Primary-cosmic-ray energy spectrum up to 50 TeV derived from sea-level muon measurements

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(Received 15 November 1984)

The energy spectrum of the primary cosmic radiation has been derived from measurements of the muon energy spectrum at sea level with the DEIS spectrometer. The measured data have been fitted with production models using least-squares fit techniques. The obtained primary spectrum is in agreement with results from direct measurements at lower energies. In the energy range 1—50 TeV the power index has the value $\gamma = 2.72 \pm 0.02$.

In the lower energy range up to about 1 TeV the primary energy spectrum is obtained by direct measurements with satellites, and in the energy range beyond 100 TeV information stems from air-shower measurements. In only one experiment direct results have been obtained beyond 1 TeV in a series of balloon flights of emulsion chambers.[1] It is therefore of particular interest if additional information can be obtained in this energy range even by an indirect method. From sea-level muon spectra the primary energy spectrum can be derived.[2]

With the DEIS spectrometer the near-horizontal muon spectrum was measured at sea level in the energy range 10 to 7000 GeV with very high statistics.[3] From this the primary spectrum was derived with model calculations from Liland.[4] In the Liland model the diffusion equation for mesons in the atmosphere has been solved analytically taking into account the increase with energy of the inelastic nucleon—air-nucleus cross sections along with meson production by mesons. For the ratio of neutrons to nucleons in the primary component a value of 0.125 has been assumed and the contribution of α particles has been taken into account, based on CERN ISR data from α-α interactions. Cross sections for inelastic and inclusive interactions of nucleons and mesons for hadron production (pions, kaons, nucleons) have been taken from accelerators based on scaling behavior and have been normalized by beryllium as target nucleus, which approximates best the mixture of air nuclei. This model uses for the moments

$$F_{ig} = \int u^{\gamma} g_{i\gamma} \left[E, \frac{E}{u} \right] du$$

the values

$$F_{p\pi^+} = 0.0424 + 0.066E^{-1/2} ,$$

$$F_{p\pi^-} = 0.0305 - 0.0103E^{-1/2} ,$$

$$F_{pK^+} = 0.0074 - 0.0065E^{-1/2} ,$$

$$F_{pK^-} = 0.0027 - 0.0032E^{-1/2} ,$$

where E is in GeV. With the meson intensities the diffusion equation for muons has been solved analytically, taking into account energy loss and decay of muons.

The measured results from the DEIS spectrometer have been compared with the described model calculations and with further models from Murakami *et al.*,[5] Stephens,[6] Dardo, Alessio, and Sitte,[7] Das and De,[8] Badhwar, Stephens, and Golden,[9] and Thompson and Whalley.[10] The assumptions of the different models are summarized

