# The electric charge of interacting cosmic ray particles at sea level

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# The electric charge of interacting cosmic ray particles at sea level

**Abstract.** The magnitude of the electric charge of sea level cosmic ray particles producing energy transfers greater than or approximately equal to 25 GeV in a 22·9 cm thick steel target have been measured. The charge distribution shows a peak at the electron charge and an apparent high charge tail. Spurious effects contributing to the high charge tail are knock-on electrons, and nuclear interactions in the proportional counter walls, which are used to measure the charge. The limit obtained on the flux of $4e/3$, $5e/3$ and $7e/3$ quarks is less than $8{\cdot}2\times10^{-10}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$.

The possibility of stable compound states of quarks of charge $4e/3$, $5e/3$ etc. was first proposed by de Swart (1967) although there have been few experiments to search for such objects in cosmic rays. The present experiment was undertaken to search for $4e/3$, $5e/3$ and $7e/3$ quark states in cosmic rays and is part of a program at Durham in which a systematic search is being made for quarks in cosmic rays.

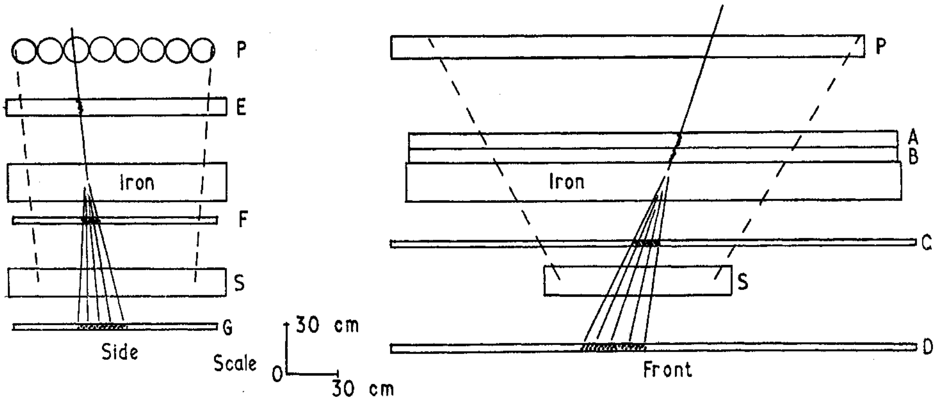

Figure 1. Experimental arrangement. P—proportional counters; A,B,C,D,E, F,G—flash tubes; S—scintillation counter.

The apparatus used is shown in figure 1 and the idea was to select events in which an incident charged particle traversed the proportional counter layer and produced an interaction in the steel target of energy transfer greater than 25 GeV. The known particles producing such events are high energy protons, pions and muons and such triggers enabled the most probable pulse height produced by high energy particles of charge $e$ to be continuously monitored throughout the experiment.

The actual electronic selection used required a pulse of more than 0·2 $P$ from any one proportional counter, and a pulse greater than 25 $S$ from the scintillation counter. $P$ is the most probable pulse height produced by a charged particle of minimum ionization traversing the internal diameter (14 cm) of the proportional counter, and $S$ the pulse height produced by a minimum ionizing particle traversing the scintillation counter at normal incidence. For each event the pulse heights from all eight proportional counters and the scintillator were measured and photographs taken of the flash tube trays in both the front and side views. For an event to be accepted it was required that the axis of the burst indicated by the flash tubes in both the front and side elevations of figure 1 should (i) be within the limits shown by the broken lines of figure 1 and (ii) that the track in the proportional counter should have a maximum distance of more than 1 cm from the counter wall. These two conditions define the acceptance aperture of the apparatus which is 0·49 $m^2$ sr for isotropic radiation. For an event satisfying the above conditions the measured proportional counter pulse height was normalized to a standard track length of 14 cm in the proportional counter gas. Figure 2 shows the frequency distribution of 110 such events observed in a running time of 86 hours. The peak at low pulse height is due to protons, pions and muons producing bursts, and the high charge tail contains possible $4e/3$, $5e/3$ and $7e/3$ candidates. As the Lorentz factors of protons, pions and muons producing bursts of size greater than 25 $S$ in the scintillator are all close to the plateau value of ionization in the proportional counter gas, the calculation of the expected shape of the ionization loss distribution is comparatively simple. The result is shown as the broken line in figure 2 and has been calculated using the theory of Blunck and Leisegang (1950) and Blunck and Westphal (1951), account also being taken of the error in track length determination in the proportional counter gas of standard deviation 2·8 cm.

