Muon bundles in extensive air showers

1971 J. Phys. A: Gen. Phys. 4 L34

(http://iopscience.iop.org/0022-3689/4/2/020)

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Muon bundles in extensive air showers

Abstract. It is suggested that coherent production of pions in pion–air nucleus interactions is responsible for the bundles of muons observed in extensive air showers.

The muon component of extensive air showers has been studied in detail for several decades and information has been derived of relevance to the energy spectrum of the cosmic ray particles responsible for the showers and to the characteristics of very high energy interactions.

There are, at present, two features which are difficult to understand: the presence of muon-poor showers, that is showers with much less than the usual number of muons (Firkowski *et al.* 1962, Suga *et al.* 1963) and the observation by several workers of groups of muons—'muon bundles' (Vernov and Khristiansen 1967, Vernov *et al.* 1970). It is with the interpretation of the muon bundles that the present letter is concerned.

Although a number of observations of muon bundles have been made, mainly by way of underground detectors with which the muon component alone could be distinguished, conflicting interpretations have arisen. These have occurred because of problems associated with statistical fluctuations in numbers of 'normal' muons observed with the rather small detectors employed. Further problems have arisen because of the undoubted presence of penetrating groups of particles (mainly pions) generated by the nuclear interactions of energetic muons in the overlying material. However, very recent experiments with large detectors by Vernov *et al.* (1970) and Hibner *et al.* (1971) are comparatively free of ambiguities and it does seem as though the bundles are present as a nontrivial phenomenon and thus worthy of serious analysis.

The work of Vernov *et al.* is well documented and it is useful to examine it in a little detail. In the experiment, detectors were operated at a depth of 40 hg cm^{-2} below the Moscow State University EAS (extensive air shower) array; in particular, spark chamber telescopes of total area 4 m^2 were used to give precise information about muons which, with others, were also detected by another detector of area 40 m^2. The muon bundles manifested themselves as close (within 4 m^2) groups of parallel muons containing significantly more particles than would have been expected from the total number seen in the 40 m^2 array. These events are characterized by being near to the shower axis ($r \lesssim 8$ m) and occurring in showers within the size range 10^4 to several $\times 10^5$ particles. Their frequency is such that for $N \sim 10^5$ most showers contain about one bundle with at least five muons (the threshold energy for the muons at the depth of operation is 10 GeV).

In the work of Hibner *et al.* the statistical grouping of muons of energy above 5 GeV has also been studied with a large detector and again groupings within a few m^2 have been detected although here the frequency is about a factor of ten lower for the same shower energy.

Finally, the University of Utah neutrino detector has been used to search for muon groups with energy above approximately 600 GeV (Bergeson *et al.* 1970). A theoretical analysis has been made by Adcock *et al.* (1970) and it has been shown that no detectable muon bundles exist under these conditions.

On the basis of the experimental data it seems unlikely that the observed nontrivial bundles comprise very high energy muons and a consequence is that they are derived from interactions which are characterized by the emission of secondary particles, presumably pions, having small transverse momenta. Indeed, such a process has been observed experimentally in nuclear emulsions by Czachowska *et al.* (1967). In that work the interactions of pions of energy about 200 GeV were studied and events were seen in which the collimation of secondary particles was much stronger than would have been expected for normal interactions with mean transverse momentum 0·3–0·4 GeV/*c*. The median angle of the pions for these events (events which were selected as having no visible recoil particles : $N_h = 0$) was about six times smaller than for the normal events, restricting attention to cases of three secondary pions, and even less for events with five secondaries.

The explanation advanced by the authors was in terms of coherent interactions, this process having been predicted theoretically by Landau, Feinberg and Pomeranchuk (Feinberg *et al.* 1950) and described in some detail by Good and Walker (1960 and later publications). A number of experiments with accelerators have been performed (e.g. Allard *et al.* 1965, Anzon *et al.* 1970) in which coherent production cross sections have been measured but the realization of probable importance for EAS phenomena has come from a combination of these results with the data of Czachowska *et al.* at 200 GeV which indicate that the coherent cross section is rising quite rapidly with incident pion energy. For example, the results at 200 GeV give $\sigma_{\text{coh}}/A^{2/3} \sim 1{\cdot}6$ mbn for three pion production and approximately 0·9 mbn for five pion production (Czachowska *et al.* 1967)

Turning to the cosmic ray observations, the explanation of the non-appearance of coherent muons in the Utah experiment follows immediately: at these energies the majority of the detected particles come from pions produced in the first interaction of the primary particle and for these particles the probability of π–μ decay is very small.

Approximate calculations have been made using a model for the propagation of the various components in the atmosphere (de Beer *et al.* 1966) which has had success in accounting for other EAS phenomena. Theoretical pion spectra have been used for the various atmospheric-levels and the data of Czachowska *et al.* and its extrapolation have been adopted for the cross section for coherent production (asymptotic values of $\sigma/A^{2/3}$ were taken as follows: 1·57 mbn for 3 pions, 0·90 mbn for 5, 0·50 mbn for 7, 0·28 mbn for 9, 0·12 mbn for 11 and 0·068 mbn for 13 pions).

