ELASTIC AND INELASTIC SCATTERING OF HIGH-ENERGY PROTONS FROM HYDROGEN

G. Cocconi,* A. N. Diddens, E. Lillethun, G. Manning,†
A. E. Taylor,† T. G. Walker,‡ and A. M. Wetherell
CERN, Geneva, Switzerland
(Received November 20, 1961)

Previous measurements[1] of the momentum spectra of high-energy protons scattered from Be targets have shown the existence of an elastic peak[2] and of an inelastic bump[3] about 1 Gev/c below the elastic peak. This Letter describes measurements of p-p elastic and inelastic cross sections using a CH_2-C difference method, again with targets in the internal beam of the CERN proton synchrotron. These measurements were made at laboratory scattering angles close to 60 mrad with incident proton momenta between 12 and 27 Gev/c.

The experimental arrangement was similar to that described in reference 1, but the geometrical resolution was improved from 1% to 0.6%, and the final energy of the circulating beam in the synchrotron was stabilized to better than 0.5%. The over-all number of recorded events in this experiment was increased by using simultaneously five similar independent counter telescopes.

The CH_2 and C targets had the same surface density, about 1 g cm^{-2}, and were flipped alternately into successive beam pulses. Counts accumulated for each target were stored in separate sets of scalers. The integrated number of protons that interacted in each target was determined at the end of each run by measuring the Be^7 activity (half-life 53 days, 0.48-Mev γ ray) produced in each target. The cross section for the production of Be^7 from C is constant at[4] 11 mb from 0.2 to 5.7 Gev and is assumed here to have the same value in the region from 12 to 27 Gev.

The laboratory differential cross section for a p-p collision can be written as

$$\frac{d^2\sigma}{d\Omega dP}=\tfrac{1}{2}\sigma_{\mathrm{Be}^7}\left(\frac{\Sigma M}{\Sigma A}\right)_{\mathrm{CH}_2}\left[\left(\frac{N}{M}\right)_{\mathrm{CH}_2}-R\left(\frac{N}{M}\right)_{\mathrm{C}}\right]\frac{1}{\Delta P\Delta\Omega},$$

$$R=\left(\frac{\Sigma M}{\Sigma A}\right)_{\mathrm{C}}\Bigg/\left(\frac{\Sigma M}{\Sigma A}\right)_{\mathrm{CH}_2}, \qquad (1)$$

where σ_{Be^7} is the cross section for producing Be^7 from C, and ΣA is the integrated number of Be^7 nuclei produced during the bombardment. N is the number of protons counted in a solid angle $\Delta\Omega$ and a momentum interval ΔP for M counts in an intermediary monitor. ΣM is the integrated monitor count corresponding to ΣA.

