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Short Review on Cosmic Rays and Air Shower Simulations

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Abstract— ***The origin of high-energy cosmic rays remains one of the greatest challenges in modern physics. Cosmic rays span an enormous range of energy from about 10^9 eV to beyond 10^{20} eV. The energy spectrum of primary cosmic rays exhibits power law behavior with a steepening trend at 3 PeV, is commonly called the knee of the spectrum. Because of the presence of the knee feature, the cosmic-ray energy spectrum is an area of intense study in astroparticle physics. The proper explanation of the knee is supposed to be a foremost area in understanding the origin, acceleration, propagation and composition of primary cosmic rays. To know mainly about the origin and chemical composition of cosmic-rays (CRs) from their indirect investigation, it is very important to know how their by-products progress in the atmosphere as a cascade shower. This knowledge is obtained by Monte Carlo (MC) simulations of air shower development. Therefore, MC simulations are a crucial part of the design of different air shower experiments and also analysis of data from them. The exploration of the distant universe using the messenger 'cosmic-rays' therefore needs an amalgamation of modern instrumentation and high-power computing in various installations of giant cosmic ray air shower experiments on the globe.***

Keywords— Cosmic-rays, Origin, Composition, EAS Experiments, Monte Carlo simulation

I. INTRODUCTION

Cosmic rays (CRs) in the high-energy region (10^{14} – 10^{16} eV) have several distinguishing features, some of those are the following**: (i)** they are detected (with reasonable statistics) indirectly by means of CR extensive air showers (EAS) unlike the lower energy CRs those could be detected directly by sending detectors above the atmosphere through balloons and satellites, **(ii)** they are supposed to be originated in the galaxy unlike the highest energy (EeV range) CRs which are believed to be of extra-galactic origin, **(iii)** the energy spectrum of CRs in this energy range exhibits a *knee* feature at about 3 PeV and **(iv)** information for primary CRs at these energies cannot be obtained without employing any reliable MC code for air shower simulations.

High energy gamma-rays and neutrinos are expected to be produced in the interactions of energetic CRs with the ambient matter in the source environment and thereby CR sources should be identified, at least in principle, by observing appropriate fluxes of gamma-rays and neutrinos from a CR source. The possibility of observing such high energy (~ TeV or above) gamma-rays and neutrinos is high for galactic sources those produce CRs up to PeV energies owing to their smaller distances (relative to extra-galactic sources) and low background noise in compare to CR sources of sub-PeV energies.

II. ORIGIN OF HIGH-ENERGY COSMIC RAYS

It is generally believed that CRs with energy below 10^{16} **eV** are accelerated at the shocks in supernova remnants (SNRs). There are also possibilities for their acceleration by other extreme astrophysical environments in the galaxy which include pulsars particularly. In SNR acceleration picture the *knee* could be regarded as an indication of the attainment of maximum energy by the CRs through shock acceleration in SNRs. From an alternative view the *knee* may come from the relatively faster leakage of PeV CRs into the extragalactic space compared to lower energy CRs. It may be due to threshold interactions where e^+ - e^- pairs are formed due to interaction of PeV CRs with the ambient infrared photon background near the source [1]. Another speculation supports the view that CRs above PeV energies may produce exotic or undetectable particles during their advancement in the atmosphere [2].

Recently, with modern Cherenkov telescopes, γ-ray photons of TeV energies coming from SNRs have been detected, which gives strong indications for an efficient accelerations of charged particles to energies beyond 100 TeV, in consistency with the models of CR in young SNR shocks [3]. The origin of the γ-ray photons of TeV energies is still uncertain. An experimental validation of the hadonic origin of TeV γ-ray photons over leptonic origin would be eagerly awaited evidence for an acceleration of hadrons in SNRs.

It has recently been suggested that neutron stars inside the shells of young SNRs are the sources of PeV CRs and that the interaction of the particles with the radiation field in the SNR causes electron pair-production, which has relevance to recent observations of high positron fluxes [4]. Even, a pulsar with period 100 ms should be able to reach several PeV if the magnetic field were somewhat bigger than 10^{12} Gauss. In this context, the theoretical estimation of TeV gamma-ray and neutrino fluxes can help to throw light on the question about the origin of PeV CRs.

