Brief Reports

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Proton-proton cross sections from 1 to 100 TeV

G. B. Yodh and S. C. Tonwar*
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20740

T. K. Gaisser
Bartol Research Foundation, University of Delaware, Newark, Delaware 19711

R. W. Ellsworth
George Mason University, Fairfax, Virginia 22003
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Recent direct measurements of the energy spectrum of protons in primary cosmic rays by the Japanese-American cooperative emulsion-chamber experiment remove the most important uncertainty in deriving proton-proton total cross sections from cosmic-ray data. The data are reanalyzed and it is shown that σ_{pp} is approximately equal to $\sigma_{\bar{p}p}$ at 50 TeV. The *pp* cross section is shown to be free to a large extent of systematic uncertainties.

The basic technique for the determination of proton cross sections from cosmic-ray measurements between 0.1 and 100 TeV is to study the attenuation of primary cosmic-ray protons in the atmosphere.[1,2] This requires a comparison of data from two sets of experiments over the same energy range: (1) The flux of protons of energy E in primary cosmic rays at the top of the atmosphere $x=0$ g/cm^2, $J_p(E,x=0)$, and (2) the flux of protons of energy E surviving to an atmospheric depth of x g/cm^2, $J_s(E,x)$. These quantities are related by

$$J_s(E,x)=\exp[-x/\lambda(E)]J_p(E,0) \quad ,$$

where $\lambda(E)$ is the interaction length of protons in air. The interaction length in turn is related to a proton-air inelastic cross section by

$$\sigma^{\text{inel}}_{p\text{-air}}(E)=\frac{\langle A\rangle}{N_0\lambda(E)} \quad ,$$

where $\langle A\rangle$ is the effective atomic weight of air. These equations are combined to obtain proton-air cross sections in mb:

$$\sigma^{\text{inel}}_{p\text{-air}}(E)=\frac{24\,000}{x}\ln[J_p(E,0)/J_s(E,x)] \quad . \qquad (1)$$

After determining the proton-air cross section, Glauber theory is used to derive proton-proton total cross section at high energies.[3,4]

Systematic effects which influence this procedure have been discussed in several papers.[1,5] There are two basic effects which must be taken into account.

The first is that experiments do not directly measure $J_s(E,x)$, the surviving proton flux, but measure the so-called unaccompanied-charged-particle flux $J_u(E,x)$.[6–8] Note, however, that J_s is bounded by J_u: $J_s \leq J_u$. If we knew $J_p(E,0)$ precisely then the cross section calculated from Eq. (1) with J_u used in place of J_s would be a lower bound to the true cross section.[1] An improvement on the lower bound can be obtained in experiments where the pion fraction of the charged-particle flux (r) and the ratio of neutral to charged hadrons (R) is measured; specifically, $J_s<(1-r-R)J_u$.[9] The values of $\sigma^{\text{inel}}_{p\text{-air}}$ derived in this paper included the correction for pion and secondary-proton content of the unaccompanied flux where measured. We also note that the unaccompanied flux will approach the surviving flux at high energies where the efficiency of anticoincidence array increases.[7]

The second effect was due to the previously existing controversy about the shape of the primary proton spectrum above 2 TeV. The experiments on the Proton-series satellites by Grigorov *et al.*[10] indicated an apparent steepening of the proton spectrum above about 2 or 3 TeV. Possible instrumental causes for this steepening have been examined[11] and it was suggested that they could be due to effects of back current of particles from the energy-measuring calorimeter at high energies. More importantly, recent measurements by the Japanese-American cooperative emulsion-chamber experiment (JACEE)[12,13] have extended direct measurement of the proton spectrum up to several hundred TeV in a series of balloon exposures at 5 g/cm^2 near the top of the atmosphere. They see no evidence of a steepening up to at least 300 TeV and their flux is in very good agreement with an extension of earlier measurements of Ryan *et al.*[14] The proton spectrum based on the combined data[13,14] from 0.2 to 300 TeV can be represented by

$$J_p(E,0) = 1.34\times 10^4 E^{-2.66\pm 0.1} \ ,$$

where E is in units of GeV and J_p is in units of $(m^2\,sr\,s\,GeV/c)^{-1}$. The absolute intensity of protons above 5 TeV has been measured[12] to better than 40% by the JACEE collaboration and the error quoted for the value of the spectral index is an upper limit. It is, therefore, possible now to obtain a reliable lower bound to proton-air inelastic cross section up to 100 TeV, energies comparable to that reached at the CERN SPS $\bar{p}p$ collider.

