The energy spectrum of cosmic-ray neutrons at sea level in the range 20-4000 GeV

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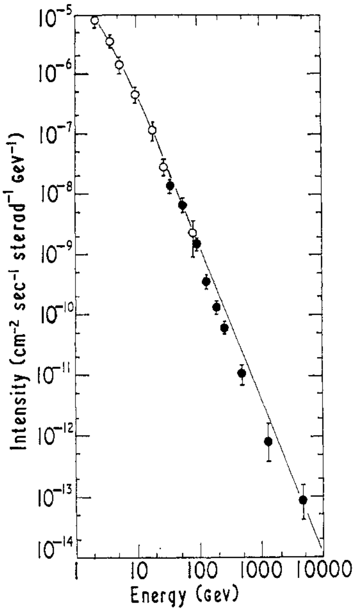
Abstract. A study has been made of the production of bursts by neutral cosmic-ray particles, presumably neutrons, in the energy range 20–4000 GeV. The energy spectrum is found to exhibit a deficiency above 100 GeV when compared with that derived from the primary nucleon spectrum, given by a number of authors, assuming a constant attenuation length. The discrepancy most likely represents a change of attenuation length with energy, but an alternative explanation involving quark production cannot be ruled out.

Preliminary results are reported of an experiment designed to examine burst production by near-vertical cosmic-ray particles at sea level. The apparatus is similar to that used by the authors in their study of muon interactions (Ashton and Coats 1967) and comprises, from top to bottom, the following: eight layers of neon flash-tubes, 25 cm iron, two layers of flash-tubes, a large 17 cm deep liquid scintillation counter and two further layers of flash-tubes. Events are selected in which a large pulse is recorded by the scintillation counter and which show a shower in the flash-tubes beneath the iron target, but with no corresponding ionizing initiating particle above it. These events, after correction for a small background of oblique protons, pions and muons which missed the upper flash-tube trays but interacted in the iron, can be used to estimate the energy spectrum of neutrons.

The method of calculation was to derive the expected burst size spectrum from the primary nucleon spectrum with the assumption of a constant attenuation length of 127 g cm^{-2}. The primary spectrum adopted comes from the work of Baradzei *et al.* (1962) with ionization chambers at great altitude and from the indirect analysis of Brooke *et al.* (1964) in which the sea-level measurements of the muon and proton components were used. Some confirmation for this spectrum, which has an integral exponent of the order of 1·6 in the energy range 10^{10}–3×10^{13} ev, has come from the measurements of Bray *et al.* (1965) and Malhotra *et al.* (1965) using nuclear emulsion techniques. In the conversion, interaction lengths in iron of 17 cm and 19·3 cm were used for nucleons and pions respectively. In both pion and nucleon interactions the multiplicity was taken to be $3E^{1/4}$, with E in GeV, and equipartition of energy among the secondary particles was assumed. The inelasticities of pion and nucleon interactions were taken to be 1·0 and 0·5 respectively. The electron–photon shower curves of Ivanenko and Samosudov (1965) were used, account being taken of the energy spectrum of electrons and photons entering the scintillator. In this way the total track length of ionizing particles in the scintillator produced by an incident high-energy primary was evaluated and from it the burst size spectrum for the expected neutron spectrum was derived. The results are shown in the figure, where the experimental points have been plotted at the median neutron energy producing a given burst size. For each point, the ratio of intensity plotted to that predicted is made equal to the ratio of the observed frequency of bursts to the expected frequency.

A comparison is made in the figure between the results of Brooke and Wolfendale (1964) and the present work. It is seen that there is agreement in the common energy region. Above 100 GeV the present measurements give intensities somewhat below the predicted spectrum. The most likely explanation is that there is a change in attenuation length with increasing energy, a reduction by about 8% being necessary for nucleon energies in excess of a few hundred GeV.

