Westgard, M. Block, B. Brucker, A. Engler, R. Gessaroli, A. Kovacs, T. Kikuchi, C. Meltzer, H. O. Cohn, W. Bugg, A. Pevsner, P. Schlein, M. Meer, N. T. Grinellini, L. Lendinara, L. Monari, and G. Puppi, Phys. Rev. Letters 7, 264 (1961).

[18]Y. Nambu and J. J. Sakurai, Phys. Rev. Letters 6, 377 (1961).

[19]W. B. Fowler, R. W. Birge, P. Eberhard, R. Ely, M. L. Good, W. M. Powell, and H. K. Ticho, Phys. Rev. Letters 6, 134 (1961).

[20]However, the prediction by d'Espagnat and Prentki (reference 2) and Treiman (reference 3) that $\alpha(\Xi^- \to \Lambda + \pi^-)$ and $\alpha(\Lambda \to p + \pi^-)$ have the same sign seems excluded by the results of Fowler et al. (reference 19).

PERIPHERAL COLLISIONS AND THE $(\frac{3}{2}, \frac{3}{2})$ RESONANCE IN THE REACTION $p+p \to n+p+\pi^+$ AT 970 Mev

V. E. Barnes and D. V. Bugg
Cavendish Laboratory, Cambridge, England

and

W. P. Dodd, J. B. Kinson, and L. Riddiford
Department of Physics, University of Birmingham, Birmingham, England
(Received September 13, 1961)

As a continuation of earlier work with a diffusion cloud chamber[1] at the Birmingham University 1-Bev proton synchrotron, proton-proton scattering has been studied with improved accuracy and statistics using a 9-inch liquid hydrogen bubble chamber.[2] Protons were scattered out of the synchrotron at 4° from a carbon target, and the collimated beam was estimated to have an energy spread of ±10 Mev at the bubble chamber. 3007 events within a 1° beam spread and a restricted fiducial region of the chamber have been analyzed so far, yielding the cross sections shown in Table I.

Table I. Cross sections for p-p scattering at 970 Mev.[a]

Reaction	No. of events	Cross section (mb)
(1) $p+p \to p+p$	1554	24.4 ±1.0
(2) $\to d+\pi^+$	35	0.55 ±0.1
(3) $\to p+n+\pi^+$	1170	18.4 ±0.8
(4) $\to p+p+\pi^0$	239	3.8 ±0.35
(5) $\to p+p+\pi^+ +\pi^-$	1	...
(6) $\to p+n+\pi^+ +\pi^0$	1	...
(7) $\to d+\pi^+ +\pi^0$	1	...
Either (3) or (4)	6	...

[a]These cross sections are normalized to a total cross section of 47.3 ±1.0 mb interpolated from the many counter experiments. The elastic scattering cross section includes a correction for scanning losses at very small angles. This table does not include data from the diffusion cloud-chamber experiment, where the number of uncertain events was greater.

In separating reactions (3) and (4), the accuracy of measurement was such that it was frequently necessary to assume only one pion to be created in the interaction and to identify proton or π^+ on the basis of bubble density. However, since only one case of reaction (6) was definitely established, and only one example of double-charged pion production (5) was observed, it is unlikely that the events classed as reactions (3) and (4) contain many cases of double pion production. In only six cases was it impossible to distinguish between (3) and (4). A useful check on the identifications is that the center-of-mass angular distributions were symmetrical backwards and forwards within statistical errors.

Chew and Low[3] have suggested that inelastic reactions in which one pion is created should be strongly influenced at low momentum transfer by poles in the S matrix lying just outside the physical region. The physical interpretation is that there is a large cross section for peripheral collisions of one nucleon with a virtual pion in the field of the other, with a small momentum transfer, Δ, to the latter. In the present experiment there are two poles, since the initial state consists of two protons, and the resulting cross section must be symmetrical between them.

Bonsignori and Selleri[4] have pointed out that, in p-p scattering, peripheral interactions will be most important in reaction (3) where the neutron acts as "spectator" and the proton and π^+ interact in a $T=\frac{3}{2}$ state. They find good agreement with the diffusion cloud chamber results for low momentum transfer. Using this approach, Selleri[5] has deduced the formula

$$\frac{\partial^2\sigma}{\partial T\partial\omega}=\frac{4f^2m}{\pi p_i^{\,2}\mu^2}\omega R(\omega)\sigma(\omega)[a(T)+b(T,\omega)+c(T,\omega)], \tag{1}$$

