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Implications of strong leptonic interactions for very high energy cosmic ray phenomena

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Abstract. An analysis is made of the implications for high energy cosmic ray phenomena of the interaction models of Pati and Salam. The effect on the size spectrum of showers, the energy spectrum and angular distribution of high energy muons and the longitudinal developments of showers is considered. It is shown that the muon data enable a lower limit of 7×10^3 GeV to be placed on the total energy in the centre-of-mass system for the onset of the phase where leptonic and semi-leptonic processes become strong.

1. Introduction

During the last few years much work has been done in an attempt to unify weak, electromagnetic and strong interactions. One idea that has arisen is that at high energies leptonic and semi-leptonic processes should eventually become strong. The asymmetric response of leptons and baryons to strong interactions would then be interpreted as a low energy phenomenon. These ideas are contained in the work of Pati and Salam (1973a, 1973b, 1974). According to their scheme, baryonic quarks ($B = 1$) and leptons ($L = 1$) are grouped together as members of the same fermionic multiplet ($F = B+L = 1$). It can be expected that in a very high energy proton–proton collision one of the protons will disintegrate into three (integrally charged) quarks which then decay into leptons. The threshold energy for such a process (we shall call it the S-process) depends on the details of the assumed model, being of the order of 300 GeV (in the centre-of-mass system) for the 'economical' model and 10^4–10^5 GeV for the 'basic' one (Pati and Salam 1974). Such energies are at present only available in cosmic rays.

The purpose of the present work is to see how the addition of the S-process would affect the propagation of cosmic rays in the atmosphere and, using existing data, what limits can be put on the parameters of such a process.

2. Characteristics of the model

The characteristics chosen for the proton interactions are as follows:

(i) The S-process takes place if the proton energy is greater than a particular threshold value.

(ii) The cross section for the S-process is the same as for ordinary nuclear interactions.

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(iii) In the S-process one of the protons disintegrates into three quarks. For the decay model of the quark we have considered two possibilities:

$$q \rightarrow l + l + \bar{l}, \qquad \text{where l denotes lepton (model I)}$$

and a more probable scheme:

$$q \rightarrow l + \pi \qquad \text{(model II)}.$$

These decay schemes follow from the arguments of Pati and Salam (1973b) where each quark carries unit charge and $B = 1$ and decays such that although B and L are not conserved individually their sum, $F = B + L$, is conserved ($F = 1$ for both sides of the decays for both models I and II). The derivation of the decay schemes is given in the appendix. Briefly in model I the proton disintegrates effectively into nine leptons:

$$p \rightarrow 3\nu_{\mu} + 2\nu_{e} + \bar{\nu}_{e} + e^{-} + e^{+} + \mu^{+}$$

so that only a small fraction of its energy goes into electromagnetic cascades. In model II it disintegrates into three pions and three leptons. If we assume equal probabilities for every decay mode of the quark allowed by charge and fermion number conservation we have, on average:

$$p \rightarrow 2{\cdot}22\pi^{+} + 0{\cdot}68\pi^{0} + 0{\cdot}11\pi^{-} + 0{\cdot}56e^{-} + 1{\cdot}89\nu + 0{\cdot}56\mu^{-}.$$

In both models equiparition of energy takes place.

(iv) For the case where the target proton disintegrates the inelasticity coefficient has been taken to be 0·3 (although this value is not critical), so that the mean inelasticity for the S-process is $K = (1 + 0{\cdot}3)/2 = 0{\cdot}65$. For an ordinary nuclear interaction the value $K = 0{\cdot}5$ is adopted.

The addition of the S-process would change the development of the cosmic ray components in the atmosphere. In the present work we have confined ourselves to an examination of its influence on three quantities:

(*a*) the size spectrum of extensive air showers (EAS);

(*b*) the energy spectrum and angular distribution of high energy muons;

(*c*) the longitudinal development of showers, in particular the position of the point of maximum electron number.

3. Effect of the S-process on cosmic ray phenomena

3.1. The size spectrum of EAS

It is a well established fact that the shower size spectrum of cosmic rays cannot be described by a single power law over the whole measured range. A good fit is found by two straight lines (on a log–log scale) with intersection at a size corresponding to a primary energy of about 3×10^{15} eV and this is usually interpreted as a sudden change of the exponent of the primary energy spectrum (from 1·6 to 2·2 in the integral spectrum). It is instructive to examine the question of whether the shape of the size spectrum can be explained by the existence of the S-process, assuming that the primary energy spectrum is described by a single power law, an assumption that has obvious attractions. (Earlier attempts, by Adcock *et al* (1968) and others, have also been made to design interaction models which would enable the measured size spectrum to be reconciled with a primary energy spectrum having a constant exponent.)

