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LETTER TO THE EDITOR

Remarks on the possibility of a pulsar-induced bump in the cosmic ray spectrum at 10^{13}–10^{16} eV/particle†

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Abstract. A recent suggestion that there is a bump in the primary cosmic ray spectrum between 10^{13}–10^{16} eV/particle (possibly protons from galactic pulsars) is considered in the light of its implications for deep-underground muon observations. A calculation based on Feynman scaling is used to make predictions for multiple muon rates for several assumptions of the primary spectrum and composition. It is concluded that a bump with the proposed prominence would be inconsistent with the muon data.

Recent analysis of the primary cosmic ray spectrum (Kempa *et al* 1974) as deduced from extensive air shower (EAS) measurements shows the possible existence of a 'bump' in the spectrum in the range 10^{13}–10^{16} eV/particle. Such a bump may be necessary (Wdowczyk and Wolfendale 1973) if the EAS spectrum at high energies ($E > 10^{15}$ eV/particle) is to be joined to the directly measured spectrum below a few times 10^{12} eV/particle (Ryan *et al* 1972). The bump is all the more interesting because of the possibility that such a bump could be explained as a superposition of a component produced by galactic pulsars (Karakula *et al* 1974, Ostriker and Gunn 1969) on some 'normal' background spectrum. We argue here that a bump with the prominence proposed by Karakula *et al* would be inconsistent with rates of underground muons (Lowe *et al* 1973) coming from showers produced by primaries in the energy interval spanned by the protuberance on the spectrum.

The muon data are a result of measurements carried out from 1967 to the present with the University of Utah muon detector (Keuffel and Parker 1967). Observations are made at underground depths ranging from 1.4×10^5 g cm^{-2} to 10^6 g cm^{-2}. Multiplicities of detected muons, n_D, ranging from 1–100 are observed and rates are assembled as a function of n_D, depth, and zenith angle. A sample of these data ($n_D < 30$) amenable to simulation by Monte Carlo techniques is used to try to put limits on the shape and composition of the primary spectrum.

Before proceeding it is necessary to understand the manner in which a muon detector located under mountainous terrain can probe a primary energy range of three orders of magnitude. By looking through progressively thicker sections of rock overburden, one looks at higher energy muons and, hence, to higher primary energies. Also, for a *fixed* depth, one looks to higher primary energies as the multiplicity of detected muons increases. An estimate of the relationship of these variables for *proton* primaries from

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our Monte Carlo simulation is shown in figure 1. Of particular interest are the high multiplicity events ($10 \leqslant n_D < 30$) recently acquired which extend our probe of the primary spectrum to near 5×10^{15} eV/particle and serve as a high energy 'anchor' in a region ordinarily reserved for EAS measurements. The sum of the measurements will be seen to cover roughly the region 10^{13}–10^{16} eV.

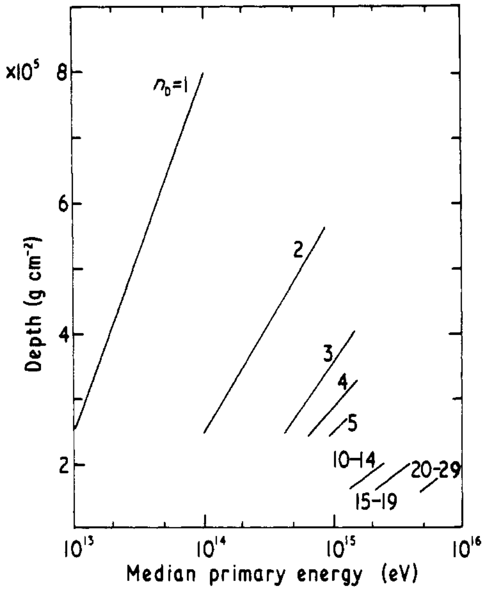

Figure 1. Estimated relationship between primary proton energy, detected muon multiplicity and depth underground. Values of n_D are shown marking each line.

Calculations of the expected rates depend on the nuclear physics assumed for the collision processes as well as the shape and composition of the primary spectrum. The nuclear physics of the present calculation is based on 'scaling' (Mason and Elbert 1973, Elbert *et al* 1973). The essential features are:

(i) p–Be and p–Al production cross sections at 19·2 GeV (Allaby *et al* 1970) are used for an interpolation to obtain p–air cross sections. Distributions for production of protons, pions, and kaons are suitably parametrized as functions of P_T and $x = 2P_L/s^{1/2}$. Scaling behaviour (Feynman 1969) is then assumed.