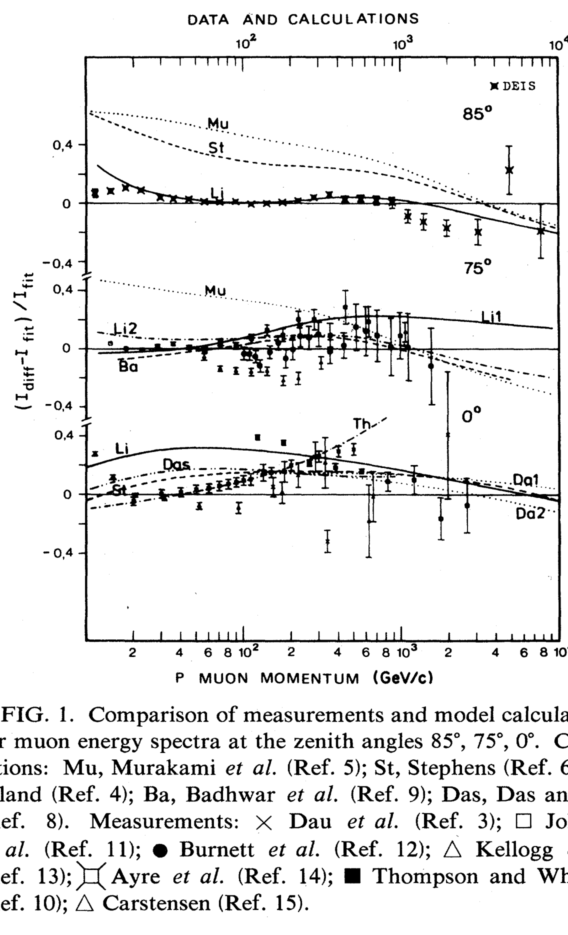

FIG. 1. Comparison of measurements and model calculations for muon energy spectra at the zenith angles 85°, 75°, 0°. Calculations: Mu, Murakami *et al.* (Ref. 5); St, Stephens (Ref. 6); Li, Liland (Ref. 4); Ba, Badhwar *et al.* (Ref. 9); Das, Das and De (Ref. 8). Measurements: × Dau *et al.* (Ref. 3); □ Jokisch *et al.* (Ref. 11); ● Burnett *et al.* (Ref. 12); △ Kellogg *et al.* (Ref. 13); ⌘ Ayre *et al.* (Ref. 14); ■ Thompson and Whalley (Ref. 10); △ Carstensen (Ref. 15).

TABLE I. Input parameters for the model calculations.

	Liland (Ref. 4) (theory)	Murakami et al. (Ref. 5)	Stephens (Ref. 6) Badhwar et al. (Ref. 9)	Dardo et al. (Ref. 7)	Das and De (Ref. 8)	Thompson and Whalley (Ref. 10)
Primary spectrum ($cm^{-2}sr^{-1}s^{-1}GeV^{-1}$) ($E$ in GeV)	$AE^{-\gamma}$	$1.74(E+0.89)^{-2.75}$ $+4\times0.127(E+0.31)^{-2.75}$	$2E^{-2.75}$ $+4\times0.086E^{-2.75}$	$\gamma_p=\gamma_\alpha=2.75$ $\gamma_L=2.95;\gamma_M=$ $\gamma_H=2.6$ $\gamma_{Fe}=2.35;2.6$	$2.48E^{-2.7}$	$1.73E^{-2.7}$ $56\times1.35\times10^{-3}E^{-20}$
Zenith angle	81° and 85°	75°–90°	0°–87°	0°–80°	0°	0°
$\eta=n/(n+p)$	0.125	0.11	0.105		0.10	Variable
Interaction lengths						
λ_N (g/cm^2)	84		90	81	Energy dependent	80
λ_π (g/cm^2)	114		120	110	120	120
λ_K (g/cm^2)	130		150	120	131	150
Absorption lengths						
$\Lambda_N=\lambda_N/(1-F_{pp}-F_{pn})$	120		125	120		120
$\Lambda_D=\lambda_N/(1-F_{pp}+F_{pn})$	87.4		104			98
λ_α	46.5		45	40 $\lambda_{Fe}=16$		
	Energy dependence up to 100 GeV for $\gamma=2.7$				for $\gamma=2.7$	for $\gamma=2.7$
$F_{p\pi^+}$	0.424				0.0411	0.0424
$F_{p\pi^+}/F_{p\pi^-}$	1.39		1.38		1.53	1.66
$F_{pK^+}/F_{p\pi^+}$	0.175				0.178	0.14
F_{pK^+}/F_{pK^-}	2.741				3.38	3.04
F_{nK^+}/F_{nk^-}	1.5		1		1	F_{pK^-}/F_{pK^+}
$F_{\pi^+\pi^+}$, $F_{\pi^-\pi^-}$	0.17, 0.048				0.192, 0.058	0.185, 0.053
$F_{K^+K^+}$, $F_{K^-K^-}$	0.17, 0.048					0, 0
Charge ratio at 100 GeV, 1 TeV	1.24, 1.27		1.28, 1.31	1.38, 1.40 decreasing above 1 TeV above 1 TeV	1.30, 1.35	1.26, 1.30