Calculations have been made of the ratio N/N_s, N being the size if the proton undergoes ordinary strong interactions only, and N_s if the S-process is included, as a function of the ratio ϵ of the proton primary energy to the threshold energy which corresponds to the kink. Figure 1 shows the dependence of this ratio on ϵ. It can be seen that model I could explain the kink but only for $\epsilon \lesssim 5$, ie for the energy range

$$3\times10^{15}\,\text{eV} < E_0 < 1{\cdot}5\times10^{16}\,\text{eV}.$$

Also shown in figure 1 is the ratio N/N_s for the case where the S-process alone occurs above threshold. The resultant variation does not give the form needed to explain the 'kink' although it is apparent that if the onset of the S-process were not abrupt but gradual it would be possible to explain the shower size data up to $\epsilon \simeq 50$. However, the assumption of the S-process being dominant is not attractive.

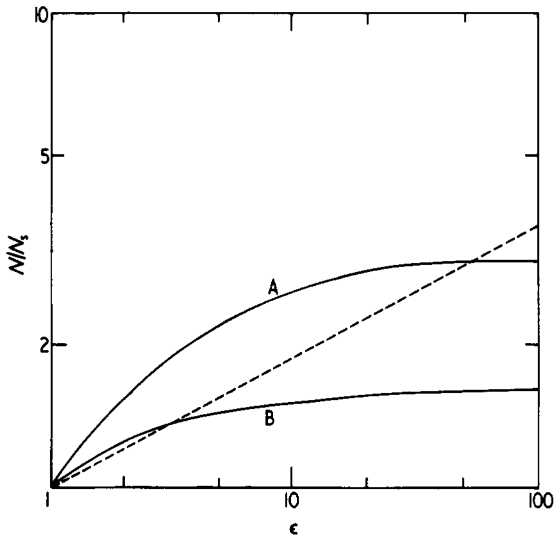

Figure 1. Ratio of shower size N (ordinary process) to shower size N_s (including S-process) as a function of ϵ, the ratio of the primary energy E_0 to the threshold energy for the S-process. The energies are measured in the laboratory system.

The ratios shown as full curves are those resulting from application of the model: curve A, S-process only; curve B, S- and ordinary process (model I). The broken line indicates the ratio needed to ensure that the measured size spectrum results from a primary cosmic ray spectrum having a constant exponent over the whole energy range.

At energies above about 10^{17} eV, the energy loss for neutrinos and muons becomes proportional to the primary energy so that it cannot cause any change in the exponent of the size spectrum. In model II the energy taken away by neutrinos and muons is much smaller and so is the change of shower size so that an explanation of the size spectrum here is even more difficult.

3.2. The energy spectrum and angular distribution of energetic muons

We now turn to an examination of the high energy muons produced in quark decays. We have calculated for both models the angular distribution of these muons deep underground, at the site of the Kolar Gold Field experiment of Menon *et al* (1967), and others (depth: $7{\cdot}6 \times 10^5$ g cm^2 of standard rock) assuming the threshold energy for the S-process to be equal to 3×10^{15} eV, as before. The integral exponent γ in the primary energy spectrum in model I has been taken to be 1·6, ie a primary spectrum without a kink. As was shown earlier, this model could account for the primary spectrum up to about $1{\cdot}5 \times 10^{16}$ eV and it is legitimate to apply it to the muon case. Figure 2 represents the results together with an approximation to the experimental muon data. The line B represents an average intensity of neutrino-induced muons from the data of Khrishnaswamy *et al* (1971) for $\theta > 50°$. It can be seen that model I gives more muons for $\theta \gtrsim 20°$ than observed experimentally.

