Proton-Proton Collisions at 19.8 GeV/c (*).

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Summary. — Elastic and inelastic 19.8 GeV/c proton-proton collisions in nuclear emulsion are examined using an external proton beam of the CERN Proton Synchrotron. Multiple scattering, blob density, range and angle measurements give the momentum spectra and angular distributions of secondary protons and pions. The partial cross-sections corresponding to inelastic interactions having two, four, six, eight, ten and twelve charged secondaries are found to be, respectively, (16.3 ± 8.4) mb, (11.5 ± 6.0) mb, (4.3 ± 2.5) mb, (1.9 ± 1.3) mb, (0.5 ± 0.5) mb and (0.5 ± 0.5) mb. The elastic cross-section is estimated to be (4.3 ± 2.5) mb. The mean charged meson multiplicity for inelastic events is 3.7 ± 0.5 and the average degree of inelasticity is 0.35 ± 0.09. Strong forward and backward peaking is observed in the center-of-mass system for both secondary charged pions and protons. Distributions of energy, momentum and transverse momentum for identified charged secondaries are presented and compared with the results of work at other energies and with the results of a statistical theory of proton-proton collisions.

1. – Introduction.

A large number of emulsion experiments have been performed in which proton-proton interactions in the energy range from 1 to 30 GeV have been examined. However, relatively few have attempted a detailed analysis of secondaries from such collisions for bombarding energies greater than about 9 GeV. We report in this paper an evaluation of the properties of proton-proton collisions at 19.8 GeV/c in hopes that it may yield information about

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the fundamental processes of inelastic nucleon-nucleon interactions and on the structure of the nucleon in this energy region. Results are obtained which include the elastic and inelastic cross-sections, the distributions of kinetic energy and scattering angle in the center of mass system for identified charged secondary particles from inelastic events and the distribution of transverse momentum for secondary protons and pions. These results are compared with the results of work at other energies and with the results of a statistical model of proton-proton collisions.

2. – Experimental procedure.

2·1. *Exposure and scanning.* – A stack of 20 Ilford K-5 emulsion pellicles, each approximately 13 cm × 20 cm × 600 μm, was exposed to an elastically scattered, external proton beam of the CERN proton synchrotron. The nominal momentum of the beam, as it entered the stack, was determined by magnetic analysis [1] to be 19.8 GeV/c.

The plates were scanned by following individual beam tracks using ×100 objectives and ×10 eyepieces. Of the entire track length examined, 40 % was followed by a rapid « motion picture » scanning technique, whereby the image of a beam track appears as a « blur » in the field of view as it is followed, while the remainder was followed more slowly. The angle of the beam tracks with respect to the plane of the emulsion was such that a single track could be followed about 8 cm from its point of entry in the emulsion.

The interactions located were divided into three classes as follows:

i) Stars (events which exhibit obvious evidence of a collision with a heavy emulsion nucleus such as a recoil blob or low energy electron, or for which the kinematics are not consistent with those of a proton-free proton collision).

ii) Clean odd-prong events (no evidence of the type listed under i) and an odd number of charged secondaries).

iii) Clean even-prong events (no evidence of the type listed under i) and an even number of charged secondaries).

Clean odd-prong events include collisions of beam protons with bound neutrons with no visible excitation of the residual nucleus and diffraction scattering of beam protons by heavy emulsion nuclei with no visible nuclear recoil. Clean even-prong events include collisions of beam protons with free protons and bound protons with no visible excitation of the residual nucleus.

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(1) Exposure, development and momentum analysis kindly furnished by the CERN emulsion group.

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2.2. *Experimental analysis of events.*

2.2.1. Determination of the number of free collisions. – The contribution of proton-bound proton collisions to the number of clean even prong events may be estimated by assuming that interactions of beam protons are equally probable with bound neutrons and bound protons and that the same fraction of all events of either type will be classified as « clean ». The fraction of clean even-prong events which are collisions with free protons is given by

$$F = 1 - N_o/N_e\,, \tag{1}$$

where N_o is the total number of clean odd-prong events, corrected for possible contribution of diffraction scattering from heavy nuclei, and N_e is the total number of clean even-prong events.