Other systematic effects that could influence the flux measurement are the efficiency of detection of unaccompanied hadrons[6,7] and systematic errors in energy estimation. In the experimental data used in this paper the former is unity and the latter can be shown to be less than 10%.

The logarithmic dependence of the cross section on particle fluxes leads to the following relation between uncertainty in σ to uncertainty in the ratio $R = J_p(E,0)/J_u(E,x)$:

$$\frac{\delta\sigma}{\sigma} = \frac{1}{\ln R}\frac{\delta R}{R} \ . \tag{2}$$

Here $\ln R$ is >7; hence an uncertainty in R of 50% would lead to less than 7% uncertainty in σ. The result is, therefore, relatively insensitive to errors in J_p or J_u.[1,2]

The calculated values for the inelastic proton-air cross sections (lower bounds) using the above primary spectrum and measurements of J_u (Refs. 9 and 15) are shown in Fig. 1. Clear evidence is seen for a continuous increase in $\sigma^{\text{inel}}_{p\text{-air}}$ between 0.5 and 50 TeV.

We can relate $\sigma^{\text{inel}}_{p\text{-air}}$ to $\sigma^{\text{tot}}_{p\text{-air}}$ by the equation[3,4]

$$\sigma^{\text{inel}}_{p\text{-air}} = \sigma^{\text{tot}}_{p\text{-air}} - \sigma^{\text{el}}_{p\text{-air}} - \sigma^{*}_{p\text{-air}} - \sigma^{D}_{p\text{-air}} \ , \tag{3}$$

where the contributions due to elastic scattering $(\sigma^{\text{el}}_{p\text{-air}})$, quasielastic scattering with target excitation but without pion production $(\sigma^{*}_{p\text{-air}})$, and diffractive dissociation of the target nucleon $(\sigma^{D}_{p\text{-air}})$ must be subtracted from $\sigma^{\text{tot}}_{p\text{-air}}$ to obtain the observed cross

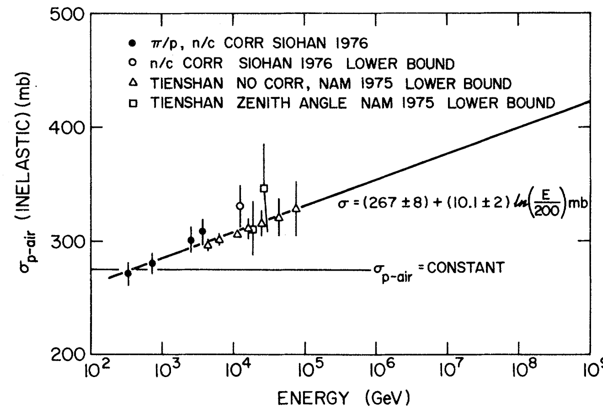

FIG. 1. Lower bounds to proton-air inelastic cross section derived from cosmic-ray data using Eq. (1). The size of error bars includes contributions from uncertainties in the knowledge of primary spectrum. A correction to the unaccompanied flux has been made for pions and secondary nucleons where these have been experimentally determined. The square-box points have been obtained by studying the zenith-angle distribution of unaccompanied hadrons by the Tien-Shan group (Ref. 15).

section. This is because cosmic-ray measurements cannot distinguish these processes from no interaction whatsoever.

To relate the measured $\sigma^{\text{inel}}_{p\text{-air}}$ to σ^{tot}_{pp} requires a calculation of each term on the right-hand side of Eq. (3) using Glauber theory.[16] The proton-proton parameters needed as input are primarily σ^{tot}_{pp} and the slope parameter b_{pp} for elastic scattering. In addition, we must assume a reasonable profile for the nucleus. The standard Glauber calculation must also be corrected for inelastic screening.[17] The net correction to $\sigma^{\text{tot}}_{p\text{-air}} - \sigma^{\text{el}}_{p\text{-air}}$ is[3,4] $\sigma^{\text{abs}}_{\text{inel}}$.

The percentage corrections for $\sigma^{\text{abs}}_{\text{inel}}$, $\sigma^{*}_{p\text{-air}}$, and $\sigma^{D}_{p\text{-air}}$ are of the order of 3.5%, 9%, and 5%, respectively, when compared with $\sigma^{\text{inel}}_{p\text{-air}}$. These are individually known to better than 20%; hence they contribute a maximum of 5% uncertainty in $\sigma^{\text{inel}}_{p\text{-air}}$. A 1% uncertainty comes from the spread in root-mean-square radius of the air nucleus[17]; the error introduced by uncertainty in proton-proton cross section and slope parameter is much smaller.