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A test for the models of origin of galactic CRs can be studied through very high energy gamma-ray astronomy. The results mainly from the last decade of the last century made it obvious that new, better gamma-ray telescopes would lead a breakthrough in the field of high-energy gamma-ray astronomy. Also, the stereo-observation technique was generally accepted as the approach that would reach sensitivities around 1% of the Crab nebula flux within 50 h observation time for achieving 5σ excess signal. High energy gamma-rays have been detected from several supernova remnants by the Cangaroo III [5], H.E.S.S. [6], MAGIC [7], VERITAS [8], HAGAR [9], MILAGRO [10], ARGO-YBJ [11]. At relatively higher energies GRAPES III [12] has a very good potential to unearth PeV hadronic sources of CRs. In near future the CTA (Cherenkov Telescope Array) [13], which will cover the energy range from 20 GeV to 100 TeV with 10 times higher sensitivity compared to H.E.S.S, is also expected to provide valuable information in this regard.

Four other projects are currently under detailed evaluation or in a first phase of construction. Advanced Gamma-ray Imaging System (AGIS) [14] and Major Atmospheric Cherenkov Experiment (MACE) [15] are Cherenkov telescopes, while the High altitude Water Cherenkov (HAWC) [16] is an extended air-shower array at high altitude for achieving a low threshold. LHAASO [17] is a facility that combines various air shower detectors elements and Cherenkov telescopes.

III. ENERGY SPECTRUM AND KNEE

Due to steeply falling flux of CRs, the measurements on the energy spectrum were performed so far only by ground based EAS experiments those are being operated in the PeV energy. These experiments improve their energy resolution and the statistics for the all-particle spectrum measurement in the course of time. On the other hand, several experiments extended the energy range and therefore make it possible to connect their own spectrum with the one measured from balloon-borne experiments at low energy and from UHECR experiments at the highest energy end.

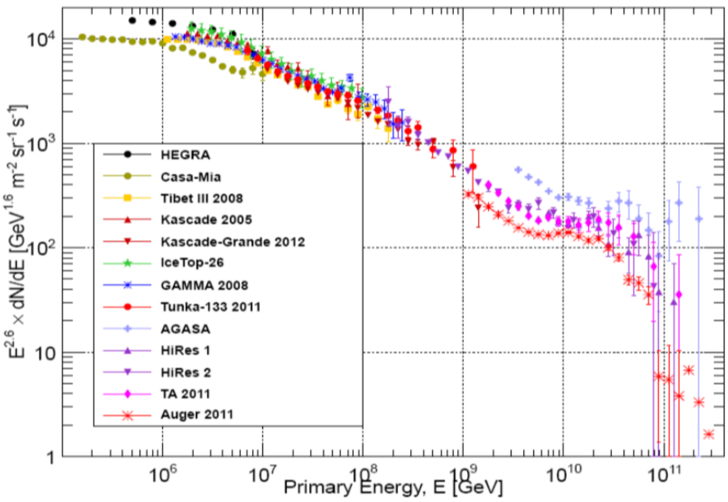

Fig. 1 All-particle energy spectrum obtained from EAS experiments [18].

The **Fig. 1** shows a compilation of currently available spectra for all particles. Interestingly all-particle spectra estimated with various detector techniques agree reasonably well with each other.

A steepening of the spectrum takes place at about 3 PeV as one may notice from the above figure which is known as the *knee* of the spectrum. The differential flux has been multiplied by $E^{2.6}$ and plotted along y-axis to show clearly the change in the slope. The CR spectrum does not have many features. Hence the *knee* is considered as a very important feature that may provide clue regarding the origin of the CRs, the central question of the astroparticle physics.

