Energy spectrum of Primary Cosmic Rays in the range of 10 GeV – 10 TeV

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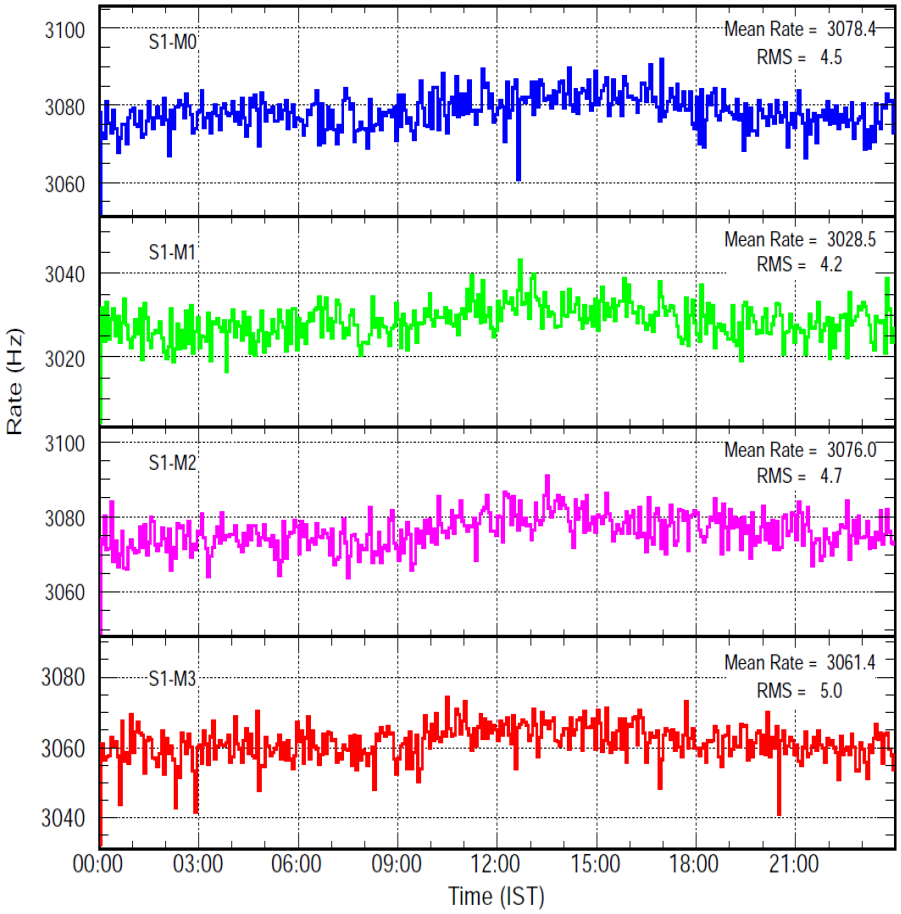
GRAPES-3 (Gamma Ray Astronomy at PeV EnergieS – 3)

- 400 scintillation detectors (1 m^2 each)
- Area covered 25000 m^2
- Hexagonal layout 8m inter-detector separation
- Measures density, arrival time of particles to estimate primary energy and direction

- 16 muon modules (35 m^2 each) = 560 m^2
- EAS trigger rate ~33 Hz
- Records muon flux (>1 GeV) spread over solid angle of 2.3 Sr in 13x13=169 directions

Muon Rate

- Muon rate in each module ~ 3000 Hz.
- ~4 billion muons/day from 169 directions, 0.002% of statistical accuracy.
- Angular distribution of muons to very high precision.
- Successfully corrected for efficiency variation of detector.
- Variation in muon rate due to various atmospheric and solar phenomena can be studied.



Motivation

- Muon angular distribution calculated using CORSIKA simulations shows dependence on assumed hadronic interaction models.

- However, before comparing an experimentally measured muon angular distribution with expectations from Monte Carlo simulations using different hadronic interaction models, it is necessary to have access to precise energy spectrum of cosmic rays.

- Muons detected in GRAPES-3 are produced by primary cosmic rays largely in 10 GeV to 10 TeV energy range.