Protons diffracted by heavy emulsion nuclei should have scattering angles of the order of λ/R, where λ is the wavelength of the incident proton in the center of mass system and R is given by $1.2\,A^{\frac{1}{3}}\cdot 10^{-13}$ cm. For the composition of emulsion and the energy of the present experiment, this leads to an expected laboratory scattering angle, projected in the plane of the emulsion, of the order of 30′ for most scatterings of this type. Although the rapid scanning yielded one elastically scattered proton with a projected angle of 16′, it is apparent that the detection efficiency drops rapidly to zero for angles less than 30′, and it is therefore assumed that such diffraction scattering makes a negligible contribution to the total number of clean odd-prong events detected by this method.

2.2.2. Elastic proton-free proton interactions. – The following criteria were applied to the clean even-prong events with two charged secondaries in order to estimate the number of elastic proton-free proton collisions:

$$|\theta_S - \mathrm{tg}^{-1}(\mathrm{ctg}\,\theta_R/\gamma_c^2)| \leqslant 1.0°, \tag{2}$$

$$|\Delta\theta_c| \leqslant 1.0°\,, \tag{3}$$

where θ_S is the laboratory scattering angle of the scattered proton, θ_R is the laboratory scattering angle of the recoil proton, γ_c relates to the center of mass system velocity in the laboratory, and $\Delta\theta_c$ is the angle between the scattered proton track and the plane defined by the incident and recoil protons.

The space angles of the secondary protons were determined directly from the measured dip and projected angles, while the coplanarity of the three proton tracks was tested by plotting them on a 40 cm diameter stereographic projection calibrated in 1° intervals. A Leitz goniometer permitted measurement of the projection of scattering angles in the plane of the emulsion to within 0.5°. Dip angles were determined to within 0.5° by measuring the change in depth of a track together with the corresponding projected track length.

2.2.3. Inelastic proton-proton collisions. – Measurements of multiple scattering, blob density and range were made on secondaries from all clean even-prong events which were not classified as elastic scatterings. For tracks which did not come to rest in the emulsion, a determination of the identity and energy was made by scattering and blob density measurements according to the method outlined by KALBACH *et al.* (2). Because of the great difficulty in distinguishing K-mesons by this technique, all secondaries were classified as protons or pions although the presence of other particles among the secondaries cannot be excluded.

Multiple scattering measurements were made on a Koristka MS-2 scattering stage by the method of second differences. In order to evaluate the contribution of noise and spurious scattering, measurements were made on beam proton tracks. By subtracting the known contribution of Coulomb scattering to the resulting second differences, corrections are calculated which may be applied to the measurements on secondaries. Table I gives the second differences which result from the combined effect of spurious scattering and noise. The combined second difference due to spurious scattering and noise for 1000 μm cells corresponds to the Coulomb scattering for a momentum times velocity of ~ 9 GeV.

TABLE I. – *Second differences due to noise and spurious scattering.*

Cell length, μm	Second difference, μm
250	0.0853
500	0.0896
1000	0.157

Secondaries which come to rest in the emulsion were identified by their characteristic track endings and their energies were obtained by range measurements.

All computations, including the analysis of multiple scattering data, particle identification, and transformations of momenta and angles to the center-of-mass system, were carried out on an IBM 650 electronic computer.

(2) R. M. KALBACH, J. J. LORD and C. H. TSAO: *Phys. Rev.*, **113**, 330 (1959).

3. – Results.

3·1. *Results of scanning.* – A total of 457 m of beam track was followed, and 904 nuclear interactions of all types were obtained, without correction for scanning efficiency. A summary of the results of scanning by the two techniques is given in Table II. These results indicate that rapid scanning provides the more sensitive means of detecting clean events under the conditions of the present experiment, and therefore, the results of cross-section determinations given in Sections **3·3** and **3·4** are based exclusively on this portion of the data.