(ii) we include production of nucleons, antinucleons, pions and kaons. The multiplicities of the produced particles vary with primary energy as ln s, ie:

$$\bar{n}_\pi = -1{\cdot}3 + 1{\cdot}18 \ln E/m_p$$

(charged and neutral pions in the forward hemisphere)

$$\bar{n}_K = -0{\cdot}39 + 0{\cdot}114 \ln E/m_p$$

(charged and neutral kaon *pairs* in the forward hemisphere)

$$\bar{n}_{\bar{p}} = -0{\cdot}37 + 0{\cdot}059 \ln s + 0{\cdot}75/s^{1/2}$$

(antiprotons, both hemispheres; Antinucci *et al* 1973).

(iii) the p–air inelastic cross section rises with energy according to:

$$\sigma_{\text{p-air}} = 280 + 2{\cdot}5\ \ln^{1{\cdot}8}(E/100\ \text{GeV}) \qquad \text{mb}$$

(Yodh *et al* 1972).

(iv) meson-induced collisions are simulated from p–air distributions according to a prescription suggested by the quark model and supported by conventional accelerator measurements (Elbert *et al* 1971). A 'leading meson' is provided.

We assume the spectral shapes of the primary components (protons, alpha particles and heavier nuclei) follow power laws of the form $AE^{-\gamma}$ (A will be referred to as the amplitude and γ as the spectral index). Because the present analysis is not very sensitive to the location of a 'kink' or break in the primary spectrum we have used air shower results to give the approximate location (3×10^{15} eV for protons) of a rigidity-dependent break in the spectrum of all primaries. Above the break the spectral index is assumed to be 3·3 (Greisen 1965). Otherwise the assumed composition is constant as a function of energy and is taken to be an extrapolation of results from measurements at energies ranging from 2 GeV/nucleon to 500 GeV/nucleon ($Z = 2$, Ryan *et al* 1972; $Z = 2$–9, Cartwright *et al* 1971; $Z = 10$–28, Shapiro and Silberberg 1970; $Z = 26$, Balasubrahmanyan and Ormes 1972). The amplitude of the resulting spectrum of all primaries (below the break) is 2·5 times the amplitude, A_p, of the primary proton spectrum.

Using a fitting procedure we found the values of the amplitude and spectral index which gave the best agreement between our measurements and predictions. The results of the fit are strikingly close to those obtained by Ryan *et al* near 10^{12} eV. The Ryan parameters are: $\gamma = 2{\cdot}75 \pm 0{\cdot}03$, $A_p = (2{\cdot}0 \pm 0{\cdot}2) \times 10^4\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{GeV}^{-1}$. Our fitted parameters are: $\gamma = 2{\cdot}75 \pm 0{\cdot}02$, $A_p = (2{\cdot}3 \pm 0{\cdot}2) \times 10^4\ \text{m}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}\ \text{GeV}^{-1}$. The fit gave $\chi^2/\nu = 36{\cdot}5/30$. Therefore, the assumptions stated above are reasonably consistent with our measurements. The all-particle primary spectrum resulting from this fit is shown by curve C in figure 2. We have observed that uncertainties in the interaction model, particularly the nucleon inclusive distribution, could allow the 'best' values of A_p and γ to vary by slightly more than the above error estimates given by the fit. The use of interaction models other than scaling could also alter these results.

We have also tested our measurements and predictions using the primary spectrum from the pulsar model of Karakula *et al.* Their proposed spectrum is curve A in figure 2. We assumed that the primary spectrum is due to proton primaries *only* in the high energy part of our energy range. This was accomplished by allowing the nuclei with $Z \geqslant 2$ to have a spectral index as high as $\gamma = 5$ (which was preferred by a fit) starting at 10^{12} eV/nucleon. The predictions for all muon event rates were thereby dominated by the primary protons. All of the predicted muon rates due to primaries of more than 100 TeV were significantly high compared to the measurements and the predicted muon rates from the highest energies were 3–6 times higher than the measurements. The χ^2 value was 1872 for 30 degrees of freedom.

Feynman scaling predicts a slowly ($\ln E$) increasing multiplicity of particles as the energy increases. Alternatives, such as the $E^{1/4}$ multiplicity law, would tend to produce *more* multiple muon events and would make it even more difficult to reconcile the bump with our underground muon data. To construct the bump from heavier nuclei instead of protons also leads to a very severe excess of multiple muon events impossible to reconcile with our data and interaction model.