Present work

- Recent direct measurement of energy spectrum and composition of cosmic rays in the relevant energy range of 10 GeV to 10 TeV responsible for production of >1 GeV muons in GRAPES-3 have been used.
- Dominant components are proton and helium.
- We have used results from balloon and satellite experiments.
  - ✓ Balloon experiments (BESS, CREAM, CAPRICE)
  - ✓ Satellite experiments (PAMELA, AMS)
- The main components used in satellite and balloon experiments are
  - ✓ Magnetic spectrometer - Rigidity
  - ✓ Calorimeter - Energy measurements
- Since, these experiments have used different techniques of measurements (energy, rigidity), therefore, energy spectrum is reported in different units.
- For our simulations total energy spectrum is required which have been generated from above measurements.

$E_{k.e.}/n(m^2\ Sr\ S\ GeV\ n^{-1})^{-1}$ into $E_T(m^2\ Sr\ S\ GeV)^{-1}$

$$\frac{dN}{dE_{k.e/n}}(m^2\ sr\ s\ GeV\ n^{-1})^{-1} = \emptyset_0 E_{k.e/n}^{-\gamma}\ (m^2\ sr\ s\ GeV\ n^{-1})^{-1}$$

$$\frac{dN}{dE_{k.e}}(m^2\ sr\ s\ GeV)^{-1} = \frac{1}{n}\emptyset_0 E_{k.e/n}^{-\gamma}\ (m^2\ sr\ s\ GeV\ n^{-1})^{-1}$$

$$\frac{dN}{dE_{k.e}}(m^2\ sr\ s\ GeV)^{-1} = \emptyset_0 E_{k.,e}^{-\gamma}(m^2\ sr\ s\ GeV)^{-1}$$

$$\frac{dN}{dE_{k.e}} = \emptyset_0(E_T - m_0c^2)^{-\gamma} = \emptyset_0 E_T^{-\gamma}\left(\frac{E_T - m_0c^2}{E_T}\right)^{-\gamma}$$

$$\frac{dN}{dE_{k.e}} = \frac{dN}{dE_T}\left(\frac{E_{k.e}}{E_T}\right)^{-\gamma}$$

$$\frac{dN}{dE_T}(m^2\ sr\ s\ GeV)^{-1} = \frac{1}{n}\left(\frac{E_{k.e}}{E_T}\right)^{\gamma}\frac{dN}{dE_{k.e/n}}\ (m^2 sr\ s\ GeV\ n^{-1})^{-1}$$

R(m^2 Sr S GV)$^{-1}$ into E_T(m^2 Sr S GeV)$^{-1}$

$$\frac{dN}{dE_{k.e/n}} = \emptyset_0 E_{k.e/n}^{-\gamma} \, (m^2 \, sr \, s \, GeV \, n^{-1})^{-1}$$

$$\frac{dN}{dR} = \emptyset_0 R^{-\gamma} (m^2 \, sr \, s \, GV)^{-1}, where \; R = \frac{pc}{|z|e}$$

$$\frac{dN}{dE_{k.e}} = \frac{dN}{dR}\frac{dR}{dE_{k.e}} \; and \;\; R = \frac{\sqrt{E_{k.e}(E_{k.e} + 2mc^2)}}{|z|e}$$

$$\frac{dN}{dR}(m^2 \, sr \, s \, GV)^{-1} = \frac{|z|\sqrt{(E_{k.e}(E_{k.e} + 2mc^2))}}{n(E_{k.e} + mc^2)} \frac{dN}{dE_{k.e/n}}(m^2 \, sr \, s \, GeV \, n^{-1})^{-1}$$

$$\frac{dN}{dE_T}(m^2 \, sr \, s \, GeV)^{-1} = \frac{(E_{k.e} + mc^2)}{|z|\sqrt{E_{k.e}((E_{k.e} + 2mc^2))}} \left(\frac{E_{k.e}}{E_T}\right)^{\gamma} \frac{dN}{dR}(m^2 \, sr \, s \, GV)^{-1}$$

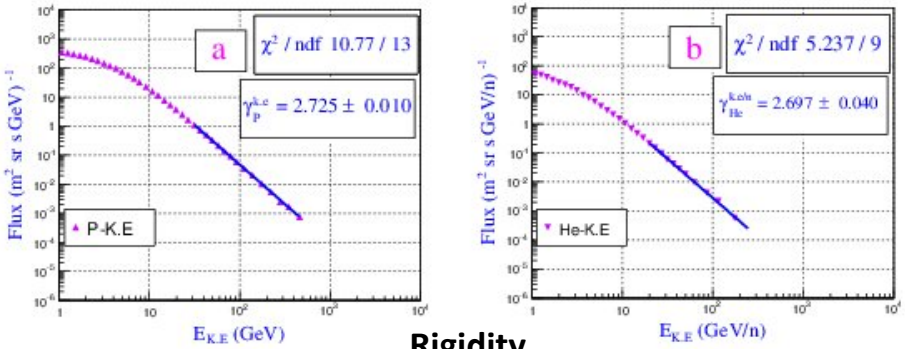
BESS

(Balloon-borne Experiment with a Superconducting Solenoid for TeV)