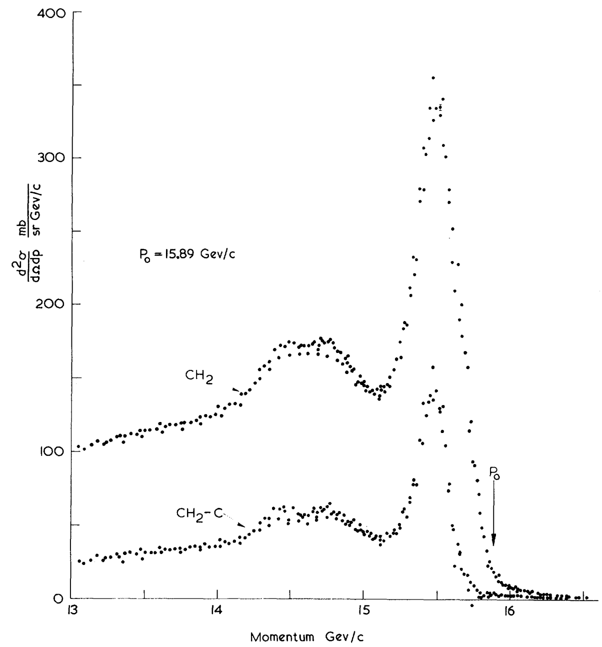
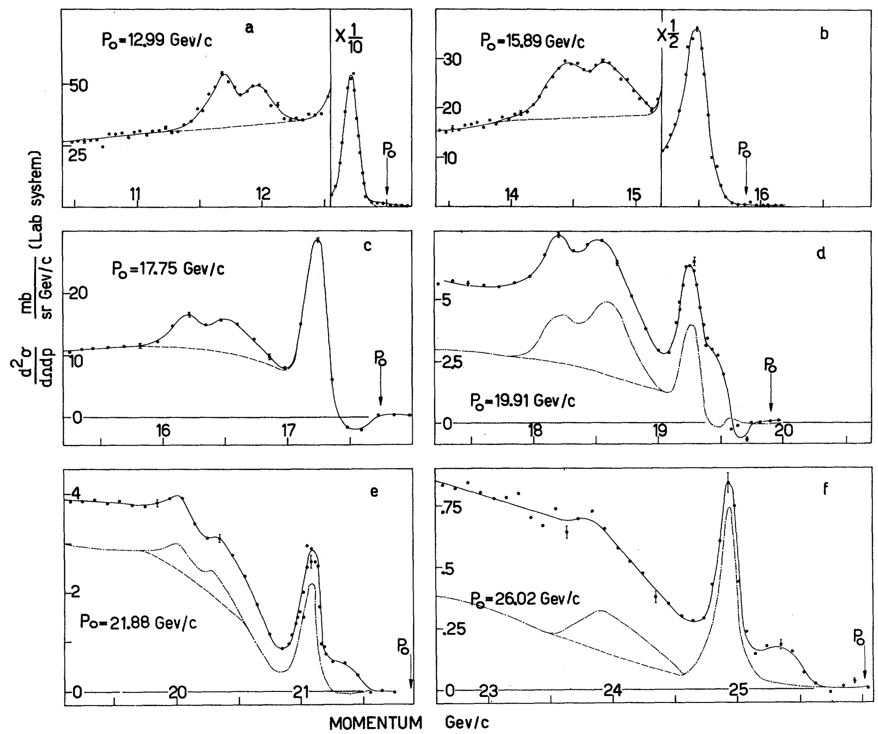


FIG. 1. Momentum spectrum of the protons from a CH_2 target and the CH_2-C difference. All experimental points from the five telescopes are shown.

Figure 1 shows a typical momentum spectrum obtained with a CH_2 target and the CH_2-C difference spectrum evaluated using Eq. (1). The experimental points recorded in all five channels are included. Figure 2 shows the p-p spectra obtained after grouping the points in small momentum intervals. All the curves of Fig. 2 show a pronounced peak at the highest momenta, followed in general by two smaller peaks at lower momenta. The first peak is identified with p-p elastic scattering, as the energy lost by the scattered proton is in agreement, within an experimental accuracy of about 100 Mev, with that calculated. The irregularities on the high-momentum side of some of the p-p elastic peaks are caused by incorrect subtraction. These occur when several measurements at different bombarding energies were made with one pair of targets and consequently an average value of R was used for all energies. A compari-

FIG. 2. Momentum spectra of protons from p-p collisions. The points shown were obtained by averaging the experimental data in small momentum intervals of about 30 Mev/c. (d), (e), and (f) show (as a broken line) the spectrum obtained by changing R [Eq. (1)] by 13 %, 8 %, and 14 %, respectively. The broken line under the two inelastic peaks indicates the area to evaluate the cross section for the inelastic bump. These values are shown in column 10 of Table I. P_0 is the incoming proton laboratory momentum.



son of the CH_2 and C spectra indicates that the normalization constant R used in these circumstances may be in error by about 10%. The value of R has been changed empirically to make the p-p cross section above the elastic peak zero, and the resulting spectra are shown as dot-dash lines in Fig. 2. This changes the elastic cross section by $\lesssim 50\%$ and is an indication of the magnitude of one source of systematic error.