TABLE II. – *Comparison of the two scanning methods.*

Number of charged secondaries	Rapid scanning	Slow scanning	Total
1	29	23	52
2	43	16	59
3	26	12	38
4	24	18	42
5	2	5	7
6	9	9	18
7	3	3	6
8	4	2	6
9	1	0	1
10	1	2	3
11	0	0	0
12	1	0	1
13	0	0	0
14	0	1	1

Mean free paths for the three classes of events, based only on the rapid scanning data, are as follows:

All interactions . . . . (0.370 ± 0.017) m ,
Clean even-prong events . . . . . (2.16 ± 0.24) m ,
Clean odd-prong events . . . . . . (2.91 ± 0.37) m .

A great many of the clean events located by rapid scanning had one secondary which was emitted approximately in the direction of the incident proton and were located by noting a slight change in motion of the track image perpendicular to the beam direction rather than by a « loss » of the beam track. It is estimated that such events are reliably detected when the projection of the smallest secondary scattering angle, in the plane of the emulsion, is greater than about 30′.

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3·2. *Estimation of the number of free collisions.* – Neglecting any contribution of nuclear diffraction scattering to the events located (see Section 2·2.1), 26 % of the clean even-prong events are examples of collisions with free protons. The present analysis indicates that the percentage of clean even-prong events which are proton-free proton collisions (26 %) is much lower than the estimate of 70 % by CVIJANOVICH *et al.* (3) at 23.5 GeV or the value of 60 % estimated from the data of JAIN *et al.* (4) at 28 GeV.

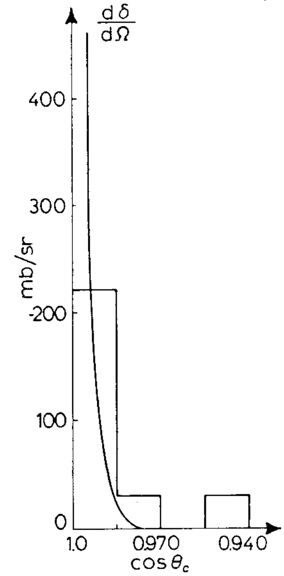

Fig. 1. – Angular distribution of elastically scattered protons in the center-of-mass system. The smooth curve is the result of the optical model calculation mentioned in the text.

3·3. *Elastic interactions.* – Of the 43 two-prong events located by the rapid scanning technique, 9 events are possible examples of elastic proton-free proton collisions. The corresponding cross-section for elastic proton-free proton scatterings is (4.3 ± 2.5) mb, the error being statistical only. The mean projected laboratory scattering angle (which served as a means of locating the events) is 48′.

The angular distribution of the elastically scattered protons in the center of mass system is shown in Fig. 1. Also shown in Fig. 1 is the angular distribution resulting from a uniform, purely absorbing optical model whose parameters are determined from the data obtained from beam scanning. Compatible values of the elastic cross-section, σ_e, inelastic cross-section, σ_i, and amplitude of the transmitted wave, a, for a uniform, purely absorbing disc of radius R result in a radius of $1.69 \cdot 10^{-13}$ cm and a transmitted amplitude of 0.781.

The value obtained for elastic cross-section agrees, within assigned errors, with the value obtained by CVIJANOVICH *et al.* (3) of 5.5 mb at 23.5 GeV/c and that of JAIN *et al.* (4) of 4.9 mb at 28 GeV.

3·4. *Inelastic interactions.*

3·4.1. Cross-sections. – The partial inelastic cross-sections are given in Table III.

The total inelastic cross-section based on 82 events found by rapid scanning

(3) G. CVIJANOVICH, B. DAYTON, P. EGLI, B. KLAIBER, W. KOCH, M. NIKOLIĆ R. SCHNEEBERGER, H. WINZELER, J. C. COMBE, W. M. GIBSON, W. O. LOCK, M. SCHNEEBERGER and G. VANDERHAEGHE: *Nuovo Cimento*, **20**, 1012 (1961).

(4) P. L. JAIN, H. C. GLAHE, G. N. SRIVASTAVA and P. D. BHARADWAJ: *Nuovo Cimento*, **21**, 859 (1961).

