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The possibility of a consistent explanation of various phenomena involving cosmic ray muons

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Abstract. A discussion is given of various cosmic ray phenomena from the point of view of the hypothesis of 'regenerated showers'. It is shown that the hypothesis, which was originally developed in order to explain muon-poor showers, gives a consistent explanation of various 'unusual' phenomena observed in cosmic rays. The most interesting result is that the hypothesis can explain the apparent discrepancy between the high energy 'muon' spectrum derived from the burst size spectrum and that deduced from other types of observation. With the additional assumption that the passive particle decays into a muon pair with lifetime of the order of 10^{-7} s, the hypothesis can also explain the abnormal angular distribution of energetic muons observed by the Utah group.

Some other phenomena which can be explained are indicated and suggestions for further experimental tests of the hypothesis are made.

1. Introduction and description of the model

Recent experimental investigations of the muon-poor showers carried out by means of the Lodz and Verrieres devices (Catz *et al* 1969, 1971) show that the showers are not due to primary γ rays. An explanation (the so called 'regenerated shower' hypothesis) which can account for all properties of the showers is that they are due to interactions of partly passive long-lived heavy particles (Gawin *et al* 1970), produced in the interactions of primary protons.

The properties of the showers can be explained best if it is assumed that the attenuation length of the particles (X-particles) is somewhere in the interval 1000–2000 g cm^{-2} and that the inelasticity of their interactions is much lower than unity. As was shown by Gawin *et al* (1970), some additional restrictions on the particle properties arise if it is assumed that the X-particles are also responsible for the abnormal angular distribution of energetic muons observed by the Utah group (Bergeson *et al* 1971). In that case upper limits to the particle mass and lifetime can be deduced. In order to relate the angular distribution to the hypothesis it is assumed that the X-particles undergo decays into muon pairs with mean lifetime of the order of 10^{-7} s. This value has been taken to give the deviation from the sec θ dependence with energy observed in the Utah experiment (the apparent decrease of the rate of the new process at energies of several thousand GeV (Keuffel *et al* 1969)). This assumption is identical with that considered as one of the possibilities in recent work by the Utah group (Carlson *et al* 1971).

In the present paper various consequences of the hypothesis are discussed. For the purpose of numerical calculations the particle mass and lifetime are chosen to give the critical decay energy $B = 1500$ GeV. The interaction length is taken as $\lambda_{int} = 400$ g cm^{-2}

and the inelasticity coefficient $K = 0{\cdot}1$. These values for λ_{int} and K are taken in order to ensure the increase of the relative muon density in the muon-poor showers with increasing zenith angle (a property of the showers that is observed experimentally (Catz *et al* 1971)). Further it is assumed that the cross section and energy spectrum of the produced particles are such that the overall production spectrum is parallel to the primary spectrum and lower by factor of $2000 (p = I_X(E)/I_0(E) = 5 \times 10^{-4})$. This value is chosen to give the correct intensity of the muon-poor showers. If the X-particles are produced in pairs and the inelasticity of the proton interactions is 0·5, the value of p corresponds to 0·2 mb.

The production threshold energy is assumed to be $1000t$ GeV, where t is the ratio of primary proton energy to the energy of the produced X-particle. The cross section dependence on the energy is taken as a step function. The properties of the X-particle are summarized in the Appendix. A discussion of the limits on the various parameters is also given there.

The propagation of the X-particles through the atmosphere has been studied by solving the diffusion equations by the method of successive generations. It is assumed that the showers resulting from the individual interactions of the X-particles are similar to ordinary EAS initiated at the same depth by individual interactions of a proton. The contributions from the successive interaction of the particles are summed; for the electromagnetic component practically always only one interaction dominates but for the muon flux several generations give comparable contributions.

The predicted differential energy spectra of the X-particles for four different angles are given in figure 1.

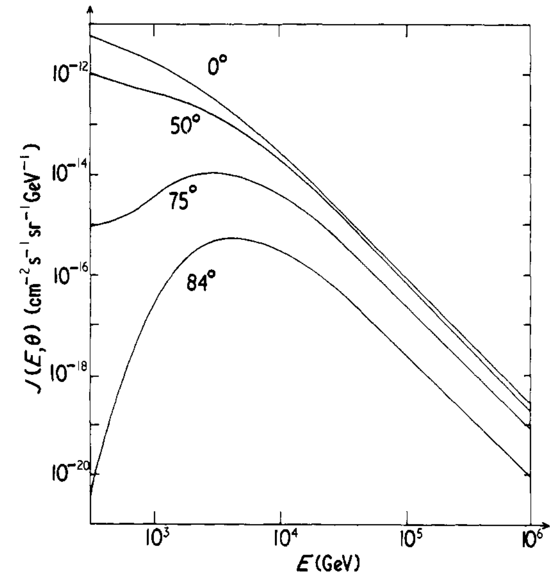

Figure 1. The differential energy spectra of X-particles at sea level for four zenith angles.

