Comment on the Evidence for Rapidly Rising p-p Total Cross Section from Cosmic-Ray Data

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Cosmic-ray measurements used to deduce evidence for rising p-p cross sections are reexamined for possible systematic effects not discussed previously. It is shown that these systematic effects are small for the data used, and that the analysis is on firm experimental basis. Recent direct measurements of p-p cross section at ISR energies (1 to 2 TeV) are above the lower bound that was deduced from cosmic-ray data.

In a recent paper,[1] it has been shown that data on unaccompanied hadron spectra at various atmospheric depths provide evidence for rising p-p total cross sections. The analysis at the highest energies (10 to 30 TeV) was based on comparing the primary proton spectrum at the top of the atmosphere with the unaccompanied hadron spectrum measured at Mt. Chacaltaya (550 g/cm^2 depth).[2] The observed intensity at 550 g/cm^2 for 10 TeV unaccompanied hadrons was a factor of five below that which would be calculated by attenuating the primary spectrum with an interaction length of protons in air equal to its value below 1 TeV (86 g/cm^2). Since the measured flux at mountain altitudes should be an upper bound to the flux of surviving protons, we deduced a lower bound to the proton-air interaction cross section. This was done by calculating an effective interaction length using fluxes at the top of the atmosphere and those at a lower altitude. The reliability of the lower bounds depends upon the confidence one can place in the knowledge of absolute fluxes. To determine absolute fluxes one must be able to (1) calculate the geometrical acceptance of the experimental arrangement for unaccompanied hadrons and (2) evaluate possible systematic effects which would reject unaccompanied hadrons.

The purpose of this note is to point out that the spectrum used in Ref. 1, which is also that given by the experimenters in their most recent report Ref. 2, is the one that should represent the best estimate of the flux. Recently, an analysis similar to that in Ref. 1 has been carried out which arrives at very different conclusions.[3] This analysis uses, however, a flux estimate[4] based on an experimental arrangement which accepts accompanied hadrons for which the geometrical factor is difficult to calculate. We show below that the use of this spectrum leads to a substantial underestimate of the proton absorption in the atmosphere.

In Fig. 1 we show two different spectra of "unaccompanied" hadrons at Mt. Chacaltaya measured with two different experimental arrangements,[2,4] called A and B hereafter. The spectrum[4] B is that used in Ref. 3, but has been divided by a factor 1.7 which takes account of the effect of of large fluctuations in burst size, as discussed by Kaneko *et al.*[2] Spectrum[2] A is the one that is used in Ref. 1. In order to discuss the systematic effects which will affect these measurements we first describe how spectra A and B were measured.

The experimental arrangements used for measuring unaccompanied hadron spectra A and B are shown in Fig. 2. The existence of an energetic hadron or hadrons is established by a burst (number of particles >2500) in one and only one of the shielded detectors. Pulse heights of all unshielded detectors are recorded. The acceptance criteria for an event are:

1. Spectrum A: In arrangement A it is required that one and only one of unshielded detectors record a signal. This counter must be directly above the shielded detector which recorded the large burst, and the pulse height of the unshielded detector must be less than or equal to that for two particles.

2. Spectrum B: In arrangement B a 3-counter telescope must record an event directly above the shielded detector which registered the burst and no other unshielded counters record a pulse. There is no pulse-height requirement on any counter in the telescope.

The experimental results are that both the spectra A and B have about the same spectral index of -2.3 ± 0.1 but spectrum A is lower in flux than spectrum B by a factor of ~ 3. Therefore, it is essential to know what effects can cause this large difference. There are two possibilities: (1) that in arrangement A the pulse-height requirement eliminates good unaccompanied hadrons or (2) that in arrangement B one accepts unwanted accompanied events.

There are two ways in which the pulse-height requirement could remove unaccompanied hadrons: (a) It has been suggested that[4,3] in the process of generating the nuclear-electromagnetic cascade which gives rise to the large burst recorded by shielded counters, the hadron may give rise to "back-scattered" particles. Some of these could enter the unshielded counters and make the pulse height of that counter greater than that for two particles. If this were to happen often then it could make the observed flux lower than the true flux. (b) The hadron may give rise to energetic δ rays above the unshielded detectors which could eliminate events.

First we discuss point (a). The distribution of a number of particles in unshielded detectors for events which pass the burst trigger threshold and the requirement that the unshielded detector which recorded a pulse was above the shielded detector (but with no pulse height of particle number cut) has been measured.[5] This distribution is shown in Fig. 3. The tail of the distribution above two particles contains ~ 50 out of a total of 400 events. Thus the pulse-height cut eliminates less than 15 percent of the events passing the above requirement. A similar pulse-height distribution for the bottom counter in the 3-counter telescope for arrangement B was determined[4] (not shown) and found to be so broad that a requirement of two or less particles would eliminate ~ 50 per-