IV. AIR SHOWER SIMULATION

Air shower simulations are a crucial part of the design of air shower experiments and analysis of their data. Numerical simulation of the shower development in the atmosphere is a powerful approach to link the properties of the measured CR shower to those of the primary particle. To arrive any specific conclusions about CRs from their indirect investigation it is very important to know how they interact with the atmosphere and how the EAS develops. This knowledge is obtained by means of computer Monte Carlo (MC) simulations. In this section a short overview of the MC EAS simulations with CORSIKA [19] code is given. Comparing features obtained from the different adopted techniques applied for data analysis of the simulated showers it is possible to estimate the mass composition and energy of the primary particle from the measured data. Interaction of the primary CR particle with air and their secondaries are described by high and low energy hadronic interaction models. The information about the primary particle and its interaction history in the cascade is stored in various average EAS observables/parameters.

A MC technique offers one of the best suited approaches to provide a convolution of all physical processes to form the complex model of an EAS. The main annoying part of the MC technique since its inception lies in the uncertainties arising from the hadronic interactions at high and low energies, is still a major concern in this field in particular. Many code packages for simulating EASs are available. The most frequently used MC programs are CORSIKA [19], AIRES [20], CONEX [21], COSMOS [22], MOCCA [23] and SENECA [24]. The predictions obtained with all simulation packages are almost similar. Currently CORSIKA is used by many air shower experiments all over the world. For the

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hadronic interactions at high energies a number of interaction models have been implemented: QGSJet, DPMJet, EPOS, SIBYLL, VENUS, NEXUS, HDPM while GHEISHA, FLUKA, UrQMD and are used for hadronic interactions at low energies.

For electromagnetic interactions a modified version of the shower program EGS4 [25] (or the analytic NKG function) can be used. Options for Cherenkov radiation and neutrinos also exist. The code can be used from 10^6 up to 10^{21} eV and beyond and it covers fifty different types of particles and nuclei up to A = 56. All these particles can be tracked until they reach the predefined observation level and energy. The code also allows production of shower images and movies of the shower development.

At the heart of a MC program is the generation of pseudo-random numbers which are produced by a random number generator such as RMMARD (between 0 and 1) from the CERN library [26]. The atmosphere is composed of 78% nitrogen, 21.5% oxygen and 0.5% argon. All other elements in the air are neglected because they contribute only 1% of the total. The atmospheric model in CORSIKA uses various atmospheres with either planar or curved options that are parameterized in 5 layers with piece-wise fitted exponential. Special versions for different locations and seasons can be introduced.

Computing time and disk space needed for a shower simulation grow approximately linear with primary energy. A single shower at 10^{21} eV, with about 10^{11} secondary particles, needs about 10^5 hours and ~30 TB disk space. Therefore, statistical sub-sampling (or thinning) [27] is used to discard most of the shower particles and follow only a representative subset of them, which carry a weight to account for the discarded ones. For a good compromise of thinning and weight limitation, typical speed-up factors of 10^4 - 10^6 are reached.

Particles information on the observation level from CORSIKA is a starting point for detector simulation in the array. From the particle densities measured in the detector array various EAS observables and their distributions are reconstructed. Development of an EAS is sensitive to a number of parameters and one can try to predict how they should be changed in EAS description to achieve better agreement with observations. As the interaction models are more and more refined now and hence discrepancies between simulations and the measurement are becoming smaller. Using such a model as reference the deficiencies of other models can be understood more clearly. Currently almost all models in the low energy regime describe observed data very well. Differences are viewed in the high energy regime but they are significantly lower at present than earlier.

Over the last 15 – 20 years the agreement of simulations with experimental data has greatly improved. Today the simulations describe consistently, within about 15 – 25 %, EAS experiments from TeV to PeV (i.e. from γ-ray regime to the region of the *knee*). The method is further extended to EeV (where Haverah Park, AGASA etc. experiments are performed) and up to the 10^{20} eV range of the Pierre Auger experiment.