The variation of the ratio of the central muon density to the electron size of the X-showers; as a function of the zenith angle, is given in figure 2. It is necessary to use the central density instead of the muon size because the former quantity is measured experimentally and its relation to the muon size is not direct when the angle is changed. This

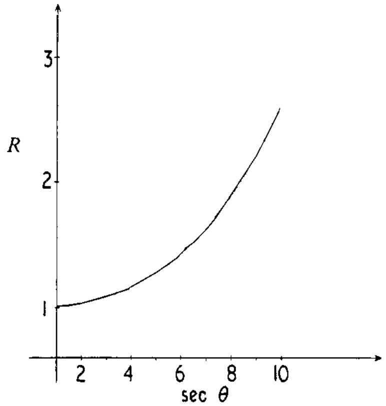

Figure 2. The variation with angle of the relative muon content in muon-poor showers, R, calculated on the basis of the X-hypothesis. $\theta = 0°$ is taken as the datum.

figure gives justification to the earlier stated assumption about the small value of the inelasticity coefficient. It is interesting to note that a further decrease of the coefficient would not change the dependence given in the figure significantly.

2. The muon energy spectrum

In figure 3 there is given the muon energy spectrum expected on the basis of the present hypothesis; the contributions from pion decay and from the X-process are marked separately. The first contribution has been calculated using a combined isobar–pionization model. It is assumed that in each interaction one pion is produced with 15 % of the primary energy and that the remaining 35 % of the energy ($K = 0{\cdot}5$) is divided

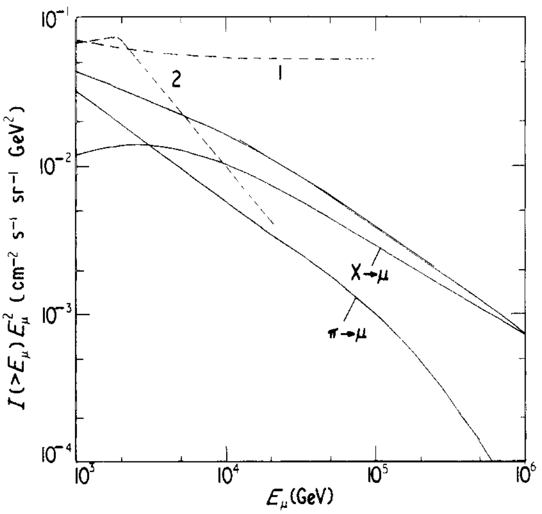

Figure 3. The predicted muon energy spectrum. The contributions from $\pi \rightarrow \mu$ decay and $X \rightarrow \mu$ decay are marked separately. The broken curves show the muon spectra predicted on the basis of the W-absorption model (1) and the X-peak model (2) (see text).

among other pions on the basis of the CKP formula. The broken curves show the predictions of the Utah group for the W-absorption model (1) and the X-peak model (2) quoted after Wolfendale (1971).

The derived muon spectrum is compared with experimental results in figure 4. Comparison is made with the spectra obtained on the basis of the depth–intensity relation and with use of x ray and emulsion chambers. The 'muon' spectra obtained

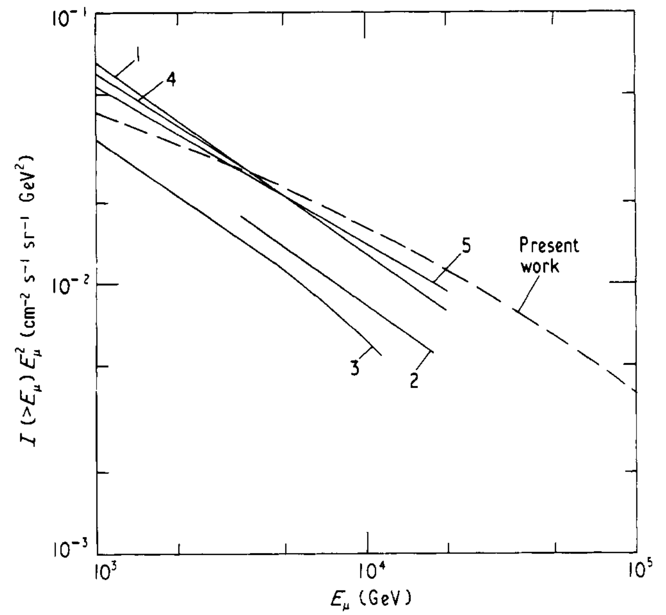

Figure 4. Comparison of the predicted muon energy spectrum (broken curve) with experimental data. The experimental data come from the following papers: 1 Amineva *et al* (1971); 2 Baradzei *et al* (1971); 3 Mizutani *et al* (1971); 4 Chin *et al* (1969); 5 Kiraly and Wolfendale (1970).