The reliability[18] of such calculations is illustrated in Fig. 2, where we graph experimental versus theoretical values of nuclear inelastic cross sections. This is done using data, for a variety of projectiles and a range of targets from 10 to 1000 GeV.[19-21] In the 200-to-500-mb range calculations agree with experiment to better than 5%.

An application of these techniques is made to obtain $\sigma^{\text{tot}}_{pp}(E)$ from $\sigma^{\text{inel}}_{p\text{-air}}$ shown in Fig. 1. This process requires input of slope parameter as a function of energy and we have used an extrapolation based upon fits to Fermilab, CERN ISR, and SPS $\bar{p}p$ collid-

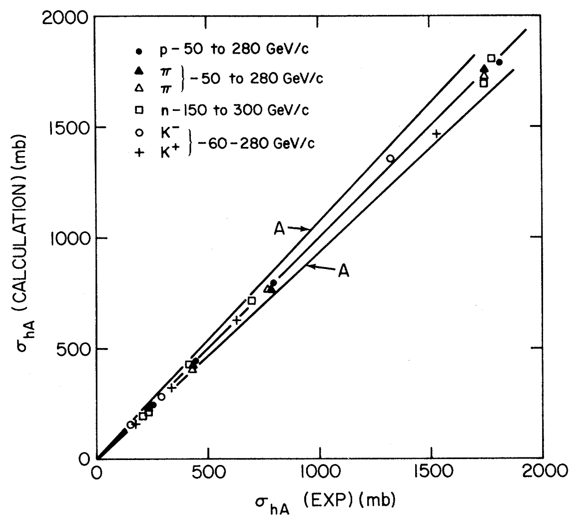

FIG. 2. Comparison of experimental inelastic cross sections and theoretical calculations for different projectiles and various target nuclei, covering an energy range from 20 to 1000 TeV.

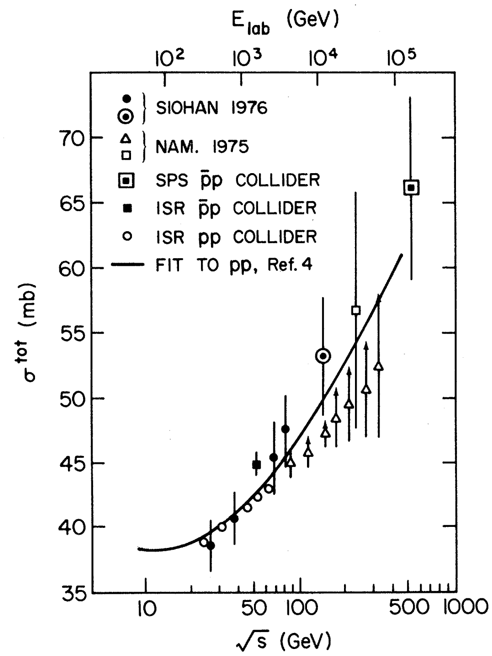

FIG. 3. Comparison of σ_{pp}^{tot} as derived from cosmic-ray data with accelerator measurements of *pp* and $\bar{p}p$ total cross sections. The *pp* cross sections are seen to be in good agreement with ISR *pp* results and SPS $\bar{p}p$ collider measurement at $\sqrt{s}=560$ GeV. The cosmic-ray values are lower bounds if the measured flux at mountain altitudes includes secondary hadrons (see discussion in text).

er data.[22,23] The results are shown in Fig. 3, along with results from accelerators and colliders for *pp* and $\bar{p}p$ measurements. We emphasize that the cosmic-ray values are lower bounds but should approach true values at the highest energies. They indicate reasonable equality with $\bar{p}p$ cross sections in the collider range. Until ISABELLE operates, these values will be the only *pp* cross-section values available between ISR and collider energies.

We hope this Brief Report shows that cosmic-ray data up to 100 TeV are not "affected by serious systematic uncertainties"[23,24] and that cosmic-ray data really show that *pp* cross sections rise at about the same rate as $\bar{p}p$ cross sections. Very preliminary indications from the Fly's Eye experiment are suggestive of continued increase of total cross section up to 10^6 TeV.[25,26]

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