In the near future the ongoing accelerator/collider experiment at the LHC (14 TeV in cms) [28] is expected to provide new experimental inputs to the cross sections, diffraction and hadronic multi-particle production, additional constraint to the interaction models and thereby improving the predictive power of EAS simulations in the PeV energy range.

V. COSMIC RAY CHEMICAL COMPOSITION

The EAS measurement aiming at reconstructing the CR chemical/mass composition is a very difficult one. The reason lies in the fact that the mass of the primary particle can only be inferred from detailed comparisons of experimental observables with EAS simulations which require hadronic interactions as input. At the air shower energies accelerator data are not yet completely available (though the LHC covers these energies now) for the kinematic region of secondaries concerning to air showers and also for relevant target–projectile combinations. As a result one has to rely on high energy interaction models leading to an uncertainty of unknown order. The uncertainties of hadronic interactions at high energy in simulations become a dominant source of systematic of estimates of the CR mass composition. Hence, identification of various EAS observables with different sensitivity to the primary mass is of extreme importance as these observables should lead to consistent conclusions about the properties of the primary CRs. Any inconsistent conclusions, on the contrary, would be indicative for incomplete knowledge of the employed hadronic interaction models in simulations.

The EAS experimental data are the convolution of the primary CR distributions with all the effects related to the atmospheric cascading, which is governed by the hadronic and electromagnetic interactions. In order to extract primary information from EAS experimental data, one has to de-convolute them during adopted analysis. The electromagnetic cascading can be well described by the subject quantum electrodynamics, while for different calculations involving hadronic interaction in EAS could be made on the basis of phenomenological models. Currently, quite a good number of hadronic interaction models are available and their agreement with observations keeps improving. For the purpose of CR studies these hadronic interaction models often use interaction cross-sections resulting from the extrapolation of the cross-section versus energy plot. The validation of this extrapolation needs to be tested and further improved.

Low energy hadronic interaction models have been tested recently by many with proton and antiproton fluxes measured by BESS and Mt. Norikura experiments. While FLUKA [29] can describe better the proton spectrum than other two models, UrQMD [30] and GHEISHA [31] on the contrary, show much better agreement with antiproton spectrum.

It has also been found that CR experiments might contribute to the betterment of the hadronic interaction models. New measurements of the cross-section between proton and air are presented by the ARGO-YBJ and TienShan experiments. These experiments measured a smaller cross-section than what had been adopted in the hadronic models.

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By comparing the model calculation and KASCADE observation, both QGSJET [32] and EPOS [33] prefer a lower cross-section for the proton-air interaction.

Having very good temporal and spatial resolutions, the ARGO-YBJ carpet containing large number of RPCs has published results on the time structure of the EAS front [34] distribution and multi-core event search. Their data agree very well with model prediction.

A. Air Shower Observables Sensitive to Mass Composition

The question of the mass composition of high energy CRs arose very early. The determination of mass composition by EAS measurements requires the identification of quantities at the observation level which can be measured and depend on primary mass. There is a general agreement between different models of high energy hadronic interactions in reference to the observables most sensitive to primary mass. Note that in the context of mass composition at least two orthogonal measurements are needed to estimate both, the mass and energy of the shower initiating primary particle. This is feasible in EAS technique by observing say the longitudinal development or by simultaneous determination of the electromagnetic and muonic component of EAS at observational level. The study of the lateral distribution of EAS charged particles at ground level which is related to the EAS development stage, may also give some insights about the primary composition. We shall elaborate these techniques below**.**

The determination of the lateral density distribution (LDD) of particles in EAS leads to estimate the total number of charged particles, electrons or muons by fitting the measured densities to proper analytical functions. The mass and energy of the primary particle can then be deduced from the electron and muon numbers. The first method suggested by Linsely *et al* [35] followed from the observation that the number of muons (N_μ)and number of electrons (N_e) in an EAS are related by $N_\mu \sim N_e^\alpha$. Taking the simple superposition model one obtains $N_\mu \sim A^{1-\alpha} N_e^\alpha$, where 'A' is the mass number of a nucleus that initiates an EAS and 'α' acts merely as a factor.