from the burst measurements have been excluded since in our model the bursts would be due partly to the interaction of muons and partly to the direct interactions of the X-particle (this follows a remark by G T Zatsepin, at the Tbilisi Conference 1971, who called attention to the fact that the divergence between the burst spectra and the spectra recorded in the x ray film chambers could be explained by the fact that the chambers are sensitive to the central electron density and would not register cascades initiated by the interactions of the X-particles, where a strong division of the released energy is expected with consequent wide angular spread). It should be stressed that no normalization of the predicted spectrum has been made. The derived intensity of muons is a consequence of the intensity of muon-poor showers and the assumption that the cross section for X-particle production is constant above the threshold.

It can be seen that the predicted spectrum is in moderately good agreement with the experimental data and that the agreement is clearly better than that for both Utah spectra marked in figure 3. The W-absorption model gives a spectrum which is clearly too flat and the X-peak model one which is too steep.

3. Burst size spectra at shallow depths

The expected burst size spectrum is compared with the experimental data of Erlykin *et al* (1971) in figure 5. The theoretical curve is calculated for the muon spectrum given in figure 3 (the contribution from muons) and on the basis of the X-particle spectra from

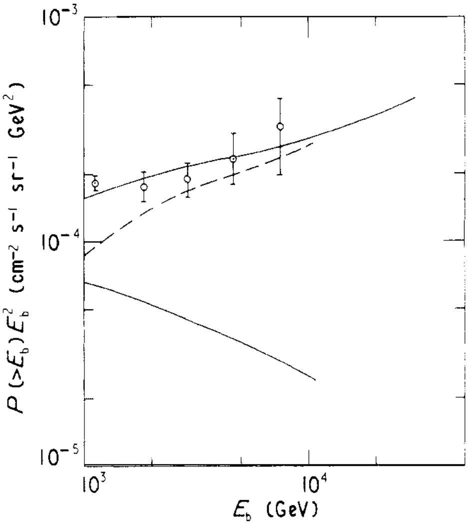

Figure 5. The predicted energy spectrum of bursts recorded at a depth of 20 hg cm^{-2}. The contributions from pions (lower curve) and from X-particles (upper broken curve) are marked separately. The experimental points come from the work of the Tian–Shan group (Erlykin *et al* 1971).

figure 1, taking into account the assumptions referred to earlier about the X-particle interactions and allowing for the attenuation of the particles by 20 hg cm^{-2} of earth. The contributions from the two processes are marked separately in the figure. In the absence of sufficient knowledge about the conversion from burst size to energy, the experimental data have been normalized to the predicted intensity, so only the shape of the spectrum should be compared with the prediction. It can be clearly seen that the burst spectrum is in far better agreement with expectation when the contributions from both muons and X-particles are taken into account (it should be noted that the contribution from muons already contains that from muons produced via the X-process).

The other experiment results on the burst spectra (Khristiansen *et al* 1971 and Krasilnikov *et al* 1971) also give support to the hypothesis since in both cases the burst spectrum is much flatter than that expected for muons. The experiment by Khristiansen *et al* (1971) has been operated at a depth of 40 hg cm^{-2} so the attenuation of the X-particles should be more important there and some reduction of the burst intensity is expected; a reduction by 2·7 is expected on the basis of the assumptions of the present work but this will not affect critically the shape of the spectrum. The expected burst spectrum has an integral exponent of about 2 and this is exactly the value which fits the experimental data from this work.

The experiment by Krasilnikov *et al* (1971) was carried out without sufficient cover to eliminate the nuclear active component and its interpretation is more complicated.

Nevertheless, the spectrum of those bursts which they are able to relate to muons is also clearly flatter than the expected one and not inconsistent with what we would expect.

4. The angular distribution of single muons

The angular dependence of the intensity of high energy muons is a superposition of the angular variation of the intensity of the muons produced via decay of pions and the variation of the muons due to the X-process. Expressing the X-produced muon angular distribution as $I_X(\theta) \propto \sec^s\theta$, the value of the coefficient s as a function of energy is shown in figure 6. The coefficient varies with energy more slowly than that obtained by simple transformation from the curve given by the Utah group for pions (Keuffel *et al* 1969) because of the fact that the interactions of the X-particles have small inelasticity.