Karakula *et al* display curve B of figure 2 as a result of an analysis by Hillas (1972) of EAS measurements. The all-particle primary spectrum obtained from our fit to our muon data, curve C, is lower than the EAS result by a factor ranging from 2–3 in the region

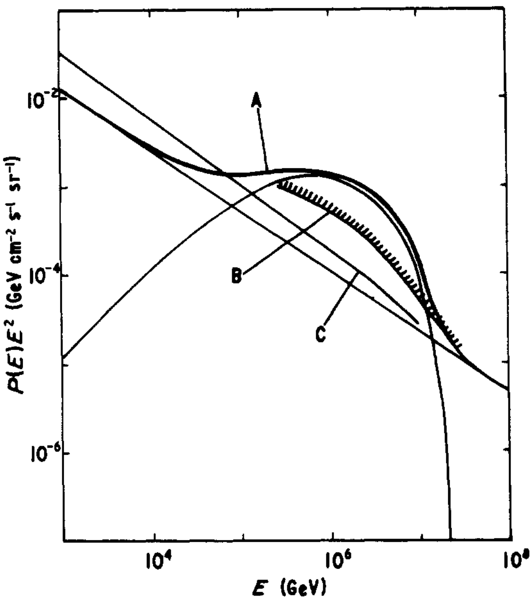

Figure 2. Differential primary cosmic ray spectra. Curve A shows the proton spectrum from the model of Karakula *et al.* The pulsar 'bump' is added to a power-law background spectrum. Curve B is the proton spectrum by Hillas, based on air shower data. Our analysis of the underground muon data gives curve C.

of comparison. Because of differences in the interaction models assumed in the EAS and muon analyses, the comparison of curves B and C might be misleading. It should also be emphasized that a significant increase in the transverse momentum of produced particles at high energy or a process of the 'gammaization' type proposed by Nikolskii (1967) could improve agreement of the muon results with the EAS results and the pulsar model. Analysis of the decoherence distribution of the Utah underground muon measurements is in progress and will study the possibility of higher average p_T values in the energy range of relevance here.

References

Allaby J V *et al* 1970 *CERN Report* 70–12

Antinucci M *et al* 1973 *Lett. Nuovo Cim.* **6** 121–8

Balasubrahmanyan V K and Ormes J F 1972 *Goddard Space Flight Center Preprint* X-661-72-447

Cartwright B G *et al* 1971 *Proc. 12th Int. Conf. on Cosmic Rays, Hobart* vol 1 (Hobart: University of Tasmania) pp 215–20

Elbert, J W, Erwin A R and Walker W D 1971 *Phys. Rev.* D **3** 2042–7

Elbert J W *et al* 1973 *Proc. Conf. of Division of Particles and Fields, Berkeley* vol 14 (New York: American Institute of Physics) pp 479–89

Feynman R P 1969 *Phys. Rev. Lett.* **23** 1415–7

Greisen K 1965 *Proc. 9th Int. Conf. on Cosmic Rays, London* vol 2 (London: The Institute of Physics and The Physical Society) pp 609–15

Hillas A M 1972 *Cosmic Rays* (Oxford: Pergamon) p 92

Karakula S, Osborne J L and Wdowczyk J 1974 *J. Phys.* A: *Math., Nucl. Gen.* **7** 437–43

Kempa J, Wdowczyk J and Wolfendale A W 1974 *J. Phys.* A: *Math., Nucl. Gen.* **7** 1213–21

Keuffel J W and Parker J L 1967 *Nucl. Instrum. Meth.* **51** 29–42

Lowe G H *et al* 1973 *Proc. 13th Int. Conf. on Cosmic Rays, Denver* vol 3 (Denver: University of Denver) pp 1878–83

Mason G W and Elbert J W 1973 *Proc. 13th Int. Conf. on Cosmic Rays, Denver* vol 3 (Denver: University of Denver) pp 2348–55
Nikolskii S I 1967 *Sov. Phys.–JETP* **24** 535–45
Ostriker J P and Gunn J E 1969 *Astrophys. J.* **157** 1395–417
Ryan M J, Ormes J F and Balasubrahmanyan V K 1972 *Phys. Rev. Lett.* **28** 985–8
Shapiro M and Silberberg R 1970 *Ann. Rev. Nucl. Sci.* **20** 323
Wdowczyk J and Wolfendale A W 1973 *J. Phys.* A: *Math., Nucl. Gen.* **6** 1594–611
Yodh G B, Pal Y and Trefil J S 1972 *Phys. Rev. Lett.* **28** 1005–8