Abstract

The present thesis reports, research works done by the author (in collaboration with a few others) on various aspects of the cosmic ray knee. The main objective of the works are

i) to review the present status of the knee in the energy spectrum,

ii) to examine whether different components of cosmic ray extensive air shower, consistently and unequivocally suggest the existence of the knee in the primary cosmic ray energy spectrum,

and

iii) to propose a new self-consistent theoretical model of the knee, which is devoid of any fine tuning problem.

Due to the rapidly falling intensity with increasing energy, higher energy cosmic rays can only be studied indirectly by observations of cosmic ray extensive air showers (EAS), which are cascades of secondary particles produced by interactions of cosmic ray particles with atmospheric nuclei, on ground based installations. To interpret the EAS results in terms of primary cosmic rays, one has to take the help of the Monte Carlo simulation that relies on the high energy particle interaction models. The knee feature has been inferred from size (total number of particles) spectrum of electrons in air showers. The Monte Carlo simulation requires particle interactions at high energies as input for constructing cosmic ray EAS events. Computation of hadron production, particularly at low transverse momenta, is not yet possible from first principles within quantum chromodynamics. One, therefore, relies on phenomenological models that are appropriately tuned to match with the prevailing experimental data. Even a parametrization of such models may be difficult as the accelerator data for the relevant target-projectile combinations covering the whole kinematic region are not available. Experimental data on hadron-hadron interactions in the forward kinematic region at high energies and the data on hadron-nucleus and nucleus-nucleus interactions at all energies covering the whole kinematic range are particularly scarce. One has to resort to theoretical models of particle interactions in such cases. Before generating EAS events to examine the knee feature, one has to make some tests of interaction models in order

to check the reliability of the interaction models and thereby to choose the proper model(s) for work.

We study the effect of particle interaction models at relatively lower energies (< 80 GeV) on the theoretical estimates of atmospheric proton and antiproton fluxes by comparing the BESS observations of proton, muon and antiproton spectra with the spectra obtained by means of a full three dimensional Monte Carlo simulation program. For such a purpose, we use two different microscopic interaction models, namely FLUKA and UrQMD to simulate proton, muon and antiproton spectra at multiple observation levels. We also compared the atmospheric proton, muon and antiproton fluxes predicted by a few popular microscopic high energy particle interaction models with each other to get an idea about the influence of such models at energies beyond the BESS upper cutoff up to about 100 GeV. We find that the FLUKA reproduces the results of BESS observations on the secondary proton spectrum reasonably well over the whole observed energy range, the model UrQMD works well at relatively higher energies. It is further noticed that the model-predicted proton fluxes at a lower altitude are quite closer to the observed proton fluxes in comparison with those at a higher altitude. The model UrQMD presents reasonable description of the BESS $\bar{p}$ *data at mountain altitude and at sea level whereas FLUKA consistently yields a higher* $\bar{p}$ *flux than the measurements at all the observation levels. Overall both UrQMD and FLUKA work reasonably well but when both proton and anti-proton fluxes are considered, UrQMD has an edge over FLUKA. So we have selected UrQMD as the low energy interaction model for simulating EAS events. At higher energies there was no way to check the validity of hadronic interaction models untill the Large Hadron Collider data were available. The comparison of different interaction models behavior with the LHC data suggest that the QGSJET 01c has a close agreement with the data and hence we select the model as the high energy interaction model for the simulation study though a small sample of data are also generated using EPOS.*

Next with the help of Monte Carlo simulation we examine whether a consistent primary energy spectrum of cosmic rays emerges from both the experimentally observed total charged particles and muon size spectra of cosmic ray extensive air showers considering primary composition may or may not change beyond the knee of the energy spectrum. It is found that EAS-TOP observations consistently infer a knee in the primary energy spectrum provided the primary is pure unchanging iron whereas no consistent primary spectrum emerges from simultaneous use of *the KASCADE observed total charged particle and muon spectra. However, it is also found that when primary composition changes across the knee the estimation of spectral index of total charged particle spectrum is quite tricky, depends on the choice of selection of points near the knee in the size spectrum.*

Finally we propose a new model of cosmic ray knee based on mass distribution of progenitor of cosmic ray sources. The proposed model can account all the major observed features about cosmic rays without invoking any fine tuning to match flux or spectra at any energy point. The proposed model predicts that the mass composition should not be changed much across the knee which is found consistent to that obtained from simultaneous use of EAS-TOP observed electron and muon size spectra. The prediction of the proposed model regarding primary composition scenario beyond the knee is quite different from most of the prevailing models of the knee and thereby can be discriminated from precise experimental measurement of the primary composition.

The material/results reported in this thesis have been published in different journals/proceedings as shown below

1. Arunava Bhadra, Biplab Bijay, Sanjay K. Ghosh, Partha S. Joarder, Sibaji Raha, *"Influence of microscopic particle interaction models on the flux of atmospheric antiprotons"*, Astroparticle Physics, **35**, 277 (2012) (DOI: 10.1016/j.astropartphys.2011.09.002)

2. Partha S. Joarder, Arunava Bhadra, Biplab Bijay, Sanjay K. Ghosh,, Sibaji Raha, *"Dependence of Simulated Atmospheric Antiproton Flux on the Microscopic Models of Particle Interactions"*, Proc: 32nd Int: Cosmic Ray Conf:, Beijing, **1**, 129 (2011) DOI: 10.7529/ICRC2011/V01/1115

3. *"Does the knee in the primary cosmic ray energy spectrum exist?"*, B. Bijay and A. Bhadra, Exploring the Cosmos, (Ed. A. Bhadra, Lambert Academic Publishing (Germany), ISBN-13: 9783844391657) p 106, (2011)

4. *"The origin of the knee of the cosmic ray energy spectrum"*, Arunava Bhadra and Biplab Bijay, Proc: 32nd Int: Cosmic Ray Conf:, Beijing, **6**, 186 (2011) DOI: 10.7529/ICRC2011/V06/1023

5. Biplab Bijay, Prabir Banik, Arunava Bhadra, *"The knee in the cosmic ray energy spectrum from the simutaneous EAS charged particles and muon density spectra"*, communicated for publication (eprint arXiv:1511.05739)

6. Biplab Bijay, Arunava Bhadra, *"Progenitor model of cosmic ray knee"*, Research Astron. Astrophys **16**, 6 (2015) (DOI: 10.1088/16744527/16/1/006)