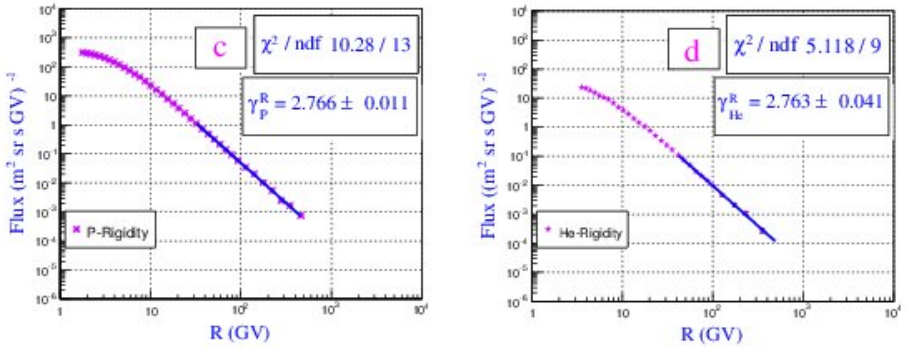
Type	K.E (GeV/n)		
		Reported	Calculated
Proton	20 – 540	2.732 ± 0.011	2.725 ± 0.010
Helium	20 – 250	2.699 ± 0.040	2.697 ± 0.040

Type	Rigidity (GV)		
		Reported	Calculated
Proton	21 – 541	-	2.766 ± 0.011
Helium	42 - 502	-	2.763 ± 0.041

Kinetic Energy per nucleon



Rigidity



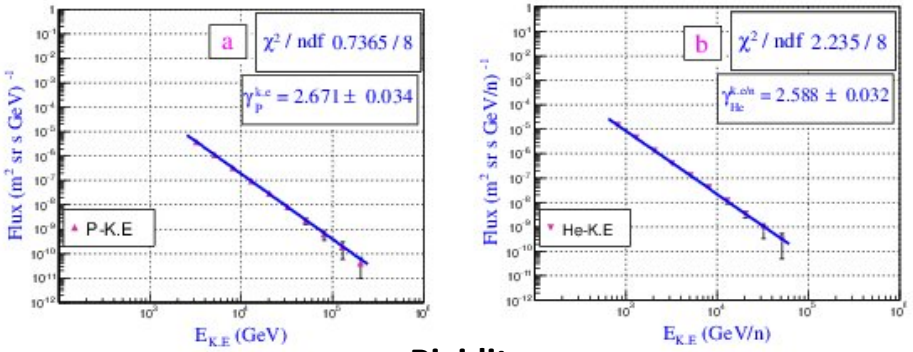
CREAM

(Cosmic Ray Energetics And Mass experiment)

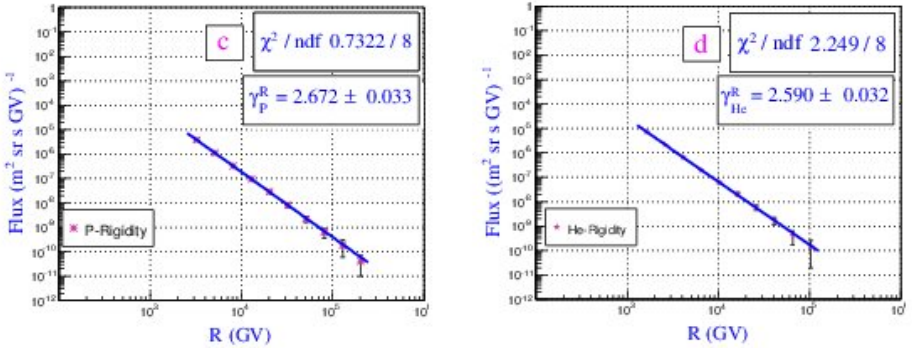
Type	K.E (GeV/n)		
		Reported	Calculated
Proton	(2.5 – 250) x 10^3	2.66 ± 0.02	2.671 ± 0.034
Helium	(0.63 – 63) x 10^3	2.58 ± 0.02	2.588 ± 0.032