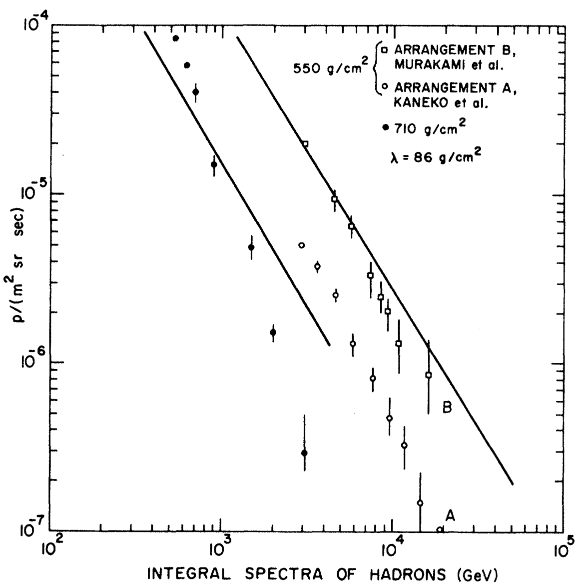

FIG. 1. Shown in the graph are spectra of unaccompanied hadrons at 550 g/cm^2 (Refs. 2 and 4). Spectrum A is the final result of experiments done during 1969–1971 at Mt. Chacaltaya in arrangement A (Ref. 2). It is the one used in Ref. 1. Spectrum B is that given in Ref. 4 for single vertical events corrected for fluctuations and accompaniment according to Ref. 2. Reference 3 used Spectrum B before correction for fluctuations. The solid curves are the expected intensity for residual protons if p-p cross section were unchanged from its value at 500 GeV, i.e., 39 mb. Also shown are the data at 700 g/cm^2 (Ref. 7).

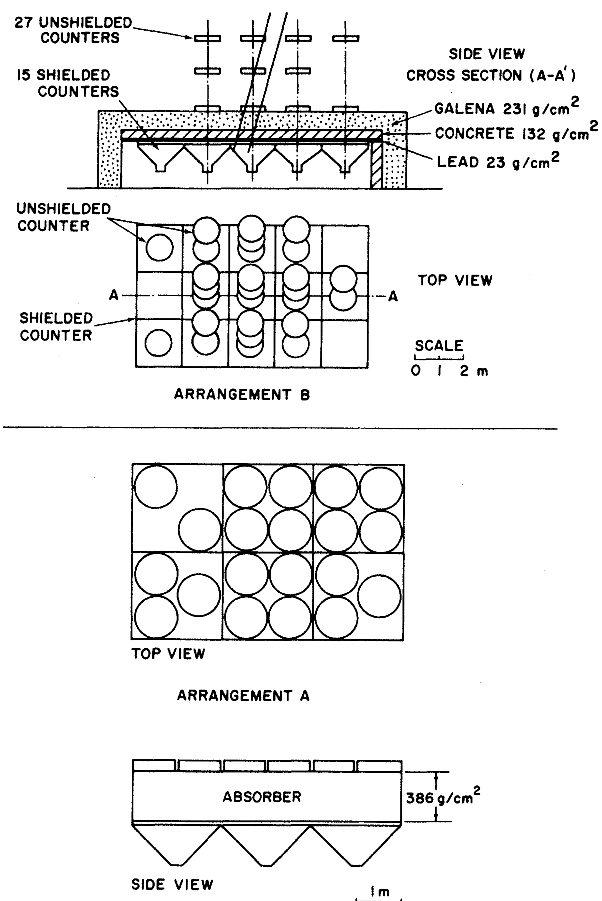

FIG. 2. Experimental arrangements A and B of the Chacaltaya burst experiment. In the arrangement B we show an accompanied event which would be accepted in the geometry which would be rejected in arrangement A. This indicated that $\Delta\Omega$ for arrangement B is not well defined. The events used in arrangement A were those incident upon the closed packed region (~ 24 m^2).

cent of the events. This broad distribution, in view of results shown in Fig. 3, is not due to back-scattering as suggested[3,4] but rather due to multiplication in top and middle counters of the 3-counter telescope, due to interactions. (Each telescope counter is a plastic scintillator about 10 cm thick). We conclude, therefore, that effect (a) does not significantly suppress detected events generated by unaccompanied hadrons.

One additional problem can arise if a significant number of high-energy cascades by a single hadron going through one unshielded counter (in arrangement A) generated a back-scattered particle which deposited sufficient energy in an adjacent counter to provide a veto for the event. These "back-scattered" particles will come primarily from target fragmentation. These nuclear fragments with energies of the order of 100 MeV/nucleon are produced with a broad angular distribution peaked at approximately 60° with respect to incident particle direction.

The angular distribution of incident hadrons is strongly peaked ($d\sigma/d\Omega \sim \cos^6\theta$) about the zenith. For such particles to be able to penetrate into an adjacent counter the starting point of the cascade in the 386-g/cm^2 absorber must occur within the first g/cm^2. One can safely conclude, therefore, that this effect is negligible.

Next we address ourselves to the point (b) and ask how large can be the elimination of wanted events due to δ rays. To register as a usable signal the δ ray must have sufficient energy to penetrate about half the thickness of an unshielded counter. This corresponds to a δ ray of energy ~ 10 MeV. The probability of producing such δ rays in the vicinity of the detector array is less than 1 percent per g/cm^2. We can safely rule out this as a cause of removing unaccompanied hadrons in arrangement A.

