

RELEVANCE OF MULTIPLE MUONS DETECTED UNDERGROUND TO THE  
MASS COMPOSITION OF PRIMARY COSMIC RAYS

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ABSTRACT

Calculations have been made of the expected frequencies of multiple muons in the Soudan underground proton decay detector. It is concluded that the flux of heavy nuclei ( $z > 10$ ) in the range  $10^{15} - 10^{16}$  eV/nucleus is at most 25% of the total particle flux in the same range.

1. Introduction. The installation of a number of large detectors underground designed to search for proton decay has led to renewed interest in the multiple muons which are recorded. Some 15 years ago we (Adcock et al., 1969, 1971) made detailed calculations of the expected number of such multiple muons for the situation of the experiment of Keuffel and co-workers in Utah. Here, we update the calculations in the light of new knowledge about the nature of high energy collisions and apply them to the condition of the Soudan I experiment (Bartlet et al., 1985, *in press*).

The objective is the same as before: to endeavour to elucidate the problem of the mass composition of cosmic ray primaries above  $10^{14}$  eV.

2. The Model. The early calculations used the CKP model. Here we use our model (Wdowczyk and Wolfendale, 1984) which fits the pp collider results, extrapolated to higher energies. The main features, summarised briefly, are:

- (i) a multiplicity coefficient,  $\alpha$ , which increases slowly with energy reaching 0.25 at  $\sim 10^{14}$  eV and being constant above.
- (ii) inelasticities for pion production such that the total is energy independent but  $K_{\pi^{\pm}}$  falls as  $(E_0/205)^{-0.061}$ , with  $E_0$  in GeV.
- (iii) the inclusion of kaons and baryons.
- (iv) multiplicity fluctuations according to the KNO formulism.

The shape of the spectra of all secondaries is the same and is as given in our 1984 paper.

3. Results for the mean numbers of muons, mean radii. As an example, we give typical values for muons of energy above 500 GeV (roughly appropriate to Soudan I) produced in vertical showers generated by primary protons. For primary energies of  $10^4, 10^5, 10^6, 10^7$  GeV the mean number and mean lateral radius (in brackets, metres) are, respectively; 0.4(7.2), 3.3(5.7), 19(4.9) and 120(4.4). An interesting result is the ratio of number of kaons from kaons to the number from pions; the ratios as a function of  $E_0$  (values as above) are, 0.55, 0.95, 1.20 and 1.42. The dependence of mean muon number on threshold energy can be considered for the important primary energy  $E_0 = 10^6$  GeV. the means are, for muon threshold energies of 500, 1000, 2000 and 3000 GeV: 19, 8.5, 2.3 and 1.2.

4. Estimated rates for the Soudan experiment and Conclusions. Estimation of the expected rates involves calculations for a variety of zenith angles with an adopted primary spectrum and mass composition, allowance for magnetic deflection and scattering of the muons and the important problem of the finite area of the detector. We find that magnetic deflection and scattering correspond to an increase of mean muon radius by approximately 10%.

The adopted trial primary spectrum is that of Gawin et al. (1985); an important parameter here is the ratio of the flux of H and Fe nuclei to the total number of nuclei; the ratios are, at  $10^{14}$ ,  $10^{15}$  and  $10^{16}$  eV/nucleus: 29%, 34%, 22% (and falling very rapidly above  $10^{16}$  eV/nucleus).

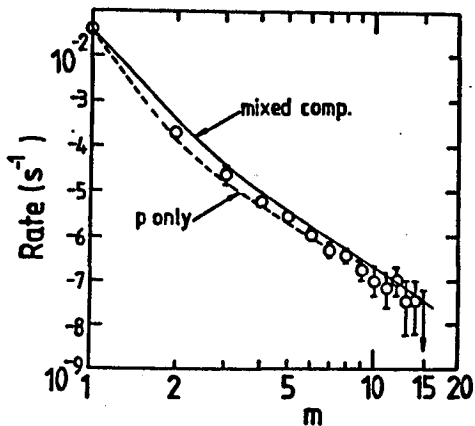


Fig. 1. Observed and predicted frequencies of muons (multiplicity  $m$ ) in the Soudan experiment. The analysis favours a very small fraction of heavy nuclei.

The corresponding total integral intensities are  $1.6 \times 10^{-8}$ ,  $4.7 \times 10^{-10}$  and  $3.2 \times 10^{-12}$   $\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$ .

Figure 1 shows a comparison between the Soudan observations and our predictions. It will be noted that there is good agreement for the number of singles but the predictions are somewhat in excess at higher multiplicities. Insofar as the contribution from heavy nuclei is relatively higher for  $m > 1$  the most likely interpretation is that the intensity of heavy nuclei is somewhat less than we have assumed. Surprisingly, perhaps, the energy range of primary heavy nuclei contributing to  $2 < m < 15$  is not large:  $2 \cdot 10^{15}$  eV =  $3 \cdot 10^{16}$  eV per nucleus. A reduction of heavy nucleus flux by about a factor 2 would give a more reasonable fit; at  $6 \cdot 10^{15}$  eV per nucleus the ratio of heavy nuclei ( $z > 10$ ) to total would then be  $\approx 12\%$  only.

Confining attention to the ratio of heavy nuclei to total particles in the  $10^{15}$ - $10^{16}$  eV/nucleus region, we have shown that 25% can be regarded as an extreme upper limit.

#### References

1. Adcock, C. et al., (1969), J.Phys.A, 2, 574; (1971), J.Phys.A. 4, 276.
2. Gawin, J. et al. (1985), in the press.
3. Wdowczyk, J., and Wolfendale, A.W. (1984), J.Phys.G. 19, 257.