The observation of the longitudinal development of the particle cascade in the atmosphere is especially well suited for composition studies. The detection of produced particles in the shower is done via fluorescence or Cherenkov light through which the signal is transferred to the detector. The mass sensitive estimator that comes out from this measurement is the slant depth (X_m) at which the EAS reaches its maximum in terms of the number of particles. A correlation exists between X_m and the slope parameter of the lateral Cherenkov light distribution which is independent of the type of the primary particle and the angle-of-incidence of the shower. In observations of the Cherenkov light by the imaging technique, the intensity pattern of Cherenkov light coming from the air shower is strongly correlated with the shower size, from which the height of maximum X_m can be determined.

The position of the maximum development of electromagnetic component of EAS in the atmosphere roughly goes as $X_m \infty \ln E$ where $E \equiv E_0/A$ is the energy per nucleon. Hence X_m depends on mass as lnA. However, X_m fluctuates event by event basis (interestingly the shower-to-shower fluctuations in X_m also carry important information about the primary particle types). Usually thus average depth of shower maximum is studied as a function of primary energy. The longitudinal development also can be studied with fluorescence technique but it is best suited at a little bit higher energies.

The second oldest method of searching for the mass of the primary CRs is the measurement of fluctuations in EAS development. The widths of the N_μ fluctuations for fixed N_e measured as $N_\mu/< N_e>$, is the main example. The fluctuations of the shower age parameter and of the height of shower origin are other examples [36].

The average transverse momentum of the secondary particles increases with energy though very slowly. As the longitudinal momentum increases faster than in proportion to the primary energy per nucleon, the emission angle of the secondary particle is smaller in a proton induced shower. As a consequence the lateral distributions of all types of shower particles, electrons, muons and hadrons are expected to be wider in an EAS induced by a heavy nucleus than one initiated by a proton. This feature can be extracted from the EAS initiated by CR particle.

The shape of the LDD of EAS also contains information about the underlying particle physics in the EAS and, thereby also about the mass of the primary particle. Generally, showers initiated by heavy primaries will exhibit a flatter LDD than those initiated by light primaries. This feature is observed both for electrons and muons. It is worthwhile to mention that the sensitivity of the LDD to the primary mass, however, is weaker as compared to the N_e - N_μ method or those techniques else.

The reconstruction of the mean heights of production of muons in EAS brings interest to learn about the longitudinal shower development. The technique was revived in the 90ies for tracking electrons and muons with the CR Tracking (CRT) detectors at HEGRA [37], the Muon Tracking Detectors at KASCADE [38] or at GRAPES [12] after 60ies of the last century.

There are few other mass sensitive observables, such as muon charge ratio, rise time of Cerenkov signal etc. which are not covered here. Interested readers may see the proceedings of bi-annual conferences of International Cosmic Ray Conferences for the detailed discussion of the mentioned and other techniques.

The KASCADE collaboration proposed a refined procedure few years back in determining mass composition from EAS measurements. The main features of their approach are: (**i**) to measure as many mass-dependent observables as possible in order to average out at least part of the fluctuations and (**ii**) to derive combinations of these measured quantities which give good estimates of energy and mass of the primary for each individual shower.

In this context, we, the NBU group have given particular focus on the characteristics of the shower age parameter, which essentially describes the slope of the lateral distribution of electrons in EAS, and the possible role that the

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parameter may play in a multi-parameter approach of studying EAS in order to understand the nature of shower initiating particles in the PeV energy regime [60-61]. We have also explored whether geomagnetic spectroscopy can be employed cleverly to extract information on primary mass [62].

B. Measurement of the Primary Mass Composition

The reliability of primary composition extracted from EAS experiments can be checked at TeV energies where direct measurements are available. To reach TeV energies, EAS experiments need to locate at high very altitudes such as the ARGO-YBJ [10] experiment that has a full coverage array (80m X 80m) having resistive plate chambers (RPCs) with excellent resolutions both in time and position. The array is competent enough to allow real time view of a propagating EAS to be obtained including its structure near the core. In the energy range from 10 to 300 TeV, the experiment measured mass composition of light components, such as protons and helium from the knowledge of particle densities in inner and outer regions surrounding the core as shown in **Fig. 2**. Their spectra agree rather well with direct measurements from CREAM [39]. The analysis of ARGO-YBJ data seems to indicate a composition similar to JACEE [40] than CREAM as can be seen from the **Fig. 2**.