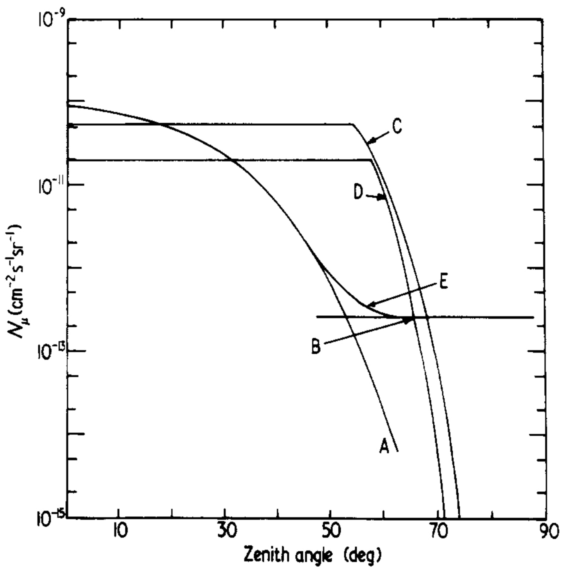

Figure 2. Angular distribution of muons at the depth of the Kolar Gold Fields experiment ($7{\cdot}6 \times 10^5$ g cm^{-2}) from the measurements of Menon *et al* (1967) and Khrishnaswamy *et al* (1971). A distinction is made between muons of atmospheric (curve A) and neutrino (curve B) origin. The predictions of the models used here are shown for $E_{th} = 3 \times 10^{15}$ eV: curve C, model I ($q \to 3l$) $\gamma = 1{\cdot}6$; Curve D, model II ($q \to \pi l$) $\gamma = 2{\cdot}2$. Curve E indicates the experimental distribution.

Although model II cannot explain the kink in the shower size spectrum it can still be considered as possible because the kink could be explained in other ways (the obvious example is that there is in fact an equivalent change of slope in the primary energy spectrum). The muon intensities have been calculated for model II, with $\gamma = 2{\cdot}2$, with the results also shown in figure 2. Again, too many muons are predicted.

The excess can be reduced by making the threshold energy for the S-process higher ($N_\mu \propto E_{th}^{-\gamma}$). We can consider the value of the threshold energy, corresponding to a decrease of the number of S-muons down to the neutrino-induced muon level in model II, as a lower limit for the onset of the S-process. The corresponding value is 2×10^7 GeV laboratory energy, ie a centre-of-mass total energy equal to about 7×10^3 GeV (changing K from 0·5 to 1 will affect this number only by about 5 %). The derived value of 7×10^3 GeV would appear to rule out the 'economical' model of Pati and Salam but it is not inconsistent with their basic model. However, it is necessary to stress that the conclusions depend strongly on the assumptions about the decay modes of the quarks, in particular into what sort of leptons they decay. If proton- and neutron-type quarks tend to decay into electron-type leptons, (as contrasted to λ quarks which would decay into μ-type leptons; Pati and Salam 1973b) then the number of S-muons would drop and so would the lower limit for the threshold energy. In this case it might be possible to restore the 'economical' model.

3.3. *Longitudinal development of EAS*

Finally, it is interesting to examine the implications of the S-process for the position of shower maximum. The possibility of explaining the fact that the measured depths of maximum (eg from the work of Bradt *et al* 1965 and Antonov *et al* 1964) are smaller than those expected makes this aspect particularly interesting (this problem has been discussed by Wdowczyk and Wolfendale 1973). The depth of maximum would be smaller for two reasons: firstly, some of the primary energy goes into neutrinos and muons and is therefore lost from the electromagnetic cascade and, secondly, the addition of one or more process would cause a quicker increase of the number of shower particles.

Examination of figure 1 shows that, for model I, the energy loss reaches a value $[1-(1/1{\cdot}6)]\times 100\,\% \simeq 37\,\%$, a value which would unfortunately cause a negligible change in the depth of maximum due to its logarithmic dependence on energy. Even if we took into account the fact that electrons themselves could cause disintegration of protons and so cause another additional energy loss, the situation would not change much. The absolute upper limit for an energy loss in an electromagnetic cascade is approximately proportional to

$$\int_0^\infty \int_{E_{\rm th}}^{E_0} E\pi(E, t)\,\mathrm{d}E\,\mathrm{d}t,$$

the coefficient of proportionality depending on details of the interaction model. In the integral, $\pi(E, t)$ denotes the number of electrons of energy in the interval E, $E+\mathrm{d}E$ at depth t and is taken from normal cascade theory. In model I the upper limit to the fractional energy loss is 40 % for $E_0/E_{\rm th} = 10^3$, and 20 % in model II. These losses are too small to cause an appreciable change in the depth of maximum. As to the displacement of the maximum depth caused by the second reason, its absolute upper limit (in g cm^{-2}) can be estimated as

$$\Delta t = 38[\ln(E_0/\beta) - \ln(E_{\rm th}/\beta)]$$

corresponding to the assumption that all electrons of energy initially above $E_{\rm th}$ are degraded to $E_{\rm th}$ very quickly, that is, with negligible track length. In the expression, β is critical energy for air. With $E_{\rm th} = 3\times 10^{15}$ eV, the values are $\Delta t = 26$, 72 and 108 g cm^{-2} for $E_0 = 6\times 10^{15}$ eV, 2×10^{16} eV and 5×10^{16} eV respectively. These displacements are in fact in the direction needed to explain the anomalously high positions of shower maximum (referred to by Wdowczyk and Wolfendale 1973) but the values are too small and their tendency with increasing E_0 is opposite to that required. Specifically, below 3×10^{15} eV no displacement is predicted here whereas Wdowczyk and Wolfendale indicate that $\Delta t \simeq 250$ g cm^{-2} is required. In summary, the comparison of expected and observed heights of maximum thus lends no support to the existence of the S-process.