The elastic cross sections given in Table I were obtained from the area under the curves, renormalized where necessary. The statistical errors are small but the large systematic errors quoted arise from uncertainties in the values of R and σ_{Be^7}, in the computation of the focusing effects of the fringing field of the proton synchrotron, and in the amount of hydrogen lost from the CH_2 during bombardment. The hydrogen loss was measured by gravimetric analysis of the bombarded CH_2 and was found to be $\lesssim 10\%$. Figure 3 shows values of $(4\pi/\sigma_{\mathrm{tot}})^2(1^2/k^2)(d\sigma/d\Omega)$, evaluated in the center-of-mass system [this is equal to $(d\sigma/dt)/(d\sigma/dt)_{t=0}$ if one uses the optical-theorem limit for the forward scattering amplitude], plotted against the square of the invariant four-momentum transfer, t. σ_{tot} is the total p-p cross section for the bombarding proton of wave number k in the center-of-mass system. The p-p cross sections for $t \gtrsim 0.2$ (Gev/c)^2 published by other authors[5-7] are included in Fig. 3. It can be seen that for values of $t \leqslant 0.5$ (Gev/c)^2, data from all energies fall approximately on a single curve,

$$\left(\frac{4\pi}{\sigma_{\mathrm{tot}}}\right)^2 \frac{1}{k^2}\frac{d\sigma}{d\Omega} = F(t) = e^{-7.5t} .$$

This can be compared with the Gaussian approximation to the black-disk optical-model prediction and gives a value for the radius of ~1 fermi. For $t \geqslant 0.5$ (Gev/c)^2, $F(t)$ appears to be no longer a function of t alone but also of k for a given t. The data indicate interest in extending these measurements to different angles and energies and in particular to higher momentum transfers.

Another feature of the p-p momentum spectra is the inelastic bump and its fine structure. Figure 2 shows that at most energies two inelastic peaks are resolved. The momentum separations ΔP_1 and ΔP_2 of those from the elastic peak are given in Table I. The rest energy W^* of the recoiling system corresponding to a peak is given by

$$W^{*2} = M^2 + 2M\Delta E - t$$
$$\sim M^2 + 2M\Delta P, \qquad (2)$$

Table I. p-p elastic and inelastic cross sections. Θ, P_0, and t are the scattering angle, the incoming momentum, and the (4-momentum transfer)^2, respectively. ΔP_1 and ΔP_2 are the momentum separations of the inelastic peaks from the elastic peak; $W_1{}^*$ and $W_2{}^*$ are the corresponding rest energies of the recoiling system. $d\sigma/d\Omega$ in column 10 is the differential cross section of the inelastic bump evaluated by integrating the areas shown in Fig. 2. x means renormalized as described in text.

	Experimental conditions			Elastic peak			Inelastic peaks		
	Θ (lab) (mrad)	P_0 (lab) (Gev/c)	t (Gev/c)^2	$d\sigma/d\Omega$ (lab) (mb/sr)	Θ (c.m.) (degree)	$d\sigma/d\Omega$ (c.m.) (mb/sr)	ΔP_1 ΔP_2 (lab) (Gev/c)	$W_1{}^*$ $W_2{}^*$ (Gev)	$d\sigma/d\Omega$ (lab) (mb/sr)
	56.5	12.99	0.524	82	17.5	2.9	0.74 1.03	1.514 1.685	10
	56.5	15.89	0.783	20	19.2	0.59	0.72 1.01	1.504 1.678	8.4
x	56.5	17.30	0.925	6.5	20.0	0.18			
	56.5	17.75	0.978	7.6	20.2	0.21	0.71 1.01	1.499 1.680	3.5
x	56.5	18.69	1.084	2.2	20.7	0.056	0.74 1.00	1.520 1.675	2.2
x	56.5	19.56	1.184	0.76	21.2	0.018			
x	56.5	19.75	1.206	1.28	21.3	0.031	0.73 1.05	1.513 1.706	0.83
x	56.5	19.91	1.221	0.77	21.4	0.018	0.73 1.04	1.513 1.700	1.7
x	56.5	21.88	1.474	0.40	22.3	0.0088	0.71 1.07	1.50 1.72	0.25
x	56.5	22.74	1.590	0.34	22.6	0.0072			0.34
x	56.5	26.02	2.071	0.14	24.2	0.0027			0.10
	60.5	18.29	1.184	0.80	21.9	0.021	0.72 1.03	1.507 1.694	1.2
	60.5	27.83	2.372	0.055	26.6	0.0010			
Errors (all ±)									
Random				≤ 5%		≤ 5%	0.04	0.02	≤ 5%
Systematic abs.	0.5	0.3 %		50%	0.2	50%			50%
Systematic rel.		0.03%		40%		40%			40%