where f^2 is the renormalized pion-nucleon coupling constant 0.08, m and μ are the nucleon and pion masses, and p_i is the laboratory momentum of the incident proton. T is the laboratory kinetic energy of the "spectator" nucleon, and ω is the total energy of the pion and the other nucleon in their own rest frame. $\sigma(\omega)$ is the π-nucleon cross section at a center-of-mass energy ω, and the functions R, a, and b are defined by

$$R(\omega)=\tfrac{1}{2}[\omega^4-2\omega^2(m^2+\mu^2)+(m^2-\mu^2)^2]^{1/2}, \tag{2}$$

$$a(T)=\Delta_2^{\,2}/(\Delta_2^{\,2}+\mu^2)^2, \tag{3}$$

$$b(T,\omega)=\Delta_1^{\,2}/(\Delta_1^{\,2}+\mu^2)^2, \tag{4}$$

with

$$\Delta_2^{\,2}=2mT, \tag{5}$$

and

$$\Delta_1^{\,2}=m^2+2m(T_i-T)-\omega^2, \tag{6}$$

where T_i is the laboratory energy of the incident proton. The poles are defined by zeros of the denominators of (3) and (4), and are shown as dashed lines in Fig. 1(a). $c(T,\omega)$ is an interference term between the two poles and is defined in reference 6.

The validity of this theory is clearly demonstrated by Fig. 1(a), where the Q values[6] of $(p\pi^+)$ pairs are plotted against the laboratory energy of the neutron for 1164 events of the type $p+p\rightarrow p+n+\pi^+$. It may be shown that the phase-space factor ρ for this reaction is given by

$$\rho\propto[R(\omega)/\omega]dQdT, \tag{7}$$

being a function of Q only. In Fig. 1(a) the scale has been distorted to allow for this in such a way that points should be uniformly distributed on a statistical basis. The clustering of points close to the phase-space boundaries clearly demonstrates the effects of the poles and the influence of the well-known $(\frac{3}{2},\frac{3}{2})$ resonance at 140 Mev, and it accords reasonably well with the contours of constant cross section calculated from (1) and shown in the figure.

Figure 1(b) compares the experimental values of $d\sigma/dT$ with the predictions of the statistical model and with Selleri's formula. The latter is

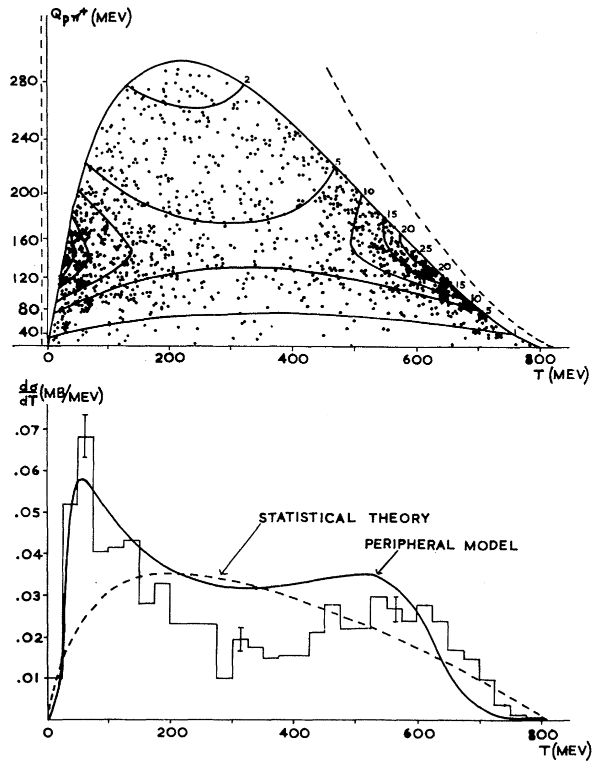

FIG. 1. (a) A scatter diagram of Q values of the $(p\pi^+)$ isobar against neutron laboratory kinetic energy for the reaction $p+p\rightarrow p+n+\pi^+$. The locations of the poles are shown by the dotted lines. Contours of the cross section predicted by Selleri's formula are shown in arbitrary units from 1 to 25. (b) The neutron laboratory energy spectrum compared with Selleri's formula and with phase space normalized to the total number of events.

in good quantitative agreement for momentum transfers less than 600 Mev/c (T less than 180 Mev) and in qualitative agreement for greater momentum transfers. A similar agreement was obtained by Selleri[5] with the diffusion cloud-chamber data.