Type	Rigidity (GV)		
		Reported	Calculated
Proton	(2.5 - 250) x 10^3	-	2.672 ± 0.033
Helium	(0.63 - 63) x 10^3	-	2.590 ± 0.032

Kinetic Energy per nucleon



Rigidity



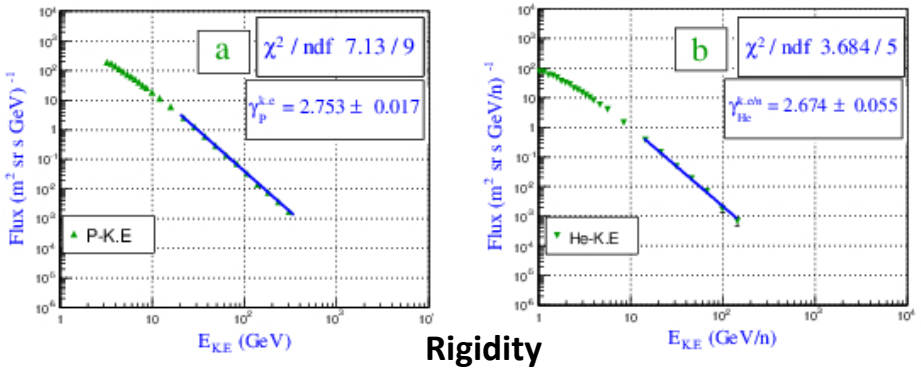
CAPRICE

(Cosmic AntiParticle Ring Imaging Cherenkov Experiment)

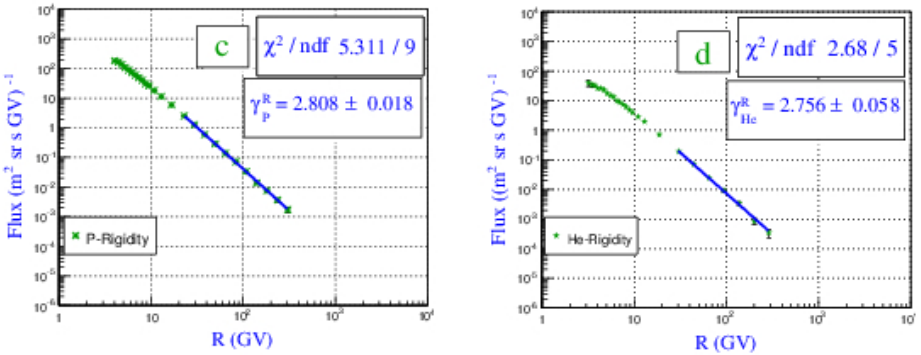
Type	K.E (GeV/n)		
		Reported	Calculated
Proton	20 – 350	2.75 ± 0.02	2.753 ± 0.017
Helium	15 – 150	2.67 ± 0.06	2.674 ± 0.055

Type	Rigidity (GV)		
		Reported	Calculated
Proton	21 - 341	-	2.808 ± 0.018
Helium	32 - 302	-	2.756 ± 0.058

Kinetic Energy per nucleon



Rigidity



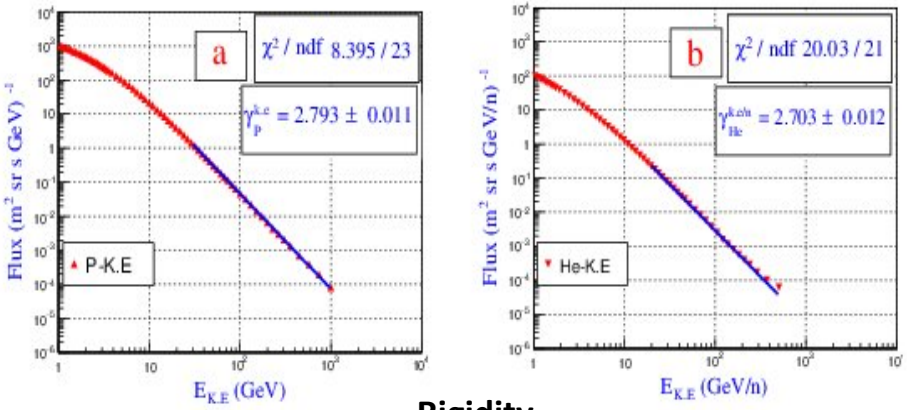
PAMELA

(Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics)