From the calculations the frequencies of bundles of muons falling on a 4 m^2 detector were derived. In so far as the transverse momentum of the pions on production was neglected in comparison with that from π–μ decay the present calculations represent upper limits to the expected frequencies. In showers of size approximately 2×10^5 particles incident in the near vertical direction the calculations give the following predictions (see table 1) for the number of bundles per shower, the term bundle referring here to the number of particles recorded by a 4 m^2 detector.

Table 1

Muon threshold energy (GeV)	Number of muons in bundle n_b 3	4	5	6	8	10
10	$2{\cdot}7$	$7{\cdot}8 \times 10^{-1}$	$3{\cdot}7 \times 10^{-1}$	$9{\cdot}5 \times 10^{-2}$	$9{\cdot}3 \times 10^{-3}$	$7{\cdot}3 \times 10^{-4}$
30	$1{\cdot}5$	$3{\cdot}6 \times 10^{-1}$	$9{\cdot}8 \times 10^{-2}$	$2{\cdot}5 \times 10^{-2}$	$1{\cdot}5 \times 10^{-3}$	$4{\cdot}4 \times 10^{-5}$
100	$5{\cdot}0 \times 10^{-1}$	$1{\cdot}1 \times 10^{-1}$	$2{\cdot}3 \times 10^{-2}$	$4{\cdot}1 \times 10^{-3}$	$1{\cdot}0 \times 10^{-4}$	$1{\cdot}2 \times 10^{-6}$

The calculations show that the majority of the interacting pions have energy in the region of several hundred GeV for detected multiplicities of four and above and the heights at which most of the important interactions occur are in the range 1–3 km. The results, which are probably accurate only to a factor 2 at this stage show that the frequency increases with N_e at a somewhat slower rate than linearly.

Comparison with experiment shows that the predicted rates are between those given in the experiment of Hibner *et al.* ($\sim 10^{-1}$ at $n_b \geqslant 4$) and those from Vernov and Khristiansen (~ 1 at $n_b \geqslant 4$). At this stage of the theoretical analysis, however, and with experimental data on this topic still in a rather rudimentary state the general situation is not unsatisfactory. What is clear is that when new and more comprehensive data are available it should be possible to make an indirect study of coherent production by pions in what is at present an inaccessible energy region (several hundred GeV).

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12th February 1971

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The possibility of detectable fluxes of cosmic ray γ rays with energy above 10^{19} eV

Abstract. Under the assumption that cosmic rays are of extragalactic origin above 10^{18} eV it is shown that the presence of the 2·7 K black body radiation may lead to a detectable flux of very energetic γ rays.

A number of arguments have been put forward which suggest that the majority of cosmic rays at energies above 10^{18} eV are of extragalactic origin. One apparent difficulty is that the black body radiation (Penzias and Wilson 1965) should cause a cut off in the primary energy spectrum at a few times 10^{19} eV, in contrast to the experimentally observed continuous spectrum. It seems, however, that under certain circumstances it is possible to have a high energy cosmic ray spectrum which does not exhibit a sharp cut off, even allowing the particles to be of Universal origin and taking into account the black body radiation: for example, Hillas (1967) considers an evolving Universe in which the production rate of cosmic rays was higher in the past and on this model the cut off is less marked. The same situation would result if the production rate of the Universal component had a maximum somewhere above 10^{20} eV.

The purpose of this letter is to call attention to another phenomenon expected in the case of the Universal origin of the highest energy particles. Interactions of the cosmic rays with the black body radiation can lead to the transference of a relatively high fraction of the primary energy to photons and in view of the fact that the attenuation length for photons of energies above a few times 10^{19} eV becomes comparable with or longer than that of protons one can anticipate a noticeable photon flux at the earth.

Calculations have been made for a steady state Universe under the assumption that the primary cosmic ray spectrum in extragalactic space is described by a single power law with constant exponent to energies exceeding 10^{21} eV. The form of the spectrum adopted is that measured directly (as summarized by Greisen 1966) at energies above 10^{18} eV and is indicated in figure 1. Below 10^{18} eV it is assumed that galactic containment causes the increase over and above the extragalactic spectrum. Use of the steady state Universe is justified, in these preliminary calculations, by the fact that the bulk of the contribution to the intensities comes from distances of the order of a tenth of the Hubble radius.

The method of calculation was as follows. The energy spectrum of high energy photons at production was calculated taking the primary spectrum referred to above and assuming that the back body temperature is 2·7 K. Data for the photoproduction process were taken from accelerator results; in view of the fact that the energy of the photon in the C-system of proton and black body photon is practically always below 1 GeV, the cross section is accurately known.