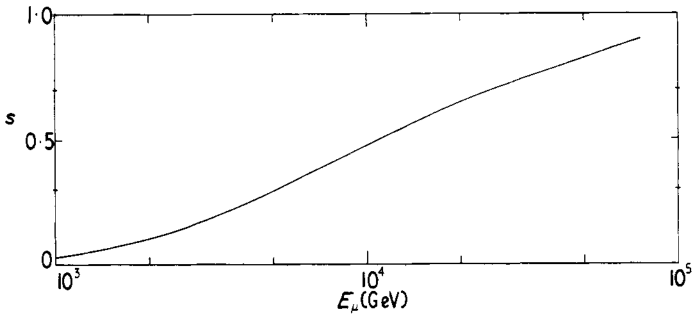

Figure 6. The variation of the s coefficient in the relation $I_\mu \simeq \sec^s\theta$ obtained on the basis of the present model for muons originating in X-particle decays.

Using the data from the Utah experiment (Bergeson *et al* 1971) one can estimate the relative contributions of the two processes to the muon flux by fitting the function

$$I_\mu(\theta) = I_{\mu\pi}\sec^{s_1}\theta + I_{\mu X}\sec^{s_2}\theta$$

where s_1 depends on energy in the manner given by the Utah group and s_2 represents the variation given in figure 6. $I_{\mu\pi}$ and $I_{\mu X}$ represent vertical intensities of the muons from the two sources and their values were chosen to give a least squares fit to the Utah data. In figure 7 there are plotted the values of the quantity $Q = I_{\mu X}(I_{\mu X}+I_{\mu\pi})^{-1}$ obtained from that fit together with the theoretical predictions obtained on the basis of figure 3. It can be seen that the agreement is good (except for the last point which does not appear to fit predictions of any model) so that it can be said that our hypothesis describes the abnormal muon angular distribution adequately.

5. Discussion and conclusions

5.1. Evidence in favour of the hypothesis

The considerations given above show that the hypothesis of the existence of a partly passive, long-lived particle provides a good explanation of several cosmic ray phenomena.

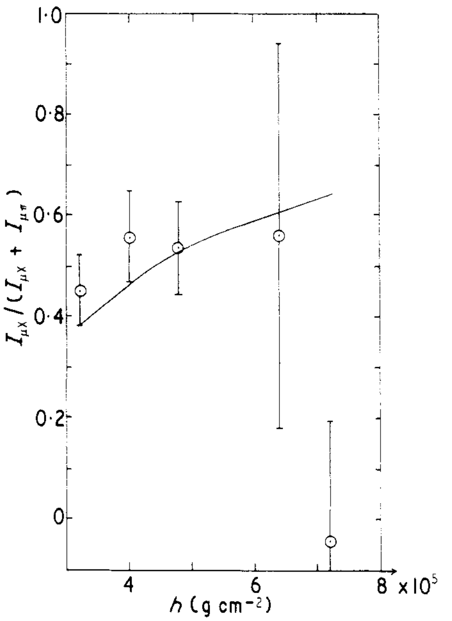

Figure 7. The variation with energy of the contribution of the muons from the X-process to the total muon flux. The experimental points come from the Utah data as processed by us on the basis of our hypothesis.

The hypothesis, originally suggested for explanation of muon-poor showers recorded at sea level, also explains the abnormal angular distribution of energetic muons and characteristics of the bursts recorded at shallow depths. In particular, it explains the striking difference between muon spectra obtained on the basis of burst measurements and those obtained using other methods.

Concerning the abnormal angular distribution of muons it should be noted that the hypothesis offers an explanation of the apparent decrease of the X-muon proportion with increasing depth observed in the Utah experiment, and at the same time gives a muon spectrum close to that observed experimentally; the two other suggested explanations, namely the W-absorption model and the X-peak model, give muon spectra which seem to be too far from the experimental data. The W-absorption model gives a spectrum which is clearly too flat compared with the results obtained using the emulsion and x ray film chambers. (The discrepancy between the muon spectrum from the W-absorption model and that deduced from the depth–intensity relation is of course not essential since in the conversion from underground intensity against depth to ground level spectrum allowance is not made for the W-absorption process.) The X-peak model, on the contrary gives a spectrum much too steep; it seems that the derived power law index of 3·25 for the integral spectrum of muons between 2×10^3 and 10^4 GeV is clearly ruled out by the experimental data.