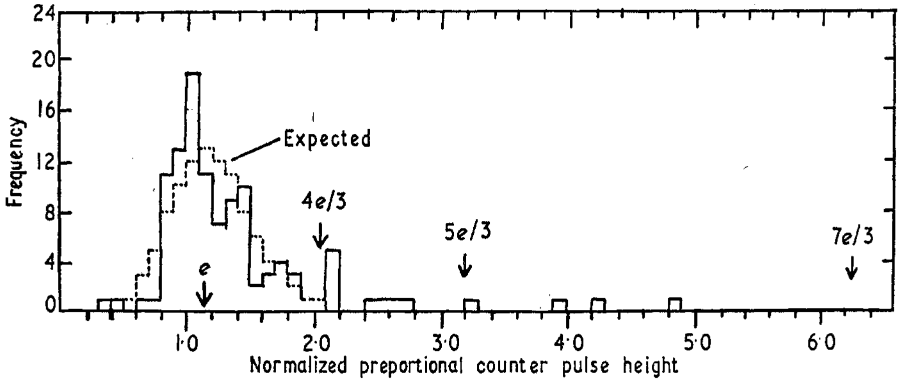

Figure 2. Frequency distribution of proportional counter pulse heights. All measured proportional counter pulse heights were normalized to a track length of 14 cm in the proportional counter gas. The expected distribution has been calculated using the theory of Blunck *et al.* (1950, 1951) and has also been broadened to account for the error in track length determination in the proportional counter gas.

It is clear from figure 2 that the shape of the measured ionization loss distribution cannot be accounted for by fluctuations in the ionization loss in the proportional counter gas alone. Possible sources of the apparent high charge tail are knock-on electrons and nuclear interactions in the proportional counter walls of thickness 0·25 cm. The average number of knock-on electrons produced by 110 charged particles traversing the proportional counter walls is calculated to be 5·2, while the average number of nuclear interactions taking place in the wall is 1·8. To calculate the latter figure it is estimated that the percentage of bursts produced by protons, pions and muons is 34·6%, 32·7% and 32·7% respectively. The total number of events expected at large pulse heights is thus 7·0 and is to be compared with the observed number of 13, the difference being 1·7 standard deviations. Clearly, the observed excess is not statistically significant, and only a limit can be placed on the flux of possible $4e/3$, $5e/3$ and $7e/3$ quark states in cosmic rays at sea level. Quark states of charge $9e/3$ would not have been observed owing to the saturation of the electronic pulse height measuring system. Basing the limit on one possible event, and assuming the quark states would interact with the target iron nuclei with a cross section given by $\pi(1{\cdot}35\,A^{1/3}10^{-13})^2$ cm$^2$, the limit is less than $8{\cdot}2\times10^{-10}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The limit refers to quark states which arrive at sea level with an electron accompaniment of less than 2 electrons/m$^2$.

The above limit can be compared with the result of Buhler–Broglin *et al.* (1967 a, 1967 b) who found $I<1{\cdot}6\times10^{-7}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for $4e/3$ quark states and also the result of Kasha *et al.* (1967) who found $I<1{\cdot}3\times10^{-10}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$ for quark states of charge greater than or equal to $4e/3$. Both these experiments used scintillation counter telescopes to determine the charge of particles that penetrated the telescope without interaction. In contrast, the present work required an interaction to take place, and then the charge of the incident particle was determined. The result obtained can thus be used to place added confidence on the limit found by Kasha *et al.*

A further point of interest relates to the possible use of proportional counters to measure the Lorentz factor of relativistic charged particles. Combined with a technique of energy determination such measurements can in principle enable the rest mass of relativistic particles to be determined. The most probable energy loss $E_p$ in proportional counter gas (90% argon plus 10% methane at atmospheric pressure) increases by 65% over the range of Lorentz factor 6 to 600. Clearly, a single layer of counters would give rise to large errors in determining $E_p$ due to the high pulse height tail, which in figure 2 contains 12% of the observed events. However if ten layers of counters were used, and the largest two pulse heights were rejected in making an estimate of $E_p$, then it is thought that the median pulse height of the remaining eight would give a precise estimate of $E_p$, and hence the Lorentz factor of the particle. A consideration of the precision of determining $E_p$ by sampling the ionization loss distribution has been given by Ramana Murthy and Demeester (1967) and Ramana Murthy (1968).

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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 $\mathrm{cm}^{-2}$ below the Moscow State University EAS (extensive air shower) array; in particular, spark chamber telescopes of total area 4 $\mathrm{m}^2$ were used to give precise information about muons which, with others, were also detected by another detector of area 40 $\mathrm{m}^2$. The muon bundles manifested themselves as close (within 4 $\mathrm{m}^2$) groups of parallel muons containing significantly more particles than would have been expected from the total number seen in the 40 $\mathrm{m}^2$ 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