and is tabulated. M is the proton mass and ΔE is the laboratory energy difference of the incoming and outgoing protons. The values found for W^* are consistent with the assumption of definite rest energies for the recoil systems and the average values are 1.51 ± 0.01 Gev and 1.69 ± 0.01 Gev. As the energies of the second and third "resonances" ($T = \frac{1}{2}$) found in the π-p scattering are 1.51 and 1.69 Gev, respectively, there appears to be a connection between the inelastic bumps and these resonances. The tabulated estimates of the cross section $d\sigma/d\Omega$ for the inelastic bump were obtained by integrating the area under the bump as indicated in Fig. 2.

Several explanations have been offered for the origin of the inelastic bump,[1,8-12] but none of them explains all the features of the experimental data.

An explanation in terms of a one-meson exchange diagram in which the target proton and the pion are left in an isobaric state has been considered.[1,8] Two main objections can be raised, however. First, as the momentum transfer in the experiments was ~1 Gev/c this one-meson exchange is not expected to be the dominant process. Secondly, the model predicts a peak corresponding to the $(\frac{3}{2}, \frac{3}{2})$ π-p resonance in addition to the observed fine structure which arises from the $T = \frac{1}{2}$ resonances. The present results show no evidence for such a peak.[13]

Recently, it has been pointed out[11,12] that these difficulties may be overcome by considering another one-meson exchange process in which the

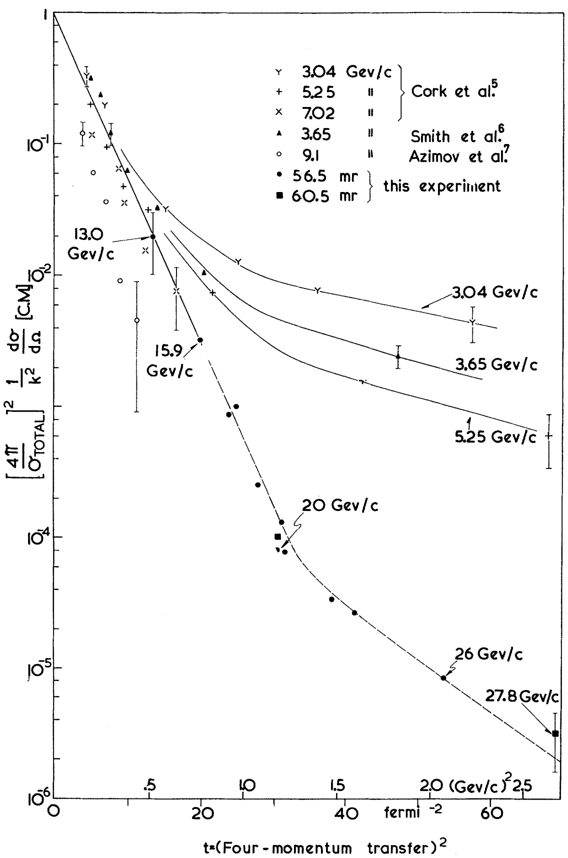


FIG. 3. The differential cross section for elastic p-p scattering, normalized to the optical-theorem value, against the square of the four-momentum transfer.

incoming proton undergoes diffraction scattering on a virtual pion of the target proton. Calculations by Drell and Hiida[12] have succeeded in predicting an inelastic bump, although its position relative to the elastic peak is less constant with energy than found in this experiment. A final-state interaction between the target proton and the pion may then qualitatively explain the double peak in the inelastic bump (the two $T=\frac{1}{2}$ resonances). The absence of the $(\frac{3}{2},\frac{3}{2})$ peak is expected since the pion and recoil nucleon are in a $T=\frac{1}{2}$ state, being formed from the target proton, and in the diffraction scattering the isotopic spin quantum number is expected to be conserved.

