DEEPLY INELASTIC PROTON-PROTON COLLISIONS*†

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We measured the differential cross section for 12.4-GeV/c proton-proton inelastic scattering on circles of fixed energy loss in the c.m. system. We varied the inelasticity from 8 to 94% and covered much of the angular range. For essentially all inelasticities the dependence on $P_\perp^2$ is approximately $e^{-3P_\perp^2}$. The absolute value of $d^2\sigma/d\Omega dp$ also depends only weakly on energy loss.

We have measured the differential cross section, $d^2\sigma/d\Omega dp$, for the inelastic scattering of protons in 12.4-GeV/c proton-proton collisions. This experiment extended the range of an earlier experiment.[1] Other groups[2-4] have also studied inelastic proton-proton scattering. While the lack of a complete theory makes comparisons between data at different energies rather difficult, there are some features which can be compared.

The quantity $d^2\sigma/d\Omega dp$ is the cross section for the inelastic scattering of one proton into the phase-space region $\Delta\Omega\Delta p$, independent of what particles are produced in the inelastic interaction and independent of what happens to the other proton. Thus it is the cross section for the process

$$p+p\to p+\text{anything}. \qquad (1)$$

This is not the cross section for a single inelastic channel, but is instead the cross section for the sum of all inelastic channels in which a proton emerges. The parameters varied in these measurements were ΔE (the energy loss or inelasticity) and $\theta_{\text{c.m.}}$ (the center-of-mass scattering angle) as shown in Fig. 1. The measurements were made on these circles of fixed energy loss to insure that these inelastic differential cross sections would be as analogous as possible to the elastic differential cross section.

The experiment was performed on the second slow extracted proton beam (EPB II) of the zero-gradient synchrotron (ZGS) at Argonne. The protons in the extracted beam hit a liquid-hydrogen target. The intensity of the incident beam I_0 was measured by monitor scintillators and gold-foil irradiations. The number of scattered protons (events) was measured with a 35-m spectrometer subtending a phase-space bite $\Delta\Omega\Delta p$. This spectrometer contained scintillation counters to define $\Delta\Omega\Delta p$, magnets for momentum analysis and steering, and a threshold Cherenkov counter to tag the particles as protons. The cross section was given by

$$\text{events}=I_0N_t(d^2\sigma/d\Omega dp)\Delta\Omega\Delta p, \qquad (2)$$

where N_t was the number of protons/cm^2 in the hydrogen target. More details on the experimental setup are given in a recent Letter on particle production using the same spectrometer.[5]

There are several corrections and uncertainties involved in determining the number of events. The statistical error was 1 to 4%. The accidental correction was negligible. The target-empty subtraction was experimentally determined to be about 25%. A correction of 1.25 ± 0.05 was made for nuclear interactions of protons in the spectrometer. The correction for multiple Coulomb scattering was normally less than (5 ± 2)%, ex-

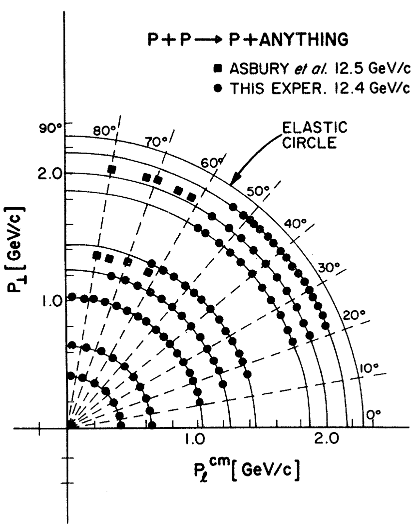

FIG. 1. Momentum plot in the c.m. system showing the elastic circle and the various inelastic circles with points where measurements were made.

cept for a few low-momentum points where it became as large as $(15 \pm 5)\,\%$. Thus the total point-to-point error, obtained by adding statistical and systematic errors in quadrature, was generally less than 10%. There was an additional 5% normalization uncertainty due to the calibration of the incident proton beam. The cross sections presented are preliminary but should not change by more than 8%.

