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Energy spectrum of the primary cosmic rays in the range 10 GeV–10 TeV

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The GRAPES-3 experiment measures directional muon flux above 1 GeV muons with very high precision. For a precise simulation of the measured muon flux, the energy spectrum of primary cosmic rays should be accurately known. We have used the data from several balloon and satellite based experiments to determine the proton and helium spectra in the GeV to TeV energy range. Since these experiments utilize different measurement techniques the results on energy spectra were represented in different units. A detailed study has been performed to evaluate the spectral indices of the proton and helium primaries in the corresponding energy ranges of 10 GeV–10 TeV and 20 GeV–20 TeV, respectively. From the present study the spectral indices for proton and helium are found to be $\gamma_P = 2.652 \pm 0.001$ and for helium, $\gamma_{He} = 2.452 \pm 0.001$, respectively.

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1. Introduction

The measurement of primary cosmic ray spectra is one of the basic tools to understand the processes for the production of cosmic rays, matter distribution in interstellar medium and their nature of propagation in the Galaxy. Energy spectrum of primary cosmic rays have been studied over a large range of energy $\sim 10^8 - 10^{20}$eV[1, 2, 3]. It has been investigated that the abundance of proton and helium nuclei are dominant up to hundreds of TeV and afterwards heavy nuclei starts dominating. Spectrum of proton and helium primaries is precisely measured from a few GeV to hundreds of TeV by using different measurement techniques in satellite and balloon borne experiments. Precise measurements of energy spectra in GeV energy range requires a sophisticated design of using hybrid combinations of various kinds of detectors. Some of these detector includes magnetic spectrometer, calorimeter, cherenkov detectors, time of flight(ToF), tracking system(drift chambers). Due to use of different measurement techniques the results are also reported in different units including energy per nucleon, energy per unit charge, momentum per unit charge (rigidity) and total energy[4, 5, 6, 7, 8, 9, 10].

In the present work, we have converted the proton and helium primary flux data from different units into a single unit mainly total energy, which we can be subsequently used in Monte Carlo simulations. Some salient features of measurements of proton and helium spectra in their corresponding energy units are given below:

1. CAPRICE98 (Cosmic AntiParticle Ring Imaging Cherenkov Experiment) [5] is mainly consisting of a superconducting magnet spectrometer(tracking system), a gas Ring Imaging CHerenkov(RICH) detector consists of 1m tall gas(C_4F_{10}) radiator and a photosensitive multi-wire proportional chambers(MWPC) contained a photosensitive saturated ethane gas, ToF device gives the trigger to data acquisition system and a silicon-tungsten imaging calorimeter provides the topology of the interacting events[5, 11, 12, 13]. Tracking system was consisted with three drift chambers along with spectrometer of superconducting magnet operated at current of 120 A and field intensity of 0.1–2.0 T and obtained maximum detectable rigidity(MDR) of 300 GV. Therefore, the wide energy range of 3–350 GeV have been covered with the help of CAPRICE98 balloon flights as compared to earlier CAPRICE94[14] and CAPRICE97 flights[15].

2. BESS-TeV (Balloon-borne Experiment with a Superconducting Solenoid for TeV)[6] BESS-TeV flights were flown with the payload of superconducting spectrometer produced magnetic field of 1 T in order to achieve cosmic ray energy spectra in TeV energy range and could improve MDR from 200 GV[16] to 1.4 TV by introducing several inner and outer drift chambers. In addition, BESS-TeV carried ToF hodoscopes[17] provides the velocity(β) and energy loss(dE/dx) measurements, first-level trigger to data acquisition given by ToF, threshold type cherenkov counter with a silica aerogel radiator an auxiliary trigger to record energetic particles without any bias or sampling. Energy ranges of 1–540 GeV and 1–250 GeV/n have been covered for proton and helium spectra respectively.