These experiments would not have been possible without the whole-hearted co-operation of the proton synchrotron machine group who operated the accelerator under the stringent conditions demanded by this experiment, developed new target techniques, and improved the energy stability of the machine. We should also like to thank L. Bird, R. Donnet, and C. A. Ståhlbrandt for their continuous assistance.

*Present address: Cornell University, Ithaca, New York.

†On leave of absence from the Atomic Energy Research Establishment, Harwell, England.

‡On leave of absence from Nuclear Institute for Research in Nuclear Science, Harwell, England.

[1]A. M. Wetherell, Proceedings of the Conference on Strong Interactions, Berkeley, December, 1960 [Revs. Modern Phys. 33, 382 (1961)]; G. Cocconi, A. N. Diddens, E. Lillethun, and A. M. Wetherell, Phys. Rev. Letters 6, 231 (1961).

[2]Measurements of proton scattering of high-energy protons from C and d indicate that this "elastic peak" probably arises from single and double quasi-elastic scattering from the nucleons in the Be nuclei. G. Cocconi, A. N. Diddens, E. Lillethun, G. Manning, A. E. Taylor, T. G. Walker, and A. M. Wetherell (to be published).

[3]This was previously called a "quasi-elastic bump" but this nomenclature is now dropped because of confusion with the normal use of quasi-elastic, namely to describe elastic scattering from nucleons in a nucleus.

[4]J. M. Dickson and T. C. Randle, Proc. Phys. Soc. (London) 64, 902 (1951); E. Baker, G. Friedländer, and J. Hudis, Phys. Rev. 112, 1319 (1958); P. A. Penioff, University of California Radiation Laboratory Report UCRL-8780, 1959 (unpublished).

[5]B. Cork, W. A. Wenzel, and C. W. Causey, Phys. Rev. 107, 859 (1957).

[6]G. A. Smith, H. Courant, E. C. Fowler, H. Kraybill, J. Sandweiss, and H. Taft, Phys. Rev. 123, 2160 (1961).

[7]S. A. Azimov, B. P. Bannik, V. G. Grishin, Do In Seb, L. F. Kirillova, P. K. Markov, V. A. Nikitin, L. G. Popova, I. N. Silin, L. V. Silvestrov, E. N. Tsyganov, M. G. Shafranova, B. A. Shahbazyan, A. A. Yuldashev, A. Zlateva, A. Peieva, L. Khristov, and Ch. Chernev, Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester (Interscience Publishers, Inc., New York, 1960), p. 91.

[8]B. T. Feld and C. Iso, Nuovo cimento 21, 59 (1961).

[9]Feld has considered isobar excitation by "quasi-elastic diffraction" scattering using a black-sphere optical model. It does not seem useful to compare the present observations with this theory as the momenta and scattering angles were such that the data lie well outside the first minimum of the black-sphere diffraction pattern. B. T. Feld, CERN Internal Reports TH-178, TH-193, 1961 (unpublished).

[10]L. Van Hove has suggested that it may be possible to explain the inelastic bump in terms of diffraction disintegration of the target nucleons (private communication).

[11]D. Amati (private communication).

[12]S. D. Drell and K. Hiida, Phys. Rev. Letters 7, 199 (1961).