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is (34.9 ± 19.2) mb. The partial cross-sections observed in this experiment are compared in Table IV with those at other energies. The values of Table IV indicate only a slight difference in the cross-section for the production of two and four charged secondaries at 19.8 GeV and the region between 5 and 6 GeV,

TABLE III. – *Partial inelastic cross-sections for proton-free proton scattering.*

Charged secondary multiplicity	Cross-section, mb
2	16.3 ± 8.4
4	11.5 ± 6.0
6	4.3 ± 2.5
8	1.9 ± 1.3
10	0.5 ± 0.5
12	0.5 ± 0.5

although the cross-sections for the production of four or more charged secondaries are consistent with a steady increase in these values over this energy interval.

TABLE IV. – *Energy dependence of inelastic cross-sections.*

Proton energy (GeV)	Partial inelastic cross-section, mb			
	2 prong	4 prong	6 prong	8 prong
23.50 (3)	13.9	12.2	7.3	2.8
19.80 (*)	16.3	11.5	4.3	1.9
6.20 (5)	15.0	7.0	1.0	—
6.20 (2)	7.3	12.1	2.7	0.3
5.30 (6)	11.3	12.1	1.5	—
4.15 (7)	16.3	11.5	0.2	0.1
3.5 (8)	24.1	7.9	—	—
2.75 (9)	21.8	4.2	—	—
1.50 (10)	25.9	1.1	—	—

(*) Present work.

(5) H. WINZELER, B. KLAIBER, W. KOCH, M. NIKOLIĆ and M. SCHNEEBERGER: *Nuovo Cimento*, **17**, 8 (1960).

(6) W. M. POWELL: *Univ. of. Calif.*, UCRL 3223, 30 (1955).

(7) M. H. BLUE, J. J. LORD, J. G. PARKS and C. H. TSAO: *Phys. Rev.*, **125**, 1386 (1962).

(8) R. J. PISERCHIO: Private communication.

(9) M. M. BLOCK, E. M. HARTH, V. T. COCCONI, E. HART, W. B. FOWLER, R. P. SHUTT, A. M. THORNDIKE and W. L. WHITEMORE: *Phys. Rev.*, **103**, 1484 (1956).

(10) W. B. FOWLER, R. P. SHUTT, A. M. THORNDIKE and W. L. WHITEMORE: *Phys. Rev.*. **103**, 1479, (1956).

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The mean charged secondary multiplicity for clean even-prong inelastic events is found to be 3.7 ± 0.5.

3'4.2. Energy and angular distributions of emitted particles. – Of the 118 inelastic p-p interactions found, the identity and energy of approximately 230 of the emitted particles were measured. The center-of-mass system energy spectra of protons from two, four, and six-prong inelastic proton-proton collisions are shown in Fig. 2. One observes little dependence of the shape of the proton-energy spectrum on the charged-secondary multiplicity and that all spectra display a peak between 1 and 1.2 GeV.

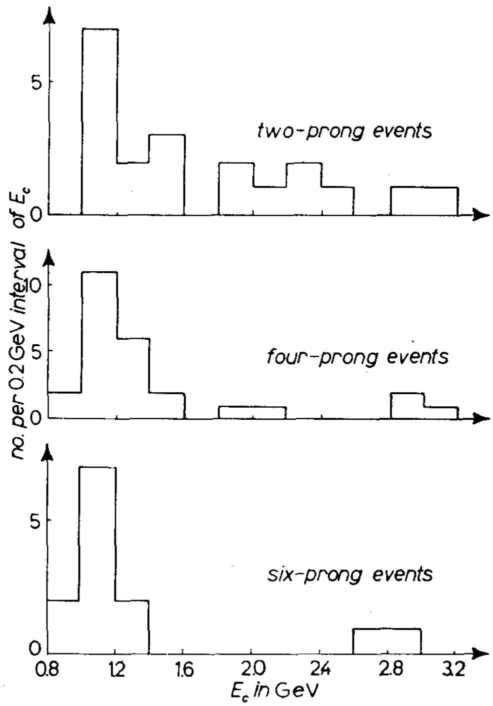

Fig. 2. – Center-of-mass system total energy distribution of the secondary protons from inelastic proton-proton interactions.

