that in proton -nucleus collisions ($k^{p\text{-}N}$) through the simple equation (Jaoshvili, 1990) as

$$k^{p\text{-}N} = A^{\delta} k^{p\text{-}p} \qquad ....(3)$$

For air A = 14.5 and $\delta \sim 0.1$.

3. Results:

The total cross section in p - p collision has been measured at the Tevatron collider at c.m. energy 1.8 TeV by E710 collaboration (Amos et al, 1992) and CDF collab. (Abe et al, 1994) but they reported discrepant results. E710 collab. measured $\sigma_t^{p\text{-}p}$ = 72.8 ± 3.1 mb while CDF collab. found $\sigma_t^{p\text{-}p}$ is equal to 80.03 ± 2.24 mb. Using both the results $k^{p\text{-}air}$ has been estimated from eqn. 1 and is presented in table 1. Here we have assumed total cross-sections in p-p and p-p(bar) are identical. The value of γ is taken as 1.80 as reported by JACEE collab. (Ashakimori et al, 1997) for proton component of primary cosmic rays from their balloon borne experiment. The values of $k^{p\text{-}p}$ obtained from $k^{p\text{-}air}$ using eqn. 3 are also shown in table 1.

Table 1: Average inelasticity in p-air and p-p collisions from EAS-TOP data at c.m. energy ~ 1.8 TeV

$\sigma_t^{p\text{-}p}$ used	$k^{p\text{-}air}$	$K^{p\text{-}p}$
72.8 mb (E710 result)	$0.77_{-.05}^{+.06}$	$0.59_{-.04}^{+.05}$
80.03 mb (CDF result)	$0.72_{-.04}^{+.05}$	$0.55_{-.03}^{+.04}$

As mentioned earlier in Akeno and EAS-TOP experiments absorption length are measured also at other energies close to the energy of Tevatron collider and extrapolation of accelerator results on $\sigma_t^{p\text{-}p}$ should not differ much (if not coincide) from the true value of $\sigma_t^{p\text{-}p}$ at these energies. $\lambda_{in}^{p\text{-}air}$ has been calculated at these energies using Donnachie & Landshoff parameterization (1992) of Regge theory for $\sigma_t^{p\text{-}p}$ and the values of $k^{p\text{-}air}$ at different energies are estimated from Akeno and EAS-TOP EAS data and are presented in table 2. The energy dependence of $k^{p\text{-}air}$ can be parameterize by the power law $k^{p\text{-}air} = 0.176\ s^{.095}$.

Table 2: Average inelasticity in p-air and p-p collisions from cosmic ray data at different energies

Experiment	EAS-TOP	Akeno		
c.m. energy (TeV)	2.0	2.27	3.00	3.95
$k^{p\text{-}air}$	0.76	0.75	0.76	0.87
$k^{p\text{-}p}$	0.58	0.57	0.58	0.67

The prediction of some important high-energy interaction models (SIBYLL (Fletcher et al, 1994), HEMAS (Forti et al, 1990), HDPM (Capdevielle ,1989) ,QGS (Kaidalov et al,1986), DPMJET (Ranf , 1995)) on inelasticity are given in table 3. These models are mainly developed on the basis of QCD and are tuned with the accelerator results and are now widely used in EAS simulation. Few results obtained indirectly by analyzing collider experimental data are also presented in the table 3. This includes the result of Bellandi et al (1994) obtained from inclusive reaction data of collider experiment and the work of de Deus & Padua (1993) in which correlation between transverse momentum and rapidity is taken account. The result obtained by Monte Carlo simulation study of nuclear interactions using collider experimental data (Navia et al, 1992) and that by considering diffractive contribution to the elasticity (Bellandi et al, 1997) are also given in table 3 .

Table 3: Average inelasticity in p-air and p-p collisions: prediction of some high-energy interaction models and result obtain in different analysis at c.m. energy 1.8 TeV

Expt./ Analy-Sis	SIBYLL	HEMAS	HDPM	QGS	DPMJET	Monte Carlo		Bellandi et al (1997)	Bellandi et al. 1994)	De Deus & Padua (1993)
						Mini Jet	Fire Tube			
$K^{p\text{-}air}$	0.61	0.60	~0.55	~.71	0.64	0.50	0.45	0.78		
$k^{p\text{-}p}$	0.55		0.45		0.55	0.27	0.15	0.59	~0.75	0.42

4 Discussion:

In the present work inelasticity in proton-air and p-p collisions has been estimated from cosmic ray air shower data using Bellandi et al formula at cm energies at and around 1.8 TeV. The results obtained from two different experiments are found to be close and are consistent within the error limit .The result obtained from cosmic ray EAS data shows inelasticity is increasing with energy.

The present result indicates that inelasticity in proton-air collisions is higher than the prediction of most interaction models that are commonly used for EAS simulations. The present result is only close to the prediction of QGS model. The value of $k^{p\text{-}air}$ obtained in this work at cm energy 1.8 TeV also agrees with the result of Bellandi et al (1997) in which diffractive contribution to elasticity is considered by making radial scaling.

Until data from CERN Large Hadron Collider (LHC) will be available, only cosmic ray study could provide information of the high-energy particle interaction in forward region. A number of presently operating EAS experiments are capable to measure absorption length of the proton component of primary cosmic rays at energies below $\sqrt{s}$ =1.8 TeV and particularly at energies equal to cm energies of CERN collider experiments and thus could provide better information on the energy dependence of inelasticity.

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