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LETTER TO THE EDITOR

Evidence for a strongly interacting particle of mass greater than 40 GeV

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Abstract. The hadron energy spectrum recently published by Baruch, Brooke and Kellermann and other spectra measured at sea level and at high altitudes under absorbers can be more easily understood if one assumes the existence of a new type of particle of mass greater than 40 GeV.

We think that the recently published hadron energy spectrum (Baruch *et al* 1973) which showed a discontinuity near 1 TeV can be interpreted more easily, and reconciled with the results of others, by assuming the existence of a new kind of particle rather than by a novel kind of interaction for hadrons of energy 10^4 GeV.

We were originally thinking along the lines suggested by Nam *et al* (1971) who found a 40% increase in the fraction of energy transferred to the electromagnetic cascade (K_γ) in the first nuclear interaction for hadrons of energy between 5×10^{12} and $1{\cdot}4\times10^{13}$ eV and concluded that the increase in K_γ probably indicates an increased fraction of pions in the total hadron flux.

Applied to our results this conclusion would imply that a very large fraction of the total hadron flux is charged pions, and we now think that the sudden change in intensity found (Baruch *et al* 1973, figure 3) is difficult to explain in this manner.

A similar enhanced intensity has been found by Babayan *et al* (1962), but we find that their suggestion that the effect is caused by electromagnetic bursts due to muons conflicts with our measurements. The cross section for electromagnetic bursts should vary with the radiation lengths of the respective material, yet the scatter diagram (Baruch *et al* 1973, figure 2) shows no dissimilarity between the number of events producing the step where the interaction occurred in our graphite absorber, and the number of (rejected) events where the interaction occurred in the top lead; many more interactions in the lead would be expected if the interactions were electromagnetic.

The cross section for muon–nuclear interactions is far too low to produce a significant fraction of the bursts seen (see Chin *et al* 1970, Bezrukov *et al* 1971). If the cross section were to rise suddenly at a given high energy, a loss of muons at great depths underground would have been noticed, but rather, an increase in the muon flux at energies above 10^{13} eV has been observed (Menon and Ramana Murthy 1967).

A completely new vista is opened up if one considers the possibility of the presence of a new kind of particle in the atmosphere. Essentially, the step in our published hadron spectrum is explained as due to the interactions of this new particle in the calorimeter.

One experimental result emerging from our data is that at least 30% of the bursts contributing to the step in the spectrum show some 'structure' (figure 1), that is, two prominent peaks separated by at least one counter width (3·5 cm), implying a wide angular spread in the majority of these bursts. This would fit in with the remark of Zatsepin (reported by Wdowczyk and Zujewska 1972), that the disagreement between the burst spectra measured using ionization chambers or proportional counters and those recorded in emulsion chambers can be understood if it is assumed that a fraction of the bursts has a wide angular spread with a consequent low electron density to which the emulsion chambers are insensitive. The simplest explanation is that structure is due to high transverse momentum of the secondary particles produced in interactions of the new particle. We suggest that this high transverse momentum is due to the loss of the rest mass of the new particles in, or immediately subsequent to their interactions. If this is so, the new particle will not survive its first nuclear interaction, that is, the inelasticity of the interaction will be 100%. Figure 2 shows the differential burst energy spectrum of the step (that is of the new particles), derived from our data (Baruch *et al* 1973) by subtracting a spectrum with a constant exponent (as calculated by A M Hillas, private communication, from the 'Proton' satellites' data on the composition of primary cosmic rays, and as expected from other sea level measurements at lower energies) from the burst energy spectrum of all events. The absolute intensity of the spectrum of the new particles is not known, since the probability of the new particles making their first interactions in the calorimeter in the graphite target is dependent upon the interaction length of the new particle. The spectrum (figure 2) corresponds to assuming that this probability is the same as for nucleons.

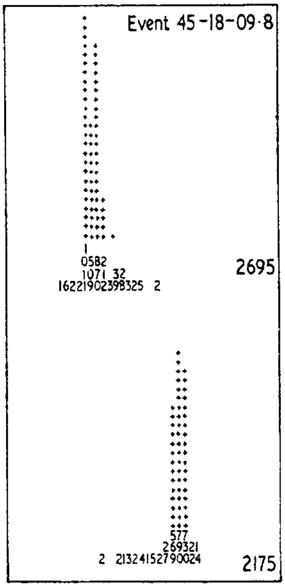

Figure 1. A typical 'structured' burst showing the ionization in the two layers of proportional counters. The figures, read vertically, give the total ionization in the relevant proportional counter in units of 12·7 minimum ionizing electrons.