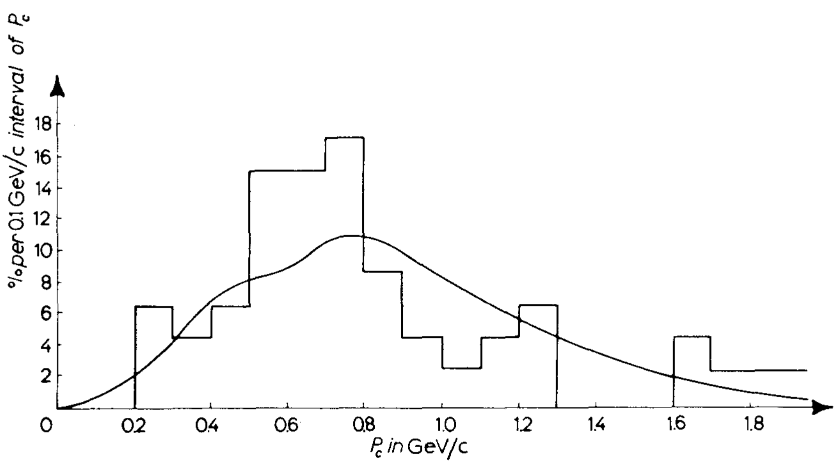

Fig. 3. – Momentum distribution of secondary protons from all inelastic proton-proton collisions plotted in center-of-mass system. The histogram represents the experimental data while the smooth curve is the result of the statistical theory for an incident energy of 25 GeV.

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The momentum spectrum of secondary protons from all inelastic collisions, shown in Fig. 3, is similar in shape to that predicted by the statistical theory of VON BEHR *et al.* ([11]) for 25 GeV proton-proton collisions which is plotted with the experimental results as a smooth curve.

The energy spectra of secondary charged pions from 2, 4 and 6-prong events are given in Fig. 4. The shape of the momentum spectra of all charged pions (Fig. 5) is similar to that

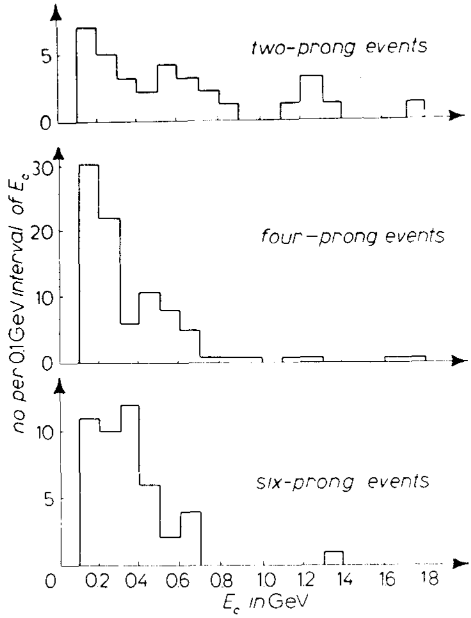

Fig. 4. – Center-of-mass system total-energy distribution of the secondary charged pions from inelastic proton-proton interactions.

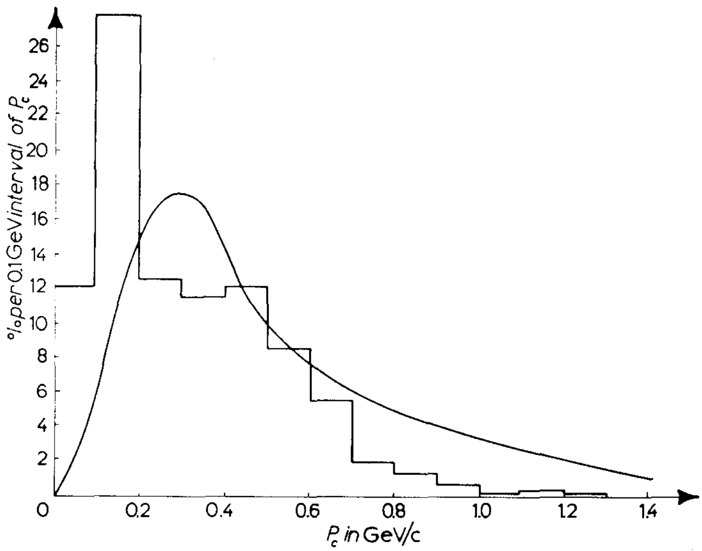

Fig. 5. – Momentum distribution of secondary charged pions from all inelastic proton-proton interactions in the center-of-mass system. The histogram represents the experimental data while the smooth curve is the result of the statistical theory for an incident energy of 25 GeV.