[13]In similar experiments performed in the energy region 1-2.7 Gev a peak corresponding to the $(\frac{3}{2},\frac{3}{2})$ resonance has been observed. The results indicate that the

excitation of this state decreases compared to the excitation of the higher "resonances" as the momentum transfer increases. The momentum transfers in these experiments were ~0.1 $(\text{Gev}/c)^2$. G. B. Chadwick, G. B. Collins, P. J. Duke, T. Fujii, N. C. Hien, and F. Turkot, International Conference on Elementary Particles, Aix-en-Provence, 1961 (unpublished). See also G. B. Chadwick, G. B. Collins, S. DeBenedetti, P. J. Duke, N. C. Hien, A. Roberts, and C. E. Swartz, Phys. Rev. Letters 4, 611 (1960).

π-MESON PRODUCTION IN 2.9-Bev *p-p* COLLISIONS*

A. C. Melissinos, G. G. Fazio, and T. Yamanouchi
Department of Physics and Astronomy, University of Rochester, Rochester, New York

and

S. J. Lindenbaum and L. C. L. Yuan
Brookhaven National Laboratory, Upton, New York
(Received November 29, 1961)

The momentum spectrum of charged π mesons produced in proton-proton collisions at an incident energy of 2.9 Bev has been measured by counter techniques. Related experiments have been recently performed in a 20-in. hydrogen bubble chamber[1,2] and the study of the recoil nucleons has been pursued with counters.[3] The present experiment, however, provides detailed momentum spectra of the π mesons as a function of angle. The shape of the momentum spectra at various angles, especially 0°, provides a crucial test for the most current theories on π production.[4]

The experiment was performed at Brookhaven's Cosmotron using the external proton beam III and a liquid H_2 target. The spectra were measured at 0°, 17°, and 32° in the laboratory and the setup is shown in Fig. 1; the circulating beam intensity ranged from 2×10^{10} to 2×10^{11} protons/pulse with 30% extraction efficiency to the second focus.

As seen in Fig. 1 all secondary beams were provided with focusing quadrupole doublets; however,

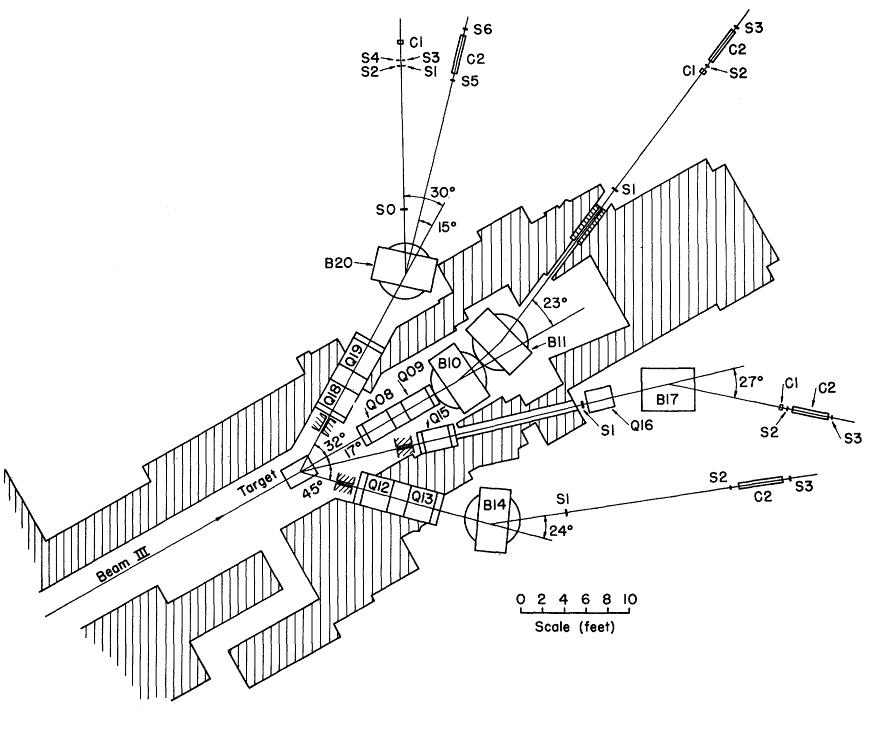


FIG. 1. The experimental setup.