In Fig. 2 we have plotted the inelastic-scattering cross section $d^2\sigma/d\Omega dp$ against the variable $P_\perp^2$, the square of the transverse momentum of the scattered proton. We have also plotted some data from an earlier experiment[1] which was in the very large angle region (see Fig. 1). The old data at $\Delta E = 0.22$ seem to fall a bit above the line, which seems a little strange. However the old data at $\Delta E = 0.83$ where there is overlap is in reasonable agreement with the new data, so that it is difficult to question the $\Delta E = 0.22$ data. Another possible explanation is that at $\Delta E = 0.22$ we were right on top of the $N^*(1688)$ in the reaction

$$p + p \to N^*(1688) + p, \qquad (3)$$

and this caused an increase in the cross section. Resonant behavior of this type was first observed by the Brookhaven group,[2] in experiments in which they varied the missing mass of the N^*. In any case we make no strong claims about the behavior of the cross section at this low inelasticity, because the idea of the experiment was to study the deeply inelastic cross section, and these points are clearly in the resonance region.

Returning to the rest of the measurements we can see several general features which seem to emerge from the data.

The cross sections appear to have essentially the same slope for all the different inelasticities. For most inelasticities the cross section drops as

$$d^2\sigma/d\Omega dp \propto e^{-3P_\perp^2} \qquad (4)$$

over most of the angular range. This seems somewhat surprising, for there have been some suggestions[6] that the slope of the production cross section should depend on the mass of the produced object.

Over a large range of inelasticity (8 to 62%) the absolute value of the center-of-mass cross section $d^2\sigma/d\Omega dp$ appears to be essentially constant for fixed $P_\perp$. This can be seen by noting how all the points fall on top of each other. This effect was first noted in a slightly different way by the Brookhaven group.[2] They found that in the

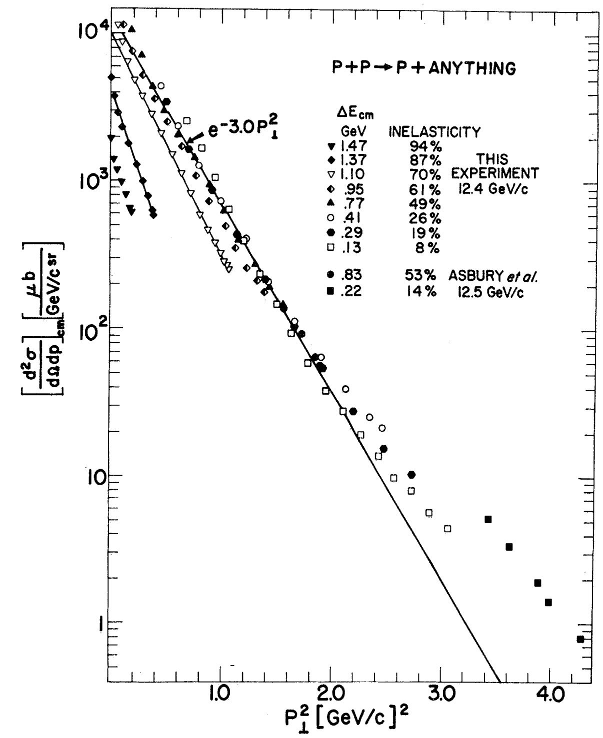

FIG. 2. Plot of the c.m. inelastic differential cross section $d^2\sigma/d\Omega dp$ against $P_\perp^2$. The lines are straight-line fits to the data. Different symbols are used to designate the different inelasticities or energy losses.

small-angle region the cross section was independent of longitudinal momentum. Our data indicate that more generally the cross section is independent of inelasticity over a wide range. For the very deep inelasticities (70 to 94%) the cross section finally starts to drop.