([11]) J. v. BEHR and R. HAGEDORN: CERN report 60-20 (1960).

given by VON BEHR *et al.* [11], but the experimental peak is lower than the theoretical peak by approxymately 150 MeV/c.

It is to be noted that the average center-of-mass system kinetic energy of charged pions, 263 MeV, is much less than that for protons, 620 MeV. Assuming that charged and neutral pions are produced in the ratio 2:1, the ratio of the average total energy carried off by pions to the total available kinetic energy in the center-of-mass system is found to be 0.35 ± 0.09.

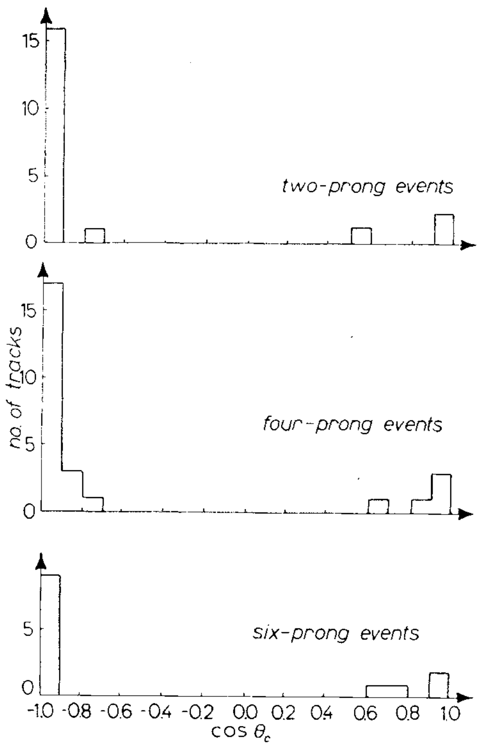

Fig. 6. – Center-of-mass system angular distribution of the secondary protons from inelastic proton-proton interactions.

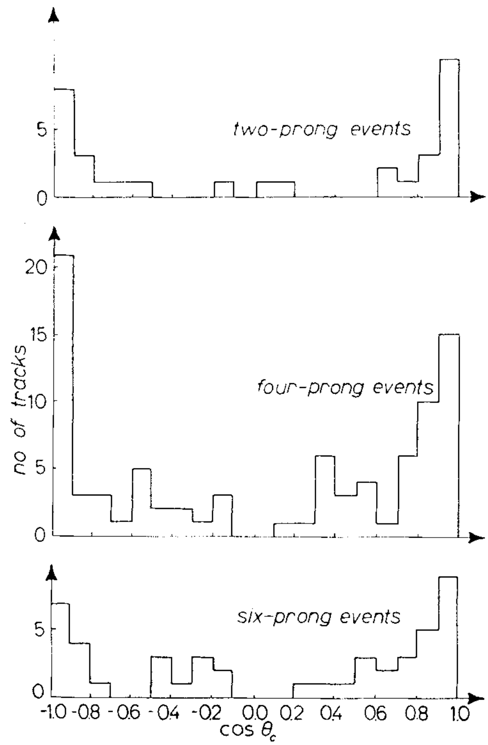

Fig. 7. – Center-of-mass system angular distribution of the secondary pions from inelastic proton-proton interactions.

Center-of-mass system angular distributions are plotted in the Fig. 6 and 7 for the secondary protons and pions from the inelastic interactions resulting in 2, 4 and 6-charged secondaries. Both the proton and pion angular distributions show a very sharp peaking in the forward and backward directions. It should be noted that peaking is more prominent in the proton angular distribution and for events with low secondary multiplicity.

The forward-backward asymmetry is attributed to the inability to determine momenta of very fast particles emitted at small scattering angles. Analysis of the events in which such particles are emitted indicates that the majority are protons with energies greater than 9 GeV.