4. Conclusions

The possibility of explaining the kink in the size spectrum by the S-process has to be rejected; a model giving a fractional energy loss increasing with primary energy and a smaller number of high energy muons is needed. Adopting the more probable model, model II, we can estimate a lower limit for the threshold energy for the S-process from experimental data on the observed frequency of high energy muons. We obtain a laboratory energy of 2×10^{16} eV, this threshold being dependent, however, on the type of leptons into which quarks decay.

The change of the depth of maximum shower development caused by the S-process is too small to explain existing discrepancies between experiment and theory, especially for showers of energy below 10^{16} eV. Thus, such evidence as there is at present does not give much support for an S-process of the particular characteristics adopted. Finally, we should like to emphasize that this paper should be treated as preliminary, and our results are rather qualitative estimations of changes in the picture of propagation of cosmic rays in the atmosphere. What is clear is that when more detailed predictions are available for processes of the type discussed here, cosmic ray data may enable their validity to be assessed.

Acknowledgments

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Appendix. Derivation of decay schemes

Following Pati and Salam (1973b) the proton can be in one of the following states:

$$(P_a^0, P_b^+, N_c^0), (P_b^+, P_c^+, N_a^-), (P_c^+, P_a^0, N_b^0).$$

The three-body quark decays are:

$$P_a^0 \to \nu_e \nu_\mu \bar{\nu}_e, \qquad N_a^- \to e^- \nu_\mu \bar{\nu}_e$$
$$P_b^+ \to \nu_e \nu_\mu e^+, \qquad N_b^0 \to e^- \nu_\mu e^+$$
$$P_c^+ \to \nu_e \nu_\mu \mu^+, \qquad N_c^0 \to e^- \nu_\mu \mu^+$$

ie the three-lepton decay scheme of model I. It can be seen that each of the proton states gives the same final disintegration scheme:

$$p \to 3\nu_\mu + 2\nu_e + \bar{\nu}_e + e^- + e^+ + \mu^+ \qquad \text{(model I)}.$$

In model II, where it is assumed that the quarks decay into a pion and a lepton, fermion and charge number conservation allow

$$Q^+ \to \pi^+ \nu, \qquad Q^0 \to \pi^+, e^-, \qquad Q^- \to \pi^0, e^-$$
$$\pi^+, \mu^- \qquad \pi^0, \mu^-$$
$$\pi^0, \nu \qquad \pi^-, \nu.$$

The proton states are now

$$(Q^+, 2Q_0), (2Q^+, Q^-), (Q^+, 2Q_0).$$

Thus the probability of the state $(Q^+, 2Q^0)$ is $\frac{2}{3}$ and that of $(2Q^+, Q^-)$ is $\frac{1}{3}$.

Using the decay schemes indicated, the proton state $(Q^+, 2Q^0)$ can decay by one of the following modes:

$$3\pi^+, 2e^-, \nu; \qquad 3\pi^+, e^-, \mu^-, \nu; \qquad 2\pi^+, \pi^0, e^-, 2\nu;$$
$$3\pi^+, e^-, \mu^-, \nu; \qquad 3\pi^+, 2\mu^-, \nu; \qquad 2\pi^+, \pi^0, \mu^-, 2\nu;$$
$$2\pi^+, \pi^0, e^-, 2\nu; \qquad 2\pi^+, \pi^0, \mu^-, 2\nu; \qquad \pi^+, 2\pi^0, 3\nu.$$

The proton state $(2Q^+, Q^-)$ can decay into one of the following modes:

$$2\pi^+, \pi^0, e^-, 2\nu; \qquad 2\pi^+, \pi^0, \mu^-, 2\nu; \qquad 2\pi^+, \pi^-, 3\nu.$$

Allowing for the $\frac{2}{3}, \frac{1}{3}$ weightings for the proton states and assuming equal probabilities for the decay modes within a state, the mean number of particles produced follows as:

$$2{\cdot}22\pi^+ + 0{\cdot}68\pi^0 + 0{\cdot}11\pi^- + 0{\cdot}56e^- + 0{\cdot}56\mu^- + 1{\cdot}89\nu.$$

It will be appreciated that positive leptons, as antifermions, cannot be produced because of fermion number conservation.

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