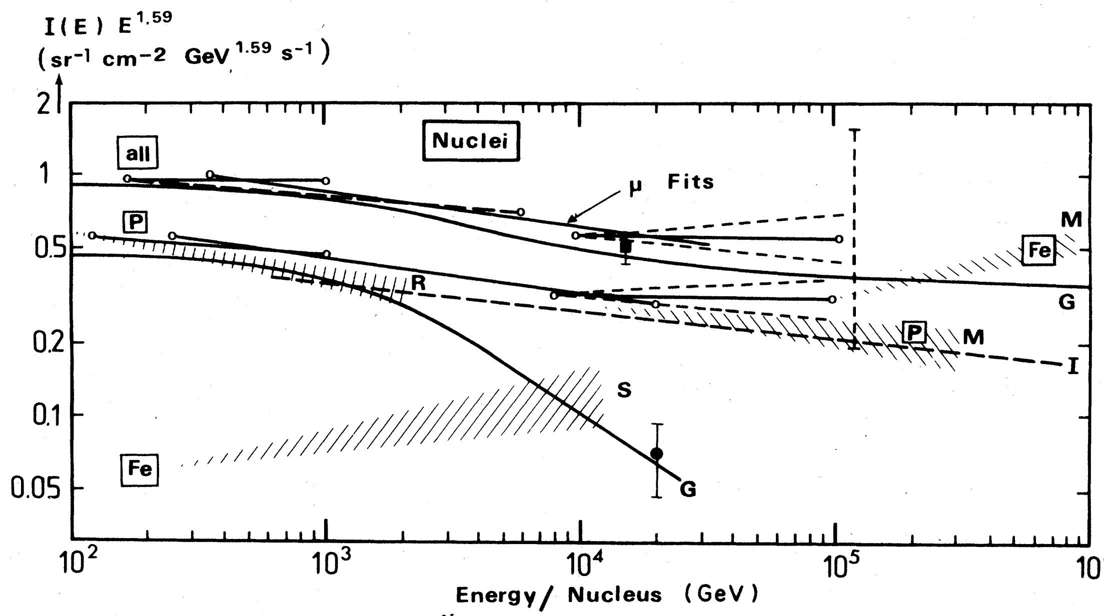

FIG. 2. The integral primary energy spectrum. [symbol], this work; *G*, Grigorov *et al.* (Ref. 17); *M*, Goodman *et al.* (Ref. 18); *R*, Ryan *et al.* (Ref. 20); *S*, Simon *et al.* (Ref. 19).

in Table I and the relative differences from the fit are demonstrated in Fig. 1 for three different angles. The reason why, for the spectrum at 85°, the Liland model fits better might be due to the fact that a variation method was used for the fitting process. The 75° spectrum is fairly well described again by the Liland model, but also by the calculations from Badhwar *et al.*[9] In the vertical direction none of the models agrees to the data well over the whole energy range. The measured data in the figure stem from measurements from Thompson and Whalley,[10] Jokisch *et al.*,[11] Burnett *et al.*,[12] Kellogg, Kasha, and Larsen,[13] Ayre *et al.*,[14] and Carstensen.[15]

For converting in vertical direction the muon energy scale to the scale of the primary spectrum the relation $E_p = 7.1 E_\mu$ was used which holds in a rough approximation for mean values.[16] For larger zenith angles this relation is energy and angular dependent. The Liland model leads to the primary spectrum which is shown in Fig. 2. In this diagram the absolute intensities are given for an energy scale energy/nucleus. The reasons stem from the fact that the composition is not measured directly in this energy range. Based on a primary spectrum of the shape

$$I_{\text{diff}} = A_p E^{-\gamma} + \tfrac{4}{12} A_p E^{-\gamma} \text{ GeV/nucleon ,}$$

the integral spectrum

$$I_{\text{int}} = \frac{A_p}{\gamma - 1} \left[1 + \frac{4^{\gamma-1}}{12} \right] E^{-\gamma+1} \text{ GeV/nucleus}$$