The spectrum of the energy transferred directly to the electromagnetic cascade in first interactions, derived from the hadron spectrum measured at an atmospheric depth of 700 g cm^{-2} by Nikolskii (1969) using the values of $\bar{K}_\gamma$ given by Nam *et al* (1971, see figure 2), could also be regarded as arising from two components. One component would be consistent with a nucleon spectrum with a constant exponent and value of K_γ (the fraction of the incident particle energy given in the first interaction to the electromagnetic cascade) which is independent of energy. The other component would agree, within the accuracy of the measurements, with the shape of the burst energy spectrum of the step observed in the sea level measurements. When the intensity measurements at both atmospheric depths are compared taking into account the different experimental arrangements (and therefore the different probabilities of observing the new particle's interactions) it is found that the lifetime of the new particles must be greater than about 2×10^{-7} s and their interaction length in the atmosphere greater than about 300 g cm^{-2}. These values are calculated for a 90 % confidence limit assuming there are either no losses due to interactions or no losses due to decay respectively. A high value of K_γ for the interactions of the new particle would also account for the increase in K_γ observed by Nam *et al.* Although the zenith angle distribution of the new particle will be different from that of pions and nucleons if its interaction length is as long as suggested above, this effect has been neglected, as a first approximation, in the present comparison between the work at 700 g cm^{-2} and near sea level.

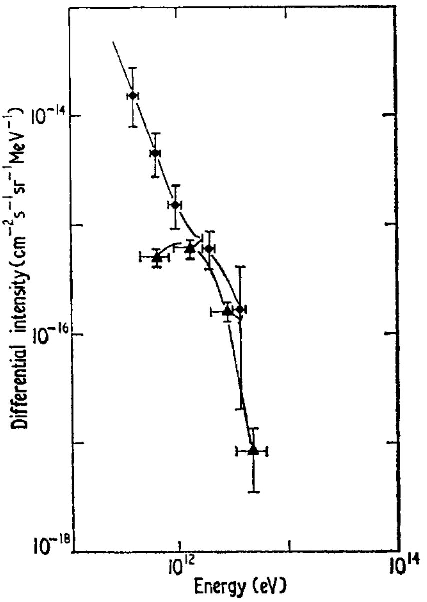

Figure 2. A comparison of the derived burst spectrum at high altitude with the measured burst energy spectrum of the step near sea level. ●, derived burst spectrum at 700 g cm^{-2}; ▲, our determination of burst spectrum of step.

A comparison of other experimental data of ours taken with only 5 cm of shielding lead on the calorimeter, with the data for 10 cm already published (Baruch *et al* 1973) shows that, within the limits of error, the absence of 5 cm of lead makes no difference in the region of the step to the absolute rate of observing bursts which originate in the graphite target. If the intensities of the particles incident on the calorimeter are determined, from the data with 5 cm and with 10 cm of shielding lead, by calculating the probability of the particle's first interaction in the calorimeter taking place in the graphite target, using the accepted values for the interaction lengths of nucleons in lead and graphite, we obtain the results shown in figure 3.

There is good agreement in rates for the two low energy points but an apparent decrease in intensity in the step when the thickness of shielding lead is reduced by 5 cm.

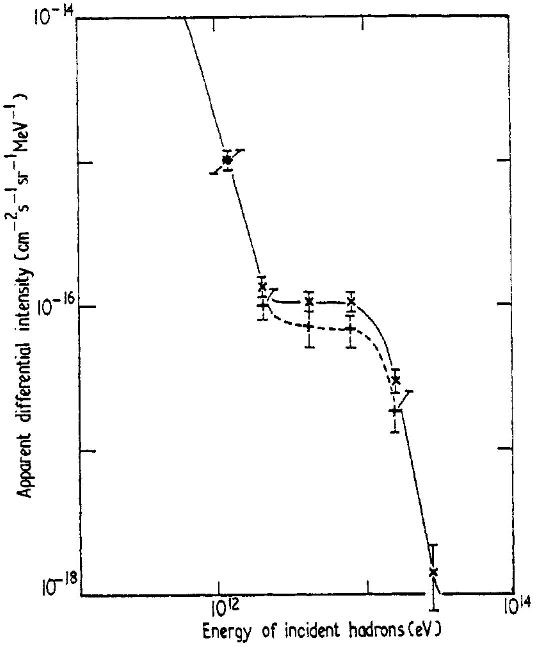

Figure 3. The apparent change in the calculated intensity incident on the calorimeter for differing shielding-lead thicknesses, assuming the incident particles to be nucleons. ×, 10 cm Pb; +, 5 cm Pb.

Just such an apparent decrease in intensity would be expected if the interaction length of the particles in the step were much greater than that of nucleons. Although the statistical significance of the apparent change in intensity of the incident particles is not high, these measurements give some support to the suggestion of a new particle with a long interaction length being responsible for the step. They also reinforce our view that 'instrumental' explanations of the step, particularly those based on transition effects, are most unlikely since then no change would be expected. (The differences between the results already published and those shown in figure 3 are due to a more detailed consideration of the effects of electromagnetic cascade fluctuations on the mean burst size.)