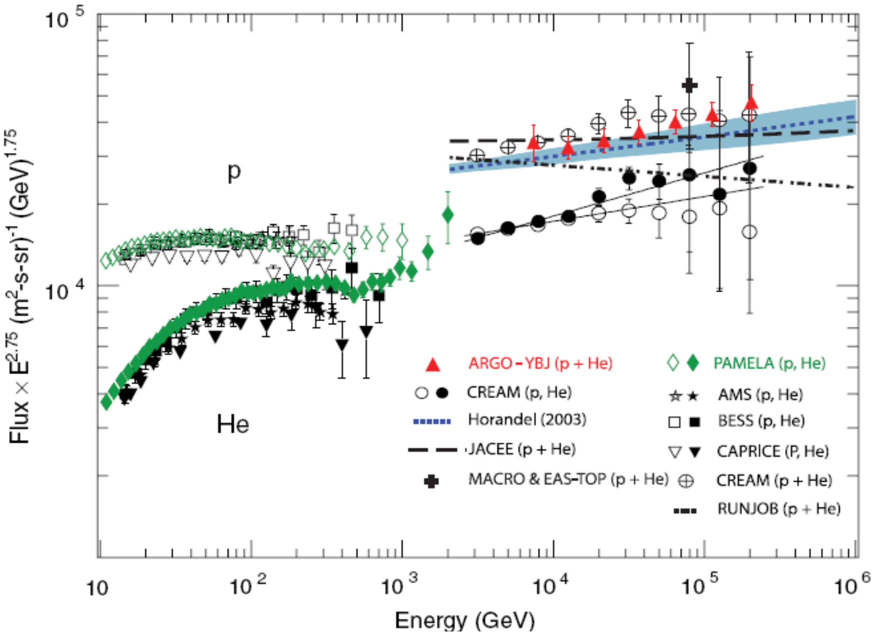

Fig. 2 Light component (p + He) spectrum of primary CRs measured by ARGO-YBJ compared with other experimental results [41].

Concerning mass composition at PeV energies muon content (or rather electron content as muon size is used to estimate the primary energy) is widely used to extract primary mass. In this approach, electron-muon discrimination achieved by employing a combination of unshielded and shielded scintillation detectors at ground level. There are number of recent experiments implemented the approach (examples AGASA, CASA-MIA, EAS-TOP, GRAPES, KASCADE and Grande, Maket-ANI, Yakutsk etc.). The muon identification through water Cherenkov detectors were employed in AUGER and Haverah Park detector. IceTop at the South pole uses tanks of frozen ice for the purpose in combination with IceCube at underground. Similar combinations of surface and underground detectors have been used by EAS-TOP and MACRO at the Gran Sasso and Baksan.

One of the major uncertainties occurs in the result due to fluctuations. It is important to realize that electron and muon numbers do not fluctuate independently on event-by-event basis, but are mutually correlated. Such an effect can be properly accounted for by a two-dimensional unfolding technique, first utilized by KASCADE-collaboration [42].

The ICECUBE [43] collaboration extracts primary composition by using the N_e - N_μ correlation. They had used muon data with E_μ^{cut} > 500 GeV and N_e from ICETOP with E_e^{cut} > 1 MeV. However, due to low statistics the composition could be probed only as a combination of protons and iron nuclei. Within error ranges the all particle spectrum was consistent with earlier measurements (Rawlins et al., 2011). Above 100 GeV the muon and muon-neutrino spectra were simulated by using primary CR spectra from KASCADE [44] for five nuclei that were extrapolated with a rigidity dependent *knee* for respective nuclei. The Auger spectra were used at UHEs and the difference between Auger and extrapolated KASCADE spectra in the overlap of energy region was attributed to an extragalactic proton component. The spectral shape of muon and muon neutrino appeared to depend on the all-particle spectra rather than the actual composition. This would lead to facilitate accurate calculation of muon and muon-neutrino fluxes at high energies.