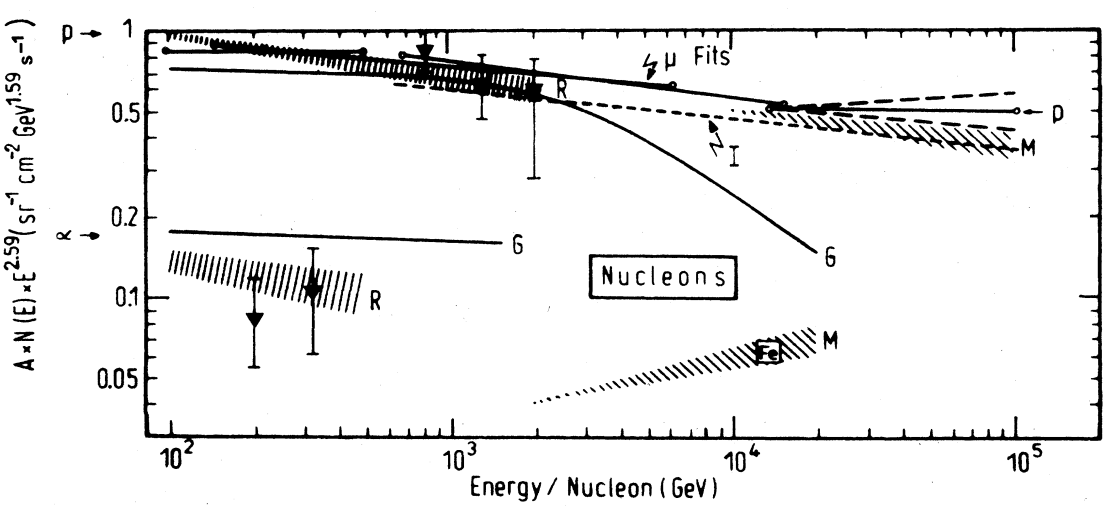

FIG. 3. The differential primary energy spectrum. [symbol], this work; *G*, Grigorov *et al.* (Ref. 17); *M*, Goodman *et al.* (Ref. 18); *R*, Ryan *et al.* (Ref. 20).

was derived [with the helium contribution $I_{\text{diff}}(\text{He})=\frac{1}{12}A_p(\frac{1}{4}E)^{-8}$ GeV/nucleus in $I'_{\text{diff}}=A_pE^{-8}+I_{\text{diff}}(\text{He})$]. The dashed curves in the muon fit at 10^4 GeV/nucleus indicate the error from the measured muon data. The power index for the primary spectrum is $\gamma_p=2.73$ for $E\geq 1.6$ TeV/nucleon and $\gamma=2.69\pm0.01$ for $E>0.4$ TeV. In the figure are presented also the results from Grigorov *et al.*,[17] the results from time-delay measurements from the Maryland group,[18] the direct measurements of the iron nuclei by Simon *et al.*,[19] and the measurements of Ryan, Ormes, and Balasubrahmanyan.[20]

In Fig. 3 the differential intensities are presented in energy scale energy/nucleon. Other results are shown again for comparison. One can conclude that the primary energy spectrum can be derived from the muon energy spectra at sea level up to 100 TeV. The results have the advantage of better statistics than the direct measurements and are in agreement with them.

We wish to thank Professor Y. Ne'eman, Professor Y. Yeivin, and Professor A. Godsman for encouraging and helping to start this project. We also acknowledge help from Mr. and Mrs. Carstensen for data processing. This work was supported by the Deutsche Forschungsgemeinschaft, Bonn, the Department of Physics and Astronomy of Tel-Aviv University, and Kiel University. We wish furthermore to express our thanks to the technical staffs at both universities.

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