The muon spectrum predicted on the basis of the present hypothesis is also slightly flatter than the experimental spectra but it is much closer to them than those discussed above. Better agreement would be obtained if a small increase of the X-particle production cross section with energy were allowed. It seems, however, that the present accuracy of the experimental data does not give the basis for such a refinement. The evidence presented in figure 7 shows, on the other hand, that the present hypothesis gives fair agreement with the experimentally observed variation of the fraction of muons from nonpions with threshold energy, so the hypothesis is equivalent to the W-absorption model and the X-peak model in this respect.

It should be added that there are other phenomena observed in cosmic rays which can be understood on the basis of the hypothesis. One of these is the observation of delayed particles in extensive air showers by the Turin group (Dardo *et al* 1971). These particles could be produced in interactions of the X-particles which, by virtue of their mass, should be delayed with respect to the shower front. Such a picture would explain the apparent discrepancy between the rate of the delayed particles and the upper limit to the intensity of quarks.

Another phenomenon which could be related to the hypothesis is the observation of muon bundles (Vernov *et al* 1969, Hibner and Wysocki 1971). The bundles could be interpreted as being at least partly due to the interactions of the particles deep in the atmosphere (or in the ground above the detectors) although it seems that the interpretation in terms of coherent interactions of π mesons (Wdowczyk and Wolfendale 1971) is more likely.

It has already been reported by Gawin *et al* (1970) that the hypothesis can also account for the excess in intensity of horizontal showers reported by groups from Tokyo (Matano *et al* 1968), Durham (Alexander *et al* 1969) and Kiel (Bohm *et al* 1969).

5.2. *Suggested further experimental studies*

A number of experiments can be suggested on the basis of the hypothesis. Of particular interest would be an accurate measurement of the angular distributions of the ordinary and muon-poor EAS and measurements of burst spectra at various depths underground. The first experiment should mainly concentrate on the angular range 60–75°, where the check of the hypothesis should be easiest due to the expected high intensity of the regenerated showers and a sufficiently low backgound of normal showers.

In respect of the burst spectrum the main prediction of the hypothesis is a rapid variation of the intensity of large bursts with depth at relatively shallow depths due to attenuation of the X-particles. The observation of this effect would provide strong evidence in favour of the hypothesis. Although there have already been burst measurements made at various depths, the range of depths and the fact that the measurements were made with different devices do not allow any conclusions concerning the change of the burst spectrum to be made so far.

Another possibility of checking the hypothesis could come from measurements of the angular variation of the bursts registered at sea level, especially those initiated by neutral particles. In the vertical direction the bursts would be initiated by neutrons, but for large angles the X-particles should take over, and the angular distribution of the bursts would be strongly dependent on the intensity of the X-particles. Again, at present there are insufficient data available on this point.

Acknowledgments

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Appendix

The properties of the X-particle assumed for the purpose of the present paper can be summarized as follows:

(i) The production spectrum above about 1000 GeV is parallel to the primary spectrum and the intensity is lower by a factor 2000. The last value is chosen to give the correct intensity of the muon-poor showers and the uncertainty of its estimation is of the order of 30%.

(ii) The lower limit to the cross section for particle production is about 0·2 mb. This value is obtained on the basis of the above stated intensity and the assumption that the X-particles are produced in pairs with total energy of the pair equal to 50% of the primary energy. The last quantity is arbitrary although it can be understood as a rough upper limit. If the value were lower the cross section would have to be correspondingly higher.

(iii) The angular distribution of the muon-poor showers is used to give the attenuation length in the interval 1000–2500 GeV. The fact that the muon content of these showers increases with angle suggests that the inelasticity of the X-particle interactions is low. For the purpose of the present paper it has been assumed that the inelasticity coefficient K is equal to 0·1 and $\lambda_{int} = 400\,g\,cm^{-2}$ corresponding to $\sigma = 8$ mb. The chosen values are somewhat arbitrary, but the model is rather insensitive to the actual values of K and λ_{int} provided that the right value of the attenuation length is adopted.

(iv) The decay mode of the particle from the point of view of the present hypothesis is

$$X^0 \rightarrow \mu^+ + \mu^-.$$

Comparison of the intensities of the 'regenerated' showers and the X-originated muons shows that this decay mode has to play an important role. At least half of the decays should proceed by this channel. The most likely other channel would be decay into electrons:

$$X^0 \rightarrow e^+ + e^-.$$

(v) The lifetime of the particles can be estimated from the fact that the best value of the decay constant is about 1500 GeV and probably not exceeding 3000–4000 GeV. Since the mass of the particle is in the range 5 to 50 GeV the lifetime lies between 10^{-7} and 10^{-8} s. A lower limit comes from the fact that the particle has not been observed in accelerator experiments and the upper limit from the threshold of the Utah effect.

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