Most of the experiments such as the CASA-MIA [44], MSU [45], HEGRA-CRT [37], KASKADE [46], EAS-TOP [47], SPASE-AMANDA [48], on the basis of muon content relative to electron content in EAS, infer that the composition becomes heavier with increasing energy in the region of *knee*.

Non-imaging observations by operating photo multiplier tube assembly with large Winston Cones looking upwards into the night-sky are perhaps the simplest and most straight forward technique of observations. This method was first

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successfully applied at energies around the *knee* by the HEGRA array [49] and by CASA-BLANCA [50]. More recent measurements have extended these measurements at Tunka [51] and Yakutsk [52] up to ultra-high energies. The slope of the lateral distribution of Cherenkov light measured within nearly 100 m is found to depend on the height of the shower maximum and hence on the mass of the primary CRs. The results of Cerenkov measurements including the DICE [53], CASA-DICE [54], CASA-BLANKA [50], TUNKA [55], HEGRA [49], and few others suggest for a mixed composition below the *knee* with either no significant change in average mass above the *knee* at least up to 10 PeV or a slowly decreasing/increasing average mass beyond the *knee.* A different conclusion is reached by only few experiments such as the CACTI [56]

Using muon multiplicity information, GRAPES-III [12] studied the primary composition up to PeV energies with SIBYLL and QGSJET models. Significant differences are seen between the two model assumptions. They found that SIBYLL model better describes data than QGSJET. Similar conclusion was obtained when comparing the composition results of the Tibet ASγ [57] with the KASCADE experiment.

The Tibet ASγ collaboration in association with a set of new detectors that included Yangbaijing air core detectors (YAC-I and II), water Cherenkov muon detectors and so on, reported several results on mass composition and the uncertainties of hadronic interaction model. They have used an artificial neural network (ANN) for data analysis exploiting extensive MC simulations for EAS events. Preliminary results from data analysis using ANN showed that the data are in good agreement with the QGSJET II and SIBYLL 2.1 models. This agreement persists in the energy range from 30 to 1800 TeV. The Tibet ASγ has also put efforts to separate proton, proton+helium, and iron candidate events that were trained for QGSJET II with a heavy dominated composition. Their technique has been cross checked by the ability to extract known contributions of protons, helium and iron nuclei from the Monte Carlo data. The fraction of proton, helium and iron nuclei were obtained from an analysis using ANN to obtain the all particle spectrum from the Tibet ASγ data.

Fukui et al. 1960 and Khristiansen et al. 1963 were the first to study the muon number fluctuations in the *knee* region and they were also the first concluding an enrichment by heavy nuclei above the *knee* energy. Similar conclusions were drawn in [58] based on a larger data set.

A noticeable result on the muon production height measurement with KASCADE-Grande is compatible with a clear transition from light to heavy primaries with increasing energy across the *knee.* The time profile of EAS particles was used by Bassi et al. 1953 at Haverah Park in the context of primary composition in UHE region.

The analysis of Miyake *et al.* 1973 carried out with data from Mt. Norikura (2770 m a.s.l.) for the measurements of primary composition using *shower age* and shower size as observables hinted a change in the composition with heavier domination beyond a size of ~ 10^7. The shower size dependence of the *age parameter* from measurements with the MAKET-ANI array located at Mt. Aragats (3200 m a.s.l.) in Armenia when compared with simulations showing the expected *age* dependence on shower size that would result for a primary beam with heavier domination starts at 10^7 onwards. The result from Akeno taking the variation of *shower age* as a function of muon size for fixed shower sizes maintained the general trend showing a rising *shower age* with an increasing muon number. They had correlated this feature with the primary mass and/or the secondary particle multiplicity. We, the NBU group also reached similar conclusions using an unambiguously measured mass sensitive observable, namely the local age parameter for the composition of primary CRs around the *knee* region [59-61].

