Role of neutrons in the propagation of extremely high energy cosmic rays

1976 J. Phys. A: Math. Gen. 9 L197

(http://iopscience.iop.org/0305-4470/9/12/006)

J. Phys. A: Math. Gen., Vol. 9, No. 12, 1976. Printed in Great Britain. © 1976

LETTER TO THE EDITOR

Role of neutrons in the propagation of extremely high energy cosmic rays

J Wdowczyk† and A W Wolfendale‡

† Department of Physics, University of Lodz and Institute of Nuclear Research, Lodz, Poland
‡ Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK

Received 14 October 1976

Abstract. Attention is given to the problem of explaining the shape of the spectrum of very energetic cosmic rays, particularly those above 10^{19} eV where evidence for a flattening of the spectrum is becoming stronger. It is proposed that the particles above 10^{9} eV are mainly extragalactic and that they originate from heavy nuclei generated in clusters of galaxies which are largely trapped but from which fragmentation neutrons are able to escape and decay to protons outside the region of confining fields.

In recent publications we have endeavoured to explain the existence of cosmic rays above 10^{17} eV or so in terms of extragalactic origin. The basic problem is well known: if the source spectrum has a constant exponent over the whole range of energy then, due to interactions with the 2·7 K black-body radiation, the measured spectrum should start to deviate downwards at around 2×10^{18} eV and fall catastrophically above some 6×10^{19} eV, in contrast to observation which indicates no downward turn as far as the limit of measurement ($\simeq 2\times10^{20}$ eV). In fact, recent data from several laboratories indicate a flattening of the primary spectrum above about 10^{19} eV, the exponent γ in the differential energy spectrum ($E^{-\gamma}$) being approximately 3 from $E = 10^{16}$–10^{19} eV and roughly 2 above 10^{19} eV. The best data probably come from the Haverah Park array (Clarke *et al* 1975), but there is supporting evidence from the large air shower arrays at Volcano Ranch, Sydney and Yakutsk (see Watson 1975, Krasilnikov 1975‖ for summaries). The data summarized by the last mentioned author have been used to estimate the likely limits to the spectrum with the result given in figure 1.

In a recent paper (Tkaczyk *et al* 1975, to be referred to as I), we examined the role of extragalactic heavy nuclei in explaining the spectrum and showed that if the spectrum had a comparatively small exponent then a somewhat better fit to the data was possible than with extragalactic protons alone (at that time the evidence for an upturn was weaker). In the model the heavy nuclei fragmented on the 2·7 K and infrared radiation and a rather complex cascade resulted.

In the present work we adopt a variant of this model. Essentially the way to explain the experimental results is to generate a spectrum of particles near production which has a small exponent above 6×10^{19} eV, so that after propagation through extragalactic space the attenuation does not reduce the high energy intensities below the measured values.

‖ Krasilnikov D D 1975 *Eur. Symp. on Cosmic Rays, University of Leeds* unpublished.