Finally we note that there appears to be a forward peak in the cross section for all those inelasticities where we were able to reach the forward direction. We think that this forward peak is real and in fact we suggest this peak may be the only direct scattering that we observe. We explain this by suggesting that the majority of events in proton-proton inelastic scattering could be of the type

$$p + p \to p + N^\dagger, \qquad (5)$$

where by $N^\dagger$ we mean an excited baryonic state which may or may not be one of the well-known resonances. This $N^\dagger$ eventually decays into a proton and some mesons. Now in a single-arm experiment one detects only the proton and has no way of knowing if it was the directly scattered proton or the proton from the decay of the $N^\dagger$. We also know that if the directly scattered proton has an angular distribution $A(P_\perp^2)$ the proton from the $N^\dagger$ must have a $B(P_\perp^2)$ which is wider because the decay can only smear things out.[7] Thus if the cross section we have observed is written as

$$d^2\sigma/d\Omega dp = A(P_\perp^2) + B(P_\perp^2), \tag{6}$$

then it unfortunately appears that at large $P_\perp^2$ the $B(P_\perp^2)$ must dominate, in spite of the fact that the $A(P_\perp^2)$ is probably the physically interesting cross section. It is also interesting to note that the large-angle cross section for protons has a slope $(e^{-3P_\perp^2})$ similar to the pion-production cross section.[5] This similarity is quite reasonable in this model in which the smearing dominates over the $A(P_\perp^2)$.

Because of this ambiguity between the two protons it may be difficult to obtain $A(P_\perp^2)$ from single-arm experiments except possibly at small angles. Thus it may be necessary to tag the directly scattered proton by observing the entire interaction. It is also possible that our pessimistic interpretation is incorrect and there is some way to obtain the form of $A(P_\perp^2)$ from $d^2\sigma/d\Omega dp$.

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[1]J. G. Asbury et al., Phys. Rev. Letters 21, 1097 (1968).

[2]E. W. Anderson et al., Phys. Rev. Letters 19, 198 (1967).

[3]C. M. Ankenbrandt et al., Phys. Rev. 170, 1223 (1968).

[4]J. V. Allaby et al., presented to the Fourteenth International Conference on High Energy Physics, Vienna, Austria, September 1968 (unpublished).

[5]J. L. Day et al., Phys. Rev. Letters 23, 1055 (1969).

[6]G. Cocconi, Nuovo Cimento 57, 837 (1968).

[7]If the $e^{-3P_\perp^2}$ really comes from pion-decay smearing, then one of our conclusions in Ref. 1 does not hold. We claimed that the model of the three regions in proton-proton elastic scattering being due to π, K, and $\bar{p}$ production was wrong because of the equality of the large-angle inelastic slopes. But as we are really observing the decay smearing rather than $A(P_\perp^2)$ we can draw no conclusions about this model [A. D. Krisch, Phys. Rev. 135, B1456 (1964)].

DIFFRACTIONAL DISINTEGRATION OF HADRONS AT SUPERHIGH ENERGIES AND THE POSSIBILITY OF LARGE QUARK PRODUCTION RATES

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The breakup of hadrons into their constituent quarks is considered in a simple model. It is demonstrated that the cross section for quark production with this mechanism could be in the millibarn range. Experimental evidence for such a process in cosmic-ray interactions is discussed.

Several recent reports by Grigorov et al.[1] and McCusker[2] indicate that in experiments on cosmic radiation there is anomalous behavior of N-N collsiions at energies far above the range of present-day accelerators. In the Soviet satellite series called Proton, an increasing p-C inelastic cross section for energies above 200 GeV and a steepening of the primary proton flux in this energy region is reported. McCusker notes that quarks may possibly be produced with a relatively large production cross section in cosmic-ray events in the earth's atmosphere. Also, the deep-mine muon experiments of Bergeson et al.[3] may be included in this category of anomalous events in N-N collisions. It is the purpose of this note to examine some of these experiments with respect to a quark production mechanism.

In general, theoretical estimates of quark-pair productions yield cross sections that are certainly no larger than a few microbarns for quarks with masses in the 5- to 10-GeV range.[4-6] This seems reasonable since there are many production processes that compete strongly with quark-pair production. However, if we are to take the quark model seriously, then we must also con-