Such a trend is not inconsistent with recent measurements by Grigorov *et al.* (1967), who find a reduction in interaction length (in carbon) by about 14%, at energies above 100 GeV, from measurements using the 'Proton' satellites. However, it must be pointed out that the primary spectrum measured in this work falls much more rapidly with energy than that used here, and the confirmation of the measured attenuation length is accordingly qualified. In view of the discrepancy with the intensities measured in the other experiments the satellite results are not regarded as proved.



The differential energy spectra of protons and neutrons at sea level in the vertical direction. The full curve represents an estimate of the neutron spectrum expected from the primary nucleon spectrum of Brooke *et al.* (1964), taken with an attenuation length for high-energy nucleons in the atmosphere of 127 g cm^{-2}. ○ Protons (Brooke *et al.* (1964); ● neutrons (present work).

A quite different possibility exists if it is allowable to invoke the existence of quarks. The argument is as follows: at sufficiently high energy a nucleon may dissociate into three quarks (all of which are charged) in making a nuclear collision, and if this occurs with appreciable frequency above threshold then a discontinuity should be observed in the sea-level neutron spectrum. The threshold processes for proton and neutron targets are

$$p+p \rightarrow (q_1+q_1+q_2)+(q_1+q_1+q_2)$$
$$p+n \rightarrow (q_1+q_1+q_2)+(q_1+q_2+q_2)$$

where q_1 and q_2 are quarks of almost the same mass and having charges $+\frac{2}{3}e$ and $-\frac{1}{3}e$ respectively, and the energy threshold is $18(M_q/M_p)M_qc^2 = 1800$ GeV for $M_q/M_p = 10$, where M_p and M_q are the nucleon and quark masses. In its passage through the atmosphere the average nucleon makes about 13 interactions, but considering nucleons of a particular energy at sea level the effect of fluctuations in path length and inelasticity coupled with the rapidly falling primary energy spectrum results in the most probable number of interactions being about five (Brooke *et al.* 1964). Thus, if it is assumed that the probability of quark production is constant and equal to f above threshold then, considering a particular sea-level energy, the probability that an average nucleon reaches sea level without dissociation is approximately $(1-f)^5$. Thus, for a quark mass of 10 GeV and $f = 0{\cdot}10$, the expected effect on the sea-level neutron spectrum at very high energies (> 1800 GeV) is a downward displacement by 50% relative to that expected neglecting quark production. The displacement will be smaller at lower energies until at 90 GeV, where the primary nucleon is above threshold only for the first interaction, it will be of the order of 10%. The observed displacements are not inconsistent with such behaviour.

At first sight such a high probability of dissociation coupled with the comparatively low mass would appear to be inconsistent with the very low upper limit to the frequency of quarks at ground level. However, it is only necessary to invoke a strong interaction with matter for the quark to remove this objection.

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Incoherent scattering cross sections of gamma rays in lead in the energy region 279–1330 kev

Abstract. The effect of electron binding on the incoherent scattering cross sections of gamma rays in lead in the energy region 279–1330 kev is studied by subtracting theoretical values of all other partial cross sections from the total experimental cross sections. It is concluded that the Thomas–Fermi model underestimates the effect of electron binding in reducing this cross section in the energy region 279–662 kev.

To study the effect of electron binding on the incoherent scattering of gamma rays a simple procedure is followed. From total experimental gamma-ray cross sections, the contributions due to theoretically computed partial cross sections (except the incoherent scattering cross section) are subtracted. The ratio of the remainder to the theoretical free-electron scattering cross section is taken as a measure of the effect of electron binding on the incoherent scattering of gamma rays. The existing investigations utilizing this procedure by Ramana Rao *et al.* (1965) and Parthasaradi and Visveswara Rao (1967) are available in low and medium atomic weight elements only. To extend these investigations to heavy elements very accurate theoretical photoelectric cross-section estimates are necessary because the contribution due to photoelectric cross sections to the total gamma-ray cross sections will be dominating for these elements. Recently very accurate theoretical photoelectric cross-section estimates are reported by Schmickley (1966, see also Schmickley and Pratt 1968) within an accuracy of less than 0·5% in most elements. With