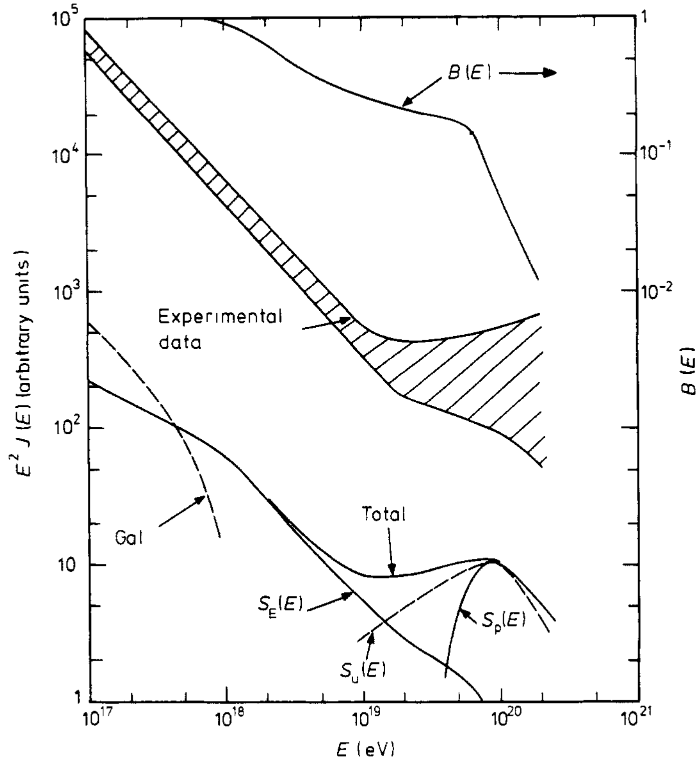

Figure 1. Attenuation of Universal cosmic ray protons by the 2·7 K background ($B(E)$), after Strong *et al* (1974), and the local energy spectrum of cosmic rays $E^2J(E)$. The experimental data lie in the shaded area and are from the work of Watson (1975) and Krasilnikov (1976, unpublished). The nomenclature for the components of the predicted spectra (which, like the experimental spectrum are expressed in arbitrary units) are: $S_p(E)$, contribution from neutron-decay protons which have escaped from clusters of galaxies, the major sources being near the centres of the clusters; $S_u(E)$, contribution from neutron-decay protons where there is a near uniform distribution of sources throughout a spherical cluster; $S_E(E)$, protons which have leaked out of clusters; the probability of leakage is chosen as 2% so as to reproduce the experimental situation; Gal, hypothesized contribution from Galactic particles. The experimental data are in the shaded area.

The basic plan is to take the idea of Brecher and Burbidge (1972) of generation and containment of cosmic rays in clusters of galaxies, but to extend it so that even the particles of the highest energies ($>10^{20}$ V rigidity) are largely trapped and have low escape probabilities. It is assumed that the clusters contain galaxies which accelerate heavy nuclei (such as iron), perhaps in massive condensed objects. These sources generate particles up to at least 10^{20} eV/nucleon i.e. 6×10^{21} eV for iron, with a constant exponent (unlike our own Galaxy, in this model, which effectively ceases to contribute particles above 10^{18} eV/nucleon) and the majority of nuclei are then trapped for a time in excess of the Hubble time ($\approx 13\times10^9$ yr). Inspection of I shows that the iron nuclei of energies above about 10^{17} eV will be rapidly fragmented on the optical, infrared and 2·7 K radiation fields. For example, the mean life for fragmentation of an iron nucleus of energy 10^{20} eV down to $A = 28$, i.e. the loss of half its nucleons, is 1/10 the Hubble time for the case of the 2·7 K radiation alone. Although the resulting protons will continue to be trapped, a fraction of the neutrons will escape from the trapping region before decaying into protons which can then propagate freely through the intergalactic medium.

The probability of escape of a neutron from a cluster is $\exp[-t/(\gamma\tau_0)] \simeq \exp(-d_m/E_{20})$ where d_m is the characteristic cluster dimension in megaparsecs and E_{20} is the neutron energy in units of 10^{20} eV. Immediately it is apparent that, since characteristic cluster dimensions are of order 1 Mpc, there is an extra source of particles in the crucial energy region 10^{19}–10^{20} eV. Uncertainties in cluster characteristics preclude an accurate calculation but a very rough analysis can be made, as follows. Consider an average cluster of galaxies, of radius 2·5 Mpc (the value quoted by Allen 1973) with the energetic sources near the centre. With a production spectrum of the form $E^{-2\cdot5}$, as appears to be the case for iron nuclei in the Galaxy (Juliusson 1975, and others), then the form of the spectrum of neutrons resulting from fragmented nuclei outside the cluster, and thus the ensuing near-cluster proton spectrum $C(E)$ can be calculated. If the clusters are distributed roughly uniformly throughout the Universe then the spectrum expected at the earth will be proportional to the product of $C(E)$ and the 2·7 K radiation attenuation factor $B(E)$ given by Strong *et al* (1974) and also shown in figure 1. This spectrum is denoted by $S_c(E)$. As expected, the spectrum peaks near 10^{20} eV.