The results of burst experiments, under large amounts of absorber, of Erlykin *et al* (1971) and Khristiansen *et al* (1971) show a similar anomaly, but no absolute intensities have been given by those authors. A comparison of our best estimates of their absolute rates with our data show them to be compatible with an interaction length of about 1000 g cm^{-2} for the new particle. The maximum value of the interaction length with a confidence limit of 90% is 2000 g cm^{-2}.

If the particle is produced directly in high energy interactions of cosmic ray nucleons in the atmosphere and if, as suggested, its interaction length and lifetime are long, its energy spectrum would be expected to have a similar exponent to the primary spectrum at energies well beyond the production threshold. That our published spectrum is significantly steeper than the primary spectrum at high energies is probably due to the exclusion of multiple events which are an increasing percentage of the events as the energy increases. For example, for the highest energy point shown in figure 2, only 27% of the bursts falling in that energy bin have been included, the remaining 73% being seen as multiples.

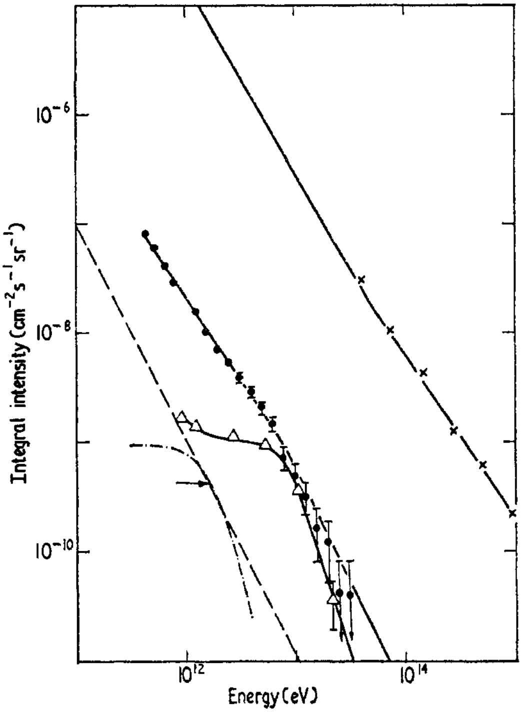

Figure 4. Integral spectra of hadrons at various depths in the atmosphere. Chain curve, integral form of burst energy spectrum of new particles, as in figure 2; arrow denotes energy (~1·5 TeV) where intensity in the step is about 50% of maximum; ×, 'Proton' satellite data; ●, 700 g cm^{-2} spectrum; △ present work; broken line, Hillas (unpublished).

Figure 4 shows the integral sea level spectrum calculated from our measured burst spectrum, assuming that bursts have one sixth of the energy of the interacting particles, together with the ionization calorimeter measurements at an atmospheric depth of 700 g cm^{-2} of Nikolskii (1969) and the spectrum of all particles measured by the 'Proton' series of satellites (Grigorov *et al* 1971). The sea level nucleon spectrum calculated by Hillas from the 'Proton' data is also shown. The chain curve shows the integral form of the burst energy spectrum of the new particles as given in figure 2. If the observed step near 1·5 TeV is due to the presence of a new particle in the cosmic ray flux, this event would correspond approximately to the laboratory system energy of the particle at the production threshold. This corresponds to a mass of about 40 GeV if the particles are produced in pairs, the decay probability is neglected, and assuming $K_\gamma \simeq 100\%$.

The change of exponent of the mountain altitude spectrum of Nikolskii at about 5 TeV does not appear to be due to a corresponding change in the primary spectrum exponent (see figure 4). Such a change could be connected with the production of new particles of mass about 40 GeV.

Because the ionization calorimeter measurements of Nikolskii do not show a significant enhanced intensity due to the new particles, we can set a minimum limit on K_γ of 40%. That is, if K_γ were less than this, the energies calculated from our sea level measurements would be high enough for the new particle intensity to be comparable to the nucleon intensity at a depth of 700 g cm^{-2} in the atmosphere.

This lower limit for K_γ gives an upper limit to the mass of 70 GeV. An upper limit to K_γ is set by the experiment of Nam *et al.*

The existence of a new particle seems at present the most probable explanation of the observations available. This particle would have a mass in the range 40–70 GeV, a mean lifetime greater than 2×10^{-7} s, an interaction length of 1000^{+1000}_{-700} g cm^{-2} and the fraction of its energy K_γ given to the electromagnetic cascade would be 40–95%. The new particle has certain properties in common with the proposed vector boson (Weinberg 1971), and with some proposed for quarks. Experiments are continuing to determine the charge and zenith angle distribution of the particles.

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