Now let us examine how the two arrangements discriminate against accompanied events of the type shown by two trajectories in Fig. 2. Events accompanied by electromagnetic debris spread over a large area would have been eliminated by the anticoincidence requirements on the rest of the unshielded detectors. However, events accompanied by a few tracks, due to hadrons which have suffered only a few interactions on the way down, such as the one shown in Fig. 2, will represent unwanted events. Such an event would be accepted by arrangement B; however, it would be rejected in arrangement A. It is difficult to exclude accompanied hadrons using only a three-counter telescope; one definitely requires visual information or a fine-counter matrix to establish accompaniment. We have observed this effect in attempting to trigger a cloud-chamber–calorimeter–spark-chamber array.[6] We find that the accompanied rate accepted in our array is three to five times greater than the single-hadron rate. Accompanied events accepted by arrangement B can account for a factor of 3 in rate. Thus, we are persuaded that spectrum A is the correct flux to use (in agreement with the conclusion of experimenters, Kaneko *et al.*[2]). Arrangement B will accept accompanied hadrons and hence spectrum B represents a contaminated sample. The contrary conclusion of Ref. 3 cannot be accepted.

For comparison we have also included the data, taken at a depth of 700 g/cm^2, for unaccompanied

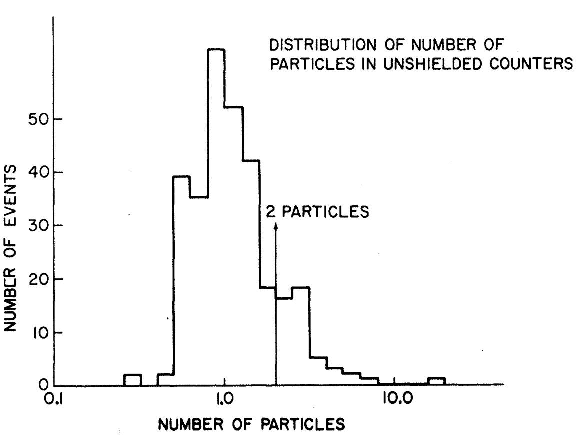

FIG. 3. Pulse-height spectrum of individual unshielded counters for single events in arrangement A (Ref. 6). Note that there is no "large" many-particle tail, and the percentage loss due to 2-particle cut is less than fifteen percent. Note that pulse height has been converted into equivalent number of particles.

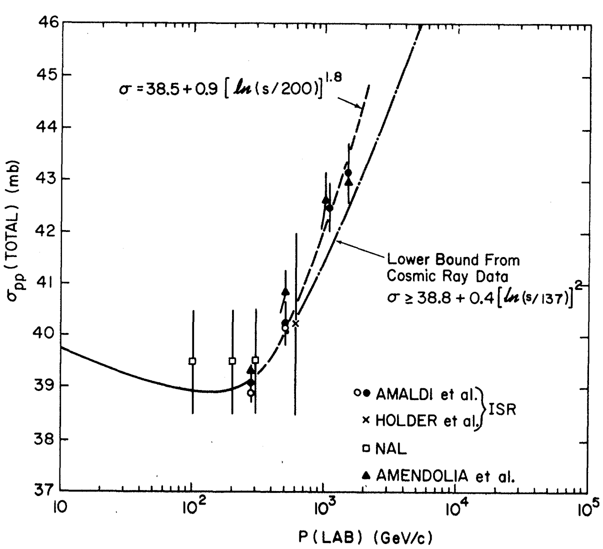

FIG. 4. The lower bound predicted (Ref. 1) from analysis of cosmic-ray data is compared with recent direct measurements of p-p total cross sections (Refs. 9 and 10).

hadrons. These data were taken with eight interaction mean free path deep calorimeters (energy resolution approximately 15 percent). In these experiments the existence of single hadrons was established either visually by means of spark chambers or with counter hodoscopes of fine enough matrix to be reliable.[7] These data, also, require a change in p-p cross section above 1 TeV. A proton-air inelastic cross section of 310 mb at 3 TeV would give consistency between spectrum A, that at 700 g/cm^2, and the primary proton spectrum.[8]

The solid curves in Fig. 1 are obtained by attenuating the primary cosmic-ray spectrum of protons by an interaction length of 86 g/cm^2 for protons in air. This corresponds to assuming constant p-p cross sections above 100 GeV. In deriving these curves we have used a primary spectrum based on the most recent measurement made at the top of the atmosphere,[8] as well as other reliable measurements. The error in the absolute value of the flux is not more than 50 percent. The slope is well determined up to ~2 TeV and an extrapolation has been made to 10 TeV with no change in spectral index.

In conclusion we maintain that the spectrum A used by Yodh, Pal, and Trefil[1] is reliable, and our observation that there is evidence for rising p-p total cross sections is on firm experimental basis. In Fig. 4, we compare the lower bound derived in Ref. 1 with recent direct measurements of p-p cross sections at NAL and ISR (CERN Intersecting Storage Rings) energies.[9,10] The measurements are in agreement with the lower bound deduced from cosmic-ray data.

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