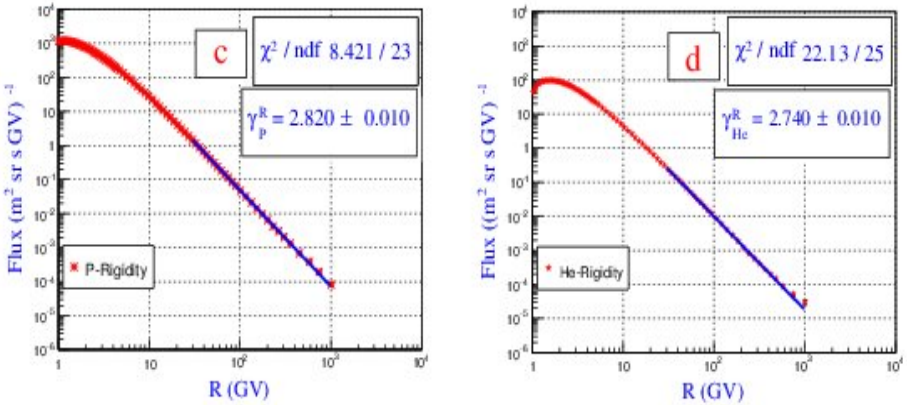
Type	K.E (GeV/n)		
		Reported	Calculated
Proton	30 - 1000	2.782 ± 0.003	2.793 ± 0.011
Helium	15 – 600	2.712 ± 0.010	2.703 ± 0.012

Type	Rigidity (GV)		
		Reported	Calculated
Proton	30-1000	-	2.820 ± 0.010
Helium	30-1000	-	2.740 ± 0.010

Kinetic Energy per nucleon



Rigidity

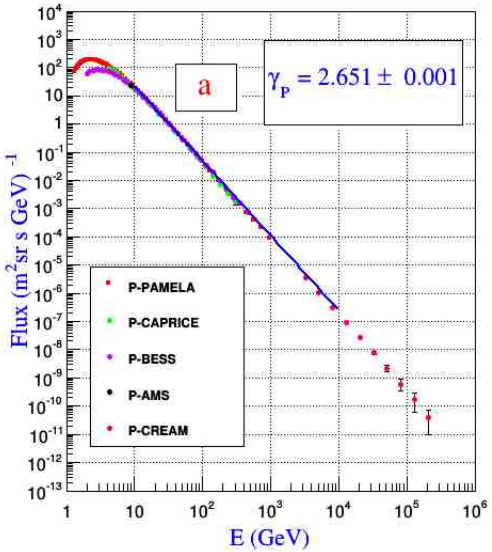


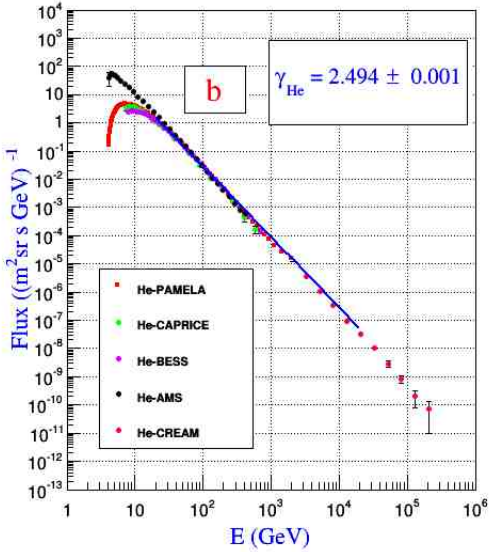
Differential total energy spectrum

Combined transformed total differential energy spectrum for protons and helium

Protons fitted in the range of 10 GeV – 10 TeV $\Upsilon_p = 2.651 \pm 0.001$

Helium fitted in the range of 20 GeV – 20 TeV $\Upsilon_{He} = 2.494 \pm 0.001$





Conclusions

- Combined cosmic ray spectrum from satellite and balloon experiments is obtained after transforming those measurements into a single unit.

- Combined differential energy spectrum 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 primaries.

- The transformation relations derived here may be used by others for conversion into other units of energy sprectrum.

Thank You