3. CREAM (Cosmic Ray Energetics And Mass experiment)[7] instrument designed to extend the energy limits for elemental cosmic ray spectra. Payload consisted of a timing charge

detector(TCD), a transition radiation detector(TRD) with a cherenkov detector(CD), a silicon charge detector(SCD), hodoscope(HDS), and a tungsten/scintillating fiber calorimeter. Whereas, TCD gives the 2.2 m^2–sr trigger geometry and determines the charge based on the fact that incident particle enters the TCD before developing a shower in the calorimeter[18]. The alignment of CD in between TRDs provides the rejection of low energy particles. The use of SCDs and scintillator fiber calorimeter gives the measurement of energy and tracking of the high energy particles[19]. The energy range measured by first flight of CREAM flights for 42 days flown in Antarctica in 2004–2005 is 2.5 TeV–250 TeV and 0.63 Tev/n–63 TeV/n for proton and helium primaries respectively.

4. PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) is a satellite based payload which is flying on board the Russian Resurs-DK1 satellite since 2006 June, in a semi polar near earth orbit. Comprises a number of highly redundant detectors. Multiple detectors are placed around a permanent magnet with a silicon micro-strip tracking system, providing charge and track deflection ($d = \pm\frac{1}{R}$) information, which basically measures particles rigidity, charge and momentum. A scintillator system provides the trigger for event acquisition, the ToF measurement, and further charge information. A silicon-tungsten calorimeter is used to perform hadron/lepton separation and energy measurements[20, 21]. The flux of proton and helium primaries have been measured in the energy range of 30–1000 GeV and 15–600 GeV/n respectively and in rigidity range of 30–1000 GV[9].

5. AMS-01 (Alpha Magnetic Spectrometer phase-01)[10] was flown on International Space Station from June 2nd to 12th 1998. The AMS-01 experiment consisted of a cylindrical permanent magnet with a bending power of 0.14 Tm^2 and an acceptance of 0.82 m^2–sr., which is covered with an arrangement of two scintillator paddles forming a ToF system. This provided a fast trigger signal as well as a measurement of velocity and charge number. The silicon tracking device consisted of six layers of double-sided silicon strip detectors mounted inside the magnet volume where charged particle trajectories were reconstructed with an accuracy of better than 20 μm. Velocity measurements were augmented with a two-layered aerogel cherenkov threshold counter(ATC) mounted underneath the lowest ToF layer, allowing e^+/p discrimination below 3 GeV/c. A detailed description of the experiment is given in[22, 23]. The proton and helium spectra have been reported in the energy range of 0.2–200 GeV and 0.1–100 GeV/n respectively.

2. Analysis

GRAPES-3(Gamma Ray Astronomy at PeV EnergieS phase 3) contains an array of 400 plastic scintillator detectors each of 1 m^2 area having 8 m inter-detector separation between two detectors, are arranged in hexagonal geometry and a muon tracking detector of 560 m^2 large area which is basically an array of 3712 proportional counters. The muon detector contains 16 modules, whereas each module contains orthogonally arranged proportional counters in 4 layers with 58 counters in each layer[24, 25]. The energy threshold of muon detector for vertical muons is 1 GeV could be achieved by keeping the telescope under the concrete of $\sim$ 550 gm-cm^{-2} thickness. The threshold energy of muons is $Sec(\theta)$ GeV along a direction with zenith angle θ and the angular resolution of the muon detector is 6°[26]. Typically, it records $\sim 4\times 10^9$ muons per day. The use of four orthogonal layers of proportional counters permits measurement of the muon direction from a fairly large solid angle (∼3 sr). This tracking capability allows the selection of muons from a given direction in the celestial hemisphere for studying cosmic ray variations. A total area of 560 m^2 of the GRAPES-3 muon detector results in a large rate of > 1 GeV muons[24]. This large rate of muons offers a very sensitive probe for studying the variations in primary cosmic rays due to a variety of atmospheric and solar phenomena. GRAPES-3 collaborators have reported Forbush decrease in muon flux due to coronal mass ejection(CME) or shocks[27, 28]. Solar diurnal anisotropy also have been observed because of precisely measured high rate of muon flux[26]. Therefore, in order to understand these solar and atmospheric phenomena more elaborately in the energy range of 10 GeV–10 TeV for proton and 20 GeV–20 TeV for helium primary induced showers, precise simulation studies have to be carried out. With the advantage of such a rich statistics of muon telescope, a precise simulation study requires precise cosmic ray spectra. Simulation studies will be helpful to compare the GRAPES-3 experimental data with the theoretical models in this energy range[29]. We use a standard simulation package of cosmic ray air shower, CORSIKA (COsmic Ray Simulations for KAscade) developed by a group of physicists in KASCADE experiment at Karlsruhe Institute of Technology, Karlsruhe, Germany[30]. CORSIKA program requires the spectral indices of primary cosmic ray spectra dependent on total energy. Henceforth, the transformation of differential spectrum dependent on total energy is required. While several experiments have measured spectrum of proton and helium primaries in terms of GeV/n or GV. Present study reveals the unified energy spectrum over total energy dependency which will be beneficial to the scientific community. Furthermore, the transformations for other units also have been performed. We try to find out spectral indices dependency on different units of measurements (GeV/n, GV and GeV).