Laboratory scattering angles were also transformed to the center of mass system with the following transformation:

$$\text{tg}\,(\theta_c/2) = \gamma_c\,\text{tg}\,\theta_L\,, \tag{4}$$

The assumption implicit in this equation, which is frequently used in experiments where no attempt is made to identify secondaries, is that the particle velocity in the center-of-mass system is equal to the velocity of the center-of-mass system with respect to the laboratory system. It is found that this transformation has the effect of decreasing the anisotropy which characterizes the angular distribution obtained by the more exact method.

3'4.3. Transverse momentum of secondaries. – Figure 8 gives the transverse-momentum distribution for charged secondaries from inelastic proton-proton collisions. For both pions and protons, the most probable value of transverse momentum lies between 50 and 100 MeV/c with a mean value of 154 MeV/c for pions and 217 MeV/c for protons. These results are in fair

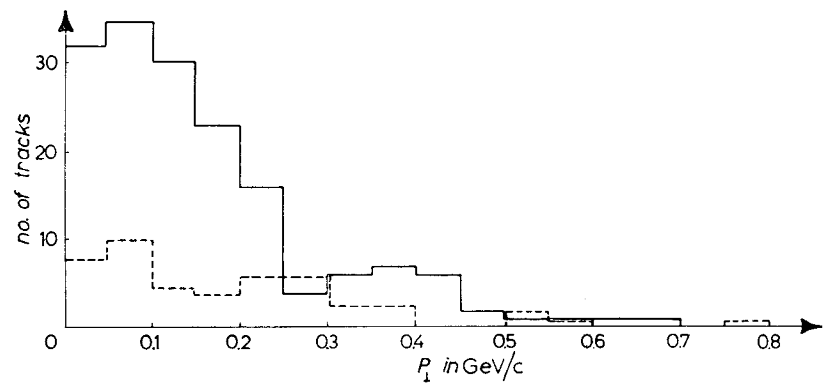

Fig. 8. – Distribution of transverse momentum of charged pions (solid curve) and protons emitted in inelastic p-p collisions.

agreement with those of BLUE *et al.* ([12]) in a similar experiment at 4.2 GeV in which mean values of 142 MeV/c and 265 MeV/c for pions and protons, respectively, were obtained. The present results are also consistent with those

([12]) M. H. BLUE, J. J. LORD, J. G. PARKS and C. H. TSAO: *Nuovo Cimento*, **10**, 274 (1961).

obtained at cosmic ray energies ([13,14]) and support the conclusion that the mean value of the transverse momentum does not vary greatly with incident energy.

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(13) R. R. DANIEL, J. H. DAVIES and D. H. PERKINS: *Phil. Mag.*, **43**, 753 (1952).
(14) M. SCHEIN, R. GLASSER and D. M. HASKIN: *Nuovo Cimento*, **2**, 647 (1955).

RIASSUNTO (*)

Per mezzo di un fascio esterno di protoni del fotosincrotrone del CERN si sono esaminate le collisioni protone-protone di 19.8 GeV/c elastiche ed anelastiche. Lo scattering multiplo, la densità di blob, le misure del percorso e dell'angolo danno gli spettri degli impulsi e le distribuzioni angolari dei protoni e pioni secondari. Si è trovato che le sezioni d'urto parziali corrispondenti ad interazioni elastiche aventi due, quattro, sei, otto, dieci e dodici secondari carichi sono, rispettivamente, (16.3 ± 8.4) mb, (11.5 ± 6.0) mb, (4.3 ± 2.5) mb, (1.9 ± 1.3) mb, (0.5 ± 0.5) mb e (0.5 ± 0.5) mb. La sezione d'urto elastica si valuta in (4.3 ± 2.5) mb. La molteplicità media dei mesoni carichi per eventi anelastici è 3.7 ± 0.5 e il grado medio di anelasticità è 0.35 ± 0.09. Si osservano forti picchi in avanti ed all'indietro sia per i pioni che per i protoni secondari carichi. Si danno le distribuzioni dell'energia, dell'impulso e dell'impulso trasversale per i secondari carichi identificati e si confrontano con i risultati dei lavori ad altre energie e coi risultati di una teoria statistica delle collisioni protone-protone.

(*) *Traduzione a cura della Redazione.*

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