The important findings of our group on the cosmic ray chemical composition are pointed out as follows.

The shower age parameter in terms of local age offers a good solution towards an unambiguous estimation of the lateral shower age. The lateral shower age offers a good estimator of the longitudinal development of an EAS cascade on a statistical basis, as also noted in some earlier works. The lateral shower age might be useful for extracting information about the mass of primary cosmic rays (see **Fig. 3**) [61]. The fluctuation of the local age parameter has also been found to be sensitive to the nature of the primary particle [60]. It appears that the local age parameter, if measured with good precision can be employed in discriminating γ-ray initiated EAS from hadron induced EAS [61].

The "muonic dipole length" in inclined EAS is found sensitive to primary mass; it is larger for iron primary in compare to that for proton [62].

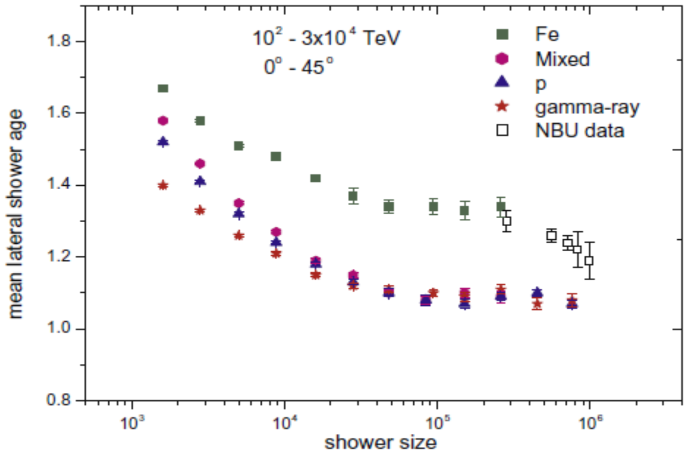

Fig. 3 Variation of mean shower age with shower size along with NBU experimental data.

VI. SUMMARY AND CONCLUSIONS

The origin of PeV CRs is still not clearly known. The SN shocks from explosion and SNRs provide sites suitable for CR acceleration up to E ~ 10^{16} - 10^{17} eV. On the other hand, acceleration in compact objects such as Pulsars, X-ray binaries etc., the CR energy may reach even up to ~10^{17} eV or so.

The proper explanation of the *knee* feature is believed to provide key insight on the origin of the *knee*. In order to understand the full story of the *knee* the mass composition needs to be estimated accurately. As stated above the CR mass composition beyond the *knee* is not definitively established yet, with some observations [59-61] suggesting that it turns lighter and others instead suggesting that the heavier components become dominant. What will the conclusion on primary mass composition be in the PeV regime**:** KASCADE, GRAPES or Tibet or else? To improve the situation concerning mass composition multi-parameter study is vital.

A precise estimation of the mass composition of CRs at PeV energies heavily relies on the progress in understanding the hadronic interaction models used in MC simulations. The LHCf experiment is studying the very forward region with proton-proton beams at the centre of mass energy of about 10^{17} eV, which is directly relevant to the EAS development in the atmosphere. With the results of this experiment the uncertainties due to our incomplete knowledge of hadronic interactions will be reduced significantly. The information of hadronic interactions extracted from EAS observations also should be important in this regard and may lead to find out new hadronic interaction models.

The ongoing and upcoming high energy gamma-ray and neutrino experiments are expected to provide concrete evidences of the sources of CRs, particularly those are within the galaxy. Meanwhile effort should be made to make the theoretical predictions for the high energy gamma-rays/neutrinos from the potential sources so that they can be effectively compared with observations in searching CR sources. Consideration of latest LHC data and the fine tuning of hadronic models with them will enhance the predictive power of the MC simulation code in order provide a more concrete information about the primary CRs and would help for designing future EAS experiments.

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