The flux of cosmic rays follows a power-law dependence over energy, $\phi = \phi_\circ.E^{-\gamma}$ (m^2 sr sec GeV $n^{-1})^{-1}$ with the spectral index (γ) of cosmic ray spectrum, small difference in the exponent reflects different components and processes [31]. Experiments did not use magnetic spectrometer, they could not measure the rigidity of cosmic ray particles[7]. On the other hand, the experiments have used magnetic spectrometer and calorimeter altogether they could measure energy as well as rigidity of the cosmic ray particles[8, 9, 5, 6]. As discussed earlier cosmic ray spectrum of differential flux can be measured in terms of kinetic energy per nucleon, momentum per unit charge, energy per unit charge. We try to convert the flux dependency from one unit of measurement (energy/rigidity) into another unit of measurement by evolving some transformation relations.

2.1 Conversion of Kinetic Energy per nucleon into Rigidity

Spectrum of cosmic rays differential flux depending upon kinetic energy per nucleon($E_{k.e/n}$) can be written as:

$$\frac{dN}{dE_{k.e/n}} = \phi_{\circ,k.e/n}.E_{k.e/n}^{-\gamma}(m^2\, sr\, sec\; GeV\, n^{-1})^{-1} \tag{2.1}$$

Similarly, differential flux can be defined in terms of rigidity (R) power law:

$$\frac{dN}{dR} = \phi_{\circ,R}R^{-\gamma} \qquad (m^2\, sr\, sec\; GV)^{-1} \tag{2.2}$$

Since, the definition of Rigidity(R) is momentum per unit charge,

$$R = \frac{pc}{|z|e} \tag{2.3}$$

where, pc is the momentum of the relativistic primary identity and ze is the total charge accompanied by primary identity.
We can write down the corresponding differential flux in kinetic energy($E_{k.e}$):

$$\frac{dN}{dE_{k.e}} = \frac{dN}{dR}\frac{dR}{dE_{k.e}} \tag{2.4}$$

By using Eq. 2.4, one can get

$$R = \frac{\sqrt{E_{k.e}(E_{k.e}+2mc^2)}}{|z|e} \tag{2.5}$$

$$\frac{dN}{dE_{k.e}}(m^2\,sr\,sec\,GeV)^{-1} = \frac{(E_{k.e}+mc^2)}{z\sqrt{E_{k.e}(E_{k.e}+2mc^2)}}\left(\frac{dN}{dR}\right)(m^2\,sr\,sec\,GV)^{-1} \tag{2.6}$$

$$\frac{dN}{dR}(m^2\,sr\,sec\,GV)^{-1} = \frac{z\sqrt{E_{k.e}(E_{k.e}+2mc^2)}}{(E_{k.e}+mc^2)}\left(\frac{dN}{dE_{k.e}}\right)\quad(m^2\,sr\,sec\,GeV)^{-1} \tag{2.7}$$

$$\frac{dN}{dR}(m^2\,sr\,sec\,GV)^{-1} = \frac{z\sqrt{E_{k.e}(E_{k.e}+2mc^2)}}{n(E_{k.e}+mc^2)}\left(\frac{dN}{dE_{k.e/n}}\right)\quad(m^2\,sr\,sec\,GeV/n)^{-1} \tag{2.8}$$

Eq. 2.8 is the transformation of differential energy flux dependency from kinetic energy per nucleon into rigidity.