Using Eq. (1), an attempt has been made to infer the π^+-p cross section using only events with momentum transfer to the neutron less than 430 Mev/c (100 Mev). Events close to both poles have been used by calculating the momentum transfer to each nucleon, and taking the one with the lower value as the "spectator"; this amounts to folding Fig. 1(a) about T values midway between the poles. Since the theory assumes contributions only from the one-pion exchange pole, the agreement shown in Fig. 2 with the known π^+-p cross section (full line) is quite good, and provides some justifica-

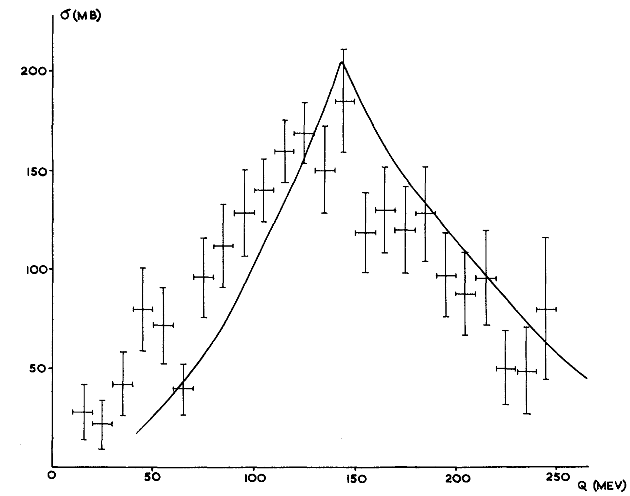

FIG. 2. The cross section for π^+-p scattering inferred from Selleri's formula using only those events in which the momentum transfer to the neutron is less than 430 Mev/c. The full line shows the cross section determined from direct π^+-p scattering experiments.

tion for similar studies of the π-π cross section from inelastic π-p scattering.[7] However, it is found that including events with momentum transfers from 430 Mev/c to 530 Mev/c reduces the agreement of Fig. 2, so that other considerations are necessary in this region. A guide to the magnitude of interference effects is that in the region of momentum transfer up to 430 Mev/c, interference of the amplitude due to the second pole through the term $c(T, \omega)$ in (1) amounts to 5 to 10%, according to the Q value; it has been allowed for in plotting Fig. 2. The original proposal of Chew and Low[3] was to infer the π-p cross section for a number of strips of Δ^2 and to extrapolate to the pole, when interference due to other poles disappears. This has been done by Smith et al.,[8] but there are insufficient events in either their or our experiment to carry out this procedure except in wide intervals of Q.

The comparison of the present results with theory shows clearly that most of the interactions arise from peripheral collisions, thus accounting for the success of the isobar model of Lindenbaum and Sternheimer[1,9] in p-p experiments. For those events with momentum transfers greater than 600 Mev/c, the Q-value distribution is, however, in good agreement with the statistical model. For π-p scattering, where peripheral collisions and isobar formation have different roles, the situation is less clear.[4,10]

We acknowledge the assistance during this work of our colleagues G. A. Doran, S. J. Goldsack, M. Jobes, and B. Tallini at Birmingham, and A. J. Oxley, J. Rushbrooke, and J. Zoll at Cambridge. A full account will be published elsewhere. We are grateful to Dr. L. Castillejo of the Mathematical Physics Department, University of Birmingham, for valuable discussions. D. V. B. and V. E. B. would like to thank Professor O. R. Frisch for helpful criticism.

[1]A. P. Batson, B. B. Culwick, J. G. Hill, and L. Riddiford, Proc. Roy. Soc. (London) A251, 218 (1959).

[2]D. C. Colley, J. B. Kinson, and L. Riddiford, Nuclear Instr. 4, 26 (1959).

[3]G. F. Chew and F. E. Low, Phys. Rev. 113, 1640 (1959).

[4]F. Bonsignori and F. Selleri, Nuovo cimento 15, 465 (1960).

[5]F. Selleri, Phys. Rev. Letters 6, 64 (1961). His expression for the cross section is too small by a factor of 2 (recent preprint by Selleri).

[6]$Q = \omega - m - \mu$.

[7]E. Pickup, F. Ayer, and E. O. Salant, Phys. Rev. Letters 5, 161 (1960); J. G. Rushbrooke and D. Radojičić, Phys. Rev. Letters 5, 567 (1960); A. R. Erwin, R. March, W. D. Walker, and E. West, Phys. Rev. Letters 6, 628 (1961).

[8]G. A. Smith, H. Courant, E. Fowler, H. Kraybill, J. Sandweiss, and H. Taft, Phys. Rev. Letters 5, 571 (1960).

[9]S. J. Lindenbaum and R. M. Sternheimer, Phys. Rev. 105, 1874 (1957).

[10]V. Alles-Borelli, S. Bergia, E. Perez Ferreira, and P. Waloschek, Nuovo cimento 14, 211 (1959).