Two additional features need to be taken into account: the fact that the sources will be distributed somewhat within the cluster and the fact there will be a range of cluster radii. The net result will be a much slower fall in $E^2J(E)$ with falling energy. The distribution of cluster radii is not known with any accuracy—the published data are clearly not an unbiased set—but calculations can be made for a distribution of sources within a cluster. The approximate result for a uniform distribution is given in figure 1 where it is denoted by $S_u(E)$. The effect of the distribution in radii will be to broaden $S_u(E)$ and it is seen that it is possible, in principle, to reproduce the part of the experimental spectrum above 10^{19} eV. (It is intended to make calculations with more reasonable cluster source distributions later.)

The present model gives essentially no information at lower energies but some general comments will be made, for completeness. Two possibilities spring to mind: that the particles below 10^{19} eV are largely Galactic or that they arise from protons which have leaked out of the clusters through incomplete trapping. If the former is the case and if the particles are protons then large anisotropies are expected. The experimental data are as yet insufficient to adjudicate on this point. An *ad hoc* explanation in terms of cluster-leakage protons can easily be made. If the leakage is momentum independent, perhaps by scattering off magnetic inhomogeneities in the intergalactic space within the cluster, and if the escaping flux of protons is 2% of that of neutrons, then the local intensity would be given in figure 1 ($S_E(E)$). In such a model, the whole region above 10^{18} eV would be populated by extragalactic particles and that below 10^{17} eV almost entirely by particles originating in the Galaxy.

The biggest problem with the neutron mechanism is the need for very efficient trapping of particles of rigidity up to at least 10^{20} V. Comparatively strong magnetic fields are required in the intergalactic space within the cluster—a mean field of at least 10^{-6} G is probably necessary (in such a field, a particle of rigidity 10^{20} V has a Larmor radius of 0·1 Mpc). Brecher and Burbidge summarize the available data on cluster parameters and conclude that the field could conceivably be as high as this although there is essentially no evidence in favour (nor much against). In fact, since we are dealing with galaxies in the cluster which are stronger than our own it is likely that their own fields are much stronger than the 5×10^{-6} G in the Galaxy and thus appreciable high energy trapping may occur in these galaxies themselves.

Finally, some remarks are necessary about the role of the supercluster (SC) in this model (its important role in a model involving protons alone was considered by us in an earlier work: Strong *et al* 1974). We have assumed so far that the Galaxy is not a member of this system (the astronomical evidence is equivocal), but, if it is, similar arguments can be put forward. In this case if there is very slow diffusion of protons from a very strong source at the centre of the SC (M87?) with consequent loss of energy the proton yield would be reduced; the neutrons, on the other hand, would quickly travel a significant fraction of the distance to the earth before decaying and the consequent protons would have an easier passage. There would then be a considerable anisotropy for the particles above 10^{19} eV with a peak intensity towards the centre of the SC ($l^{\mathrm{II}}=283°$, $b^{\mathrm{II}}=+75°$).

The authors acknowledge with gratitude useful discussions with Professors D D Krasilnikov and G D Rochester.

The Science Research Council are thanked for their support.

References

Allen C W 1973 *Astrophysical Quantities* (London: Athlone Press)

Brecher K and Burbidge G R 1972 *Astrophys. J.* 1974 253–91

Clarke A R *et al* 1975 *Proc. 14th Int. Conf. on Cosmic Rays, Munich* vol. 8 (München: Max Planck Institut für Extraterrestriche Physik) pp 2699–703

Juliusson E 1975 *Proc. 14th Int. Conf. on Cosmic Rays, Munich* vol. 8 (München: Max Planck Institut für Extraterrestriche Physik) pp 2689–97

Strong A W, Wdowczyk J and Wolfendale A W 1974 *J. Phys. A: Math., Nucl. Gen.* **7** 1767–76

Tkaczyk W, Wdowczyk J and Wolfendale A W 1975 *J. Phys. A: Math. Gen.* **8** 1518–29

Watson A W 1975 *Proc. 14th Int. Conf. on Cosmic Rays, Munich* vol. 11 (München: Max Planck Institut für Extraterrestriche Physik) pp 4019–32