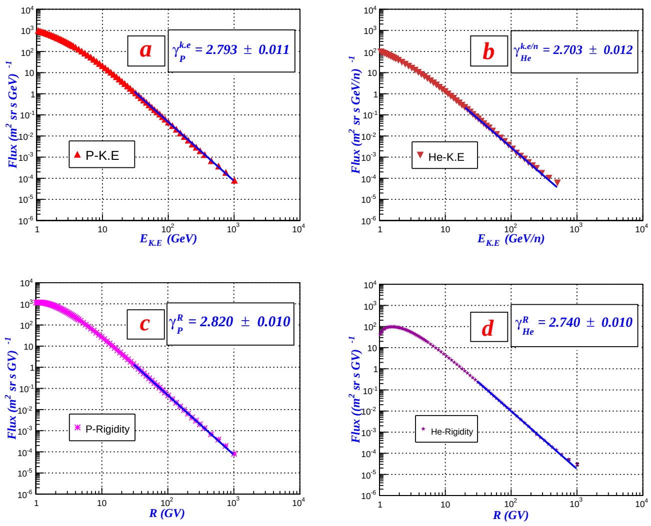

Figure 1: PAMELA spectrum of Proton(P) and Helium(He) primaries in kinetic energy(a),(b) and in rigidity(c),(d)

2.2 Conversion of Kinetic Energy per nucleon into Total Energy

Spectrum of differential flux $(m^2\, sr\, sec\; GeV\, n^{-1})^{-1}$ dependent over kinetic energy per nucleon can be defined as:

$$\frac{dN}{dE_{k.e/n}} = \phi_\circ . E_{k.e/n}^{-\gamma}$$

$$\frac{dN}{dE_{k.e}}(m^2\, sr\, sec\; GeV)^{-1} = \frac{1}{n}\phi_\circ . E_{k.e/n}^{-\gamma} \quad (m^2\, sr\, sec\; GeV/n)^{-1}$$

$$\frac{dN}{dE_{k.e}} = \phi_\circ .(E - mc^2)^{-\gamma} \tag{2.9}$$

$$\frac{dN}{dE_{k.e}} = \phi_\circ . E^{-\gamma}\left(1 - \frac{mc^2}{E}\right)^{-\gamma} \tag{2.10}$$

$$\frac{dN}{dE_{k.e}} = \frac{dN}{dE}.\left(\frac{E_{k.e}}{E}\right)^{-\gamma} \tag{2.11}$$

$$\frac{dN}{dE} = \left(\frac{E_{k.e}}{E}\right)^{\gamma} . \frac{dN}{dE_{k.e}} \qquad (m^2\, sr\, sec\; GeV)^{-1} \tag{2.12}$$

$$\frac{dN}{dE}(m^2\, sr\, sec\; GeV)^{-1} = \frac{1}{n}\left(\frac{E_{k.e}}{E}\right)^{\gamma} . \frac{dN}{dE_{k.e/n}}(m^2\, sr\, sec\; GeV/n)^{-1} \tag{2.13}$$

With the advantage of overlap in the measured energy ranges covered by different experiments

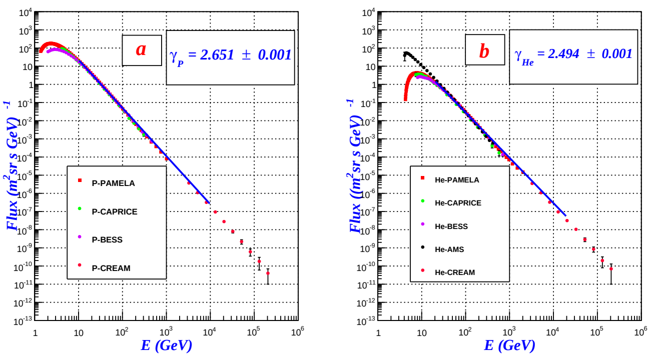

Figure 2: Differential total energy spectrum of (a)proton and (b)helium primaries for 10 GeV–10 TeV and 20 GeV–20 TeV

[5, 6, 7, 8, 10], we can combine the transformed data for the unified spectrum of proton and helium primaries in Fig.2.

3. Results and Discussions

PAMELA experiment has reported differential spectra of cosmic rays in rigidity and kinetic energy per nucleon[8, 9]. We fit the PAMELA measured spectra dependent on kinetic energy in the given energy range 30 GeV–1000 GeV and 15 GeV/n–600 GeV/n for proton and helium respectively[8] and transform it into rigidity dependent with Eq. 2.8 and fit this transformed spectra in the given rigidity range of 30 GV–1000 GV for proton and helium primary[9]. Fig.1 represents the differential flux along with the fitting spectral indices in kinetic energy per nucleon($\gamma_{k.e/n}$) and rigidity(γ_R). The difference in γ_R and $\gamma_{k.e/n}$ decreases on increasing energy ranges, which varies from 10% to 1% for 30 GV to 100 GV[8]. The calculated values of $\gamma_{k.e/n}$ and γ_R and their differences have been calculated and tabulated in Table.1 and Table.2 for proton and helium respectively along with the measured values by different five experiments. It is clear from the tables that calculated spectral indices are fairly in good agreement with the reported values and the differences between calculated spectral indices are $<4\%$.

Expt.	Energy (GeV)	Rigidity GV	$\gamma_{k.e/n}$		γ_R		Diff(%)
			Reported	Calculated	Reported	Calculated	
PAMELA	30-1000	30-1000	2.782 ± 0.003	2.793 ± 0.011	2.820 ± 0.003	2.820 ± 0.010	0.96
CAPRICE	20-350	21-351	2.75 ± 0.02	2.753 ± 0.017	–	2.808 ± 0.018	1.98
BESS	20-540	21-541	2.732 ± 0.011	2.725 ± 0.010	–	2.766 ± 0.011	1.49
CREAM	2500-250000	2501-250001	2.66 ± 0.02	2.671 ± 0.034	–	2.672 ± 0.033	0.04

Table 1: Reported and calculated values of $\gamma_{k.e/n}$ and γ_R for proton and the differences of calculated γ

Expt.	Energy (GeV/n)	Rigidity GV	$\gamma_{k.e/n}$		γ_R		Diff(%)
			Reported	Calculated	Reported	Calculated	
AMS	10-100	20-200	–	2.696 ± 0.027	2.740 ± 0.010	2.743 ± 0.022	1.73
PAMELA	15-600	30-1000	2.712 ± 0.010	2.703 ± 0.012	2.732 ± 0.005	2.740 ± 0.010	1.36
CAPRICE	15-150	32-302	2.67 ± 0.06	2.674 ± 0.055	–	2.756 ± 0.058	3.02
BESS	20-250	21-502	2.699 ± 0.040	2.697 ± 0.040	–	2.763 ± 0.041	2.42
CREAM	630-63000	631-63001	2.58 ± 0.02	2.588 ± 0.032	–	2.590 ± 0.032	0.07

Table 2: Reported and calculated values of $\gamma_{k.e/n}$ and γ_R for proton and the differences of calculated γ

After transformation of proton and helium spectra into total energy from rigidity and kinetic energy per nucleon using Eq. 2.13, data from different experiments follows a unified pattern of total energy power law spectra with the maximum likelihood fit spectral indices $\gamma_P = 2.651 \pm 0.001$ and $\gamma_{He} = 2.494 \pm 0.001$ for 10 GeV–10 TeV and 20 GeV–20 TeV respectively in Fig.2. The precise values of spectral indices will be taken as an input parameter in CORSIKA simulation[30] to compare the models[32] with the GRAPES-3 muon data.

4. Conclusions

With the help of present study, we can draw the conclusion that the unified spectra of cosmic rays in total energy could be achieved with the help of transformations applied on the data reported in different units of measurements by different experiments and shows the sense of unification in measurements of different experiments. The unified differential energy spectra can be used for further simulation studies which are relevant to the energy range of 10 GeV–10 TeV for proton and 20 GeV–20 TeV for helium. The differences in calculated γ_R and $\gamma_{k.e/n}$ are in good agreement for different experiments.

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