PRODUCTION OF THE NUCLEON ISOBARS 1236, 1410, 1518, AND 1688 MeV IN PROTON-PROTON COLLISIONS AT 2.85, 4.55, 6.06, AND 7.88 GeV/c

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(Received 11 August 1966; revised manuscript received 14 September 1966)

Momentum spectra of protons scattered inelastically in proton-proton collisions were obtained in an external beam at Nimrod using incident proton momenta of 2.85, 4.55, 6.06, and 7.88 GeV/c and various scattering angles in the range 22 to 144 mrad. There is evidence for the production of the 1410 MeV isobar at small angles. The well-known isobars of mass values 1236, 1518, and 1688 MeV are also seen. The differential cross sections are presented for the production of these isobars. They are analyzed in terms of the usual variables s and t. Fits to the observed momentum spectra indicate for the $N^*(1410)$ a mass of 1410 ± 15 MeV and a width of 125 ± 20 MeV.

We have measured the momentum distributions of protons scattered at small angles in high-energy proton-proton collisions. The experiment was performed at incident momenta of 2.85, 4.55, 6.06, and 7.88 GeV/c, and protons were momentum analyzed at various scattering angles in the range 22 to 144 mrad.

In the reaction

$$p+p \to p+X, \tag{1}$$

knowledge of the incoming and outgoing proton momenta and the scattering angle determines the invariant mass of the recoiling system X. Peaks in the momentum spectrum of the detected proton may be caused by resonant behavior of the group X. Experiments of this type have previously been carried out at various energies and angles at the Cosmotron,[1,2] CERN proton synchrotron,[3-5] Bevatron,[6] and alternating-gradient synchrotron.[7] In the present experiment the use of several incident momenta, together with a range of scattering angles for each, allows us to investigate systematically the production of various nucleon isobars as functions of the kinematical variables s and t in a relatively unexplored region. The squared total center-of-mass energy, s, varied from 7.3 $(\mathrm{GeV})^2$ at the lowest beam momentum to 16.7 $(\mathrm{GeV})^2$ at the highest. The squared four-momentum transfer, $-t$, varied from 0.03 to 0.8 $(\mathrm{GeV})^2$.

The experimental arrangement is shown in Fig. 1. An extracted beam of 10^9 to 10^{10} protons per pulse from Nimrod passed through two bending magnets $M1$ and $M2$ and was focused onto a 10 cm liquid-hydrogen target. Scintillation-counter telescopes and a magnetic spectrometer consisting of three 1-m bending magnets, $M3$, $M4$, $M5$, in series, analyzed the fast scattered protons. Six four-fold counter telescopes, spaced approximately at 5-mrad intervals, enabled spectra at six angles to be obtained simultaneously. A wider range of scattering angles was obtained with the same counter positions by varying the input beam direction by adjusting the currents in $M1$ and $M2$. The input beam directions, and hence the scattering angles, were obtained by photographing the beam profiles at two positions. The proton beam intensity was recorded by an ion chamber, which had been calibrated using the reaction $^{27}\mathrm{Al}(p, 3pn)^{24}\mathrm{Na}$ in an aluminum-foil activation. Absolute values of the momentum of the scattered protons were obtained by ref-

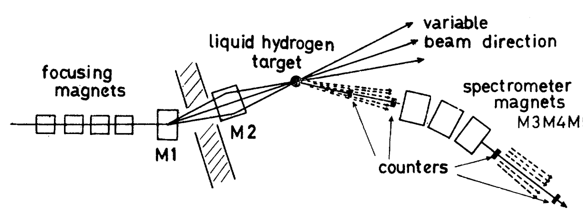

FIG. 1. Schematic representation of the apparatus. The transverse scale has been exaggerated for clarity.

erence to wire-orbit measurements simulating the trajectories through the spectrometer magnets, and checked with the known momenta of the elastic-scattering peaks, which were seen clearly at all angles. The elastic peaks also gave an experimental value for the effective momentum resolution of the experiment. The elastic peaks were all about 60-MeV/c full width at half-maximum.

Figure 2 shows several momentum spectra for Reaction (1) selected from measurements taken at each of the four beam momenta. Nearly a hundred such spectra were measured with a statistical accuracy of about 3 to 5% on each of about 50 points in each spectrum. The following qualitative features were apparent:

(1) The production of the 1236-MeV nucleon isobar can be seen at all but the largest momentum transfers. The shoulder on the high-momentum side of the peak, which could be explained by the detection of the decay proton from a 1236-MeV isobar, is particularly clear at low momentum transfers.

(2) The two $T=\frac{1}{2}$ nucleon isobars at 1518 and 1688 MeV are seen at the three higher incident momenta. The change in production cross section of these isobars with angle is not so rapid as that of the $T=\frac{3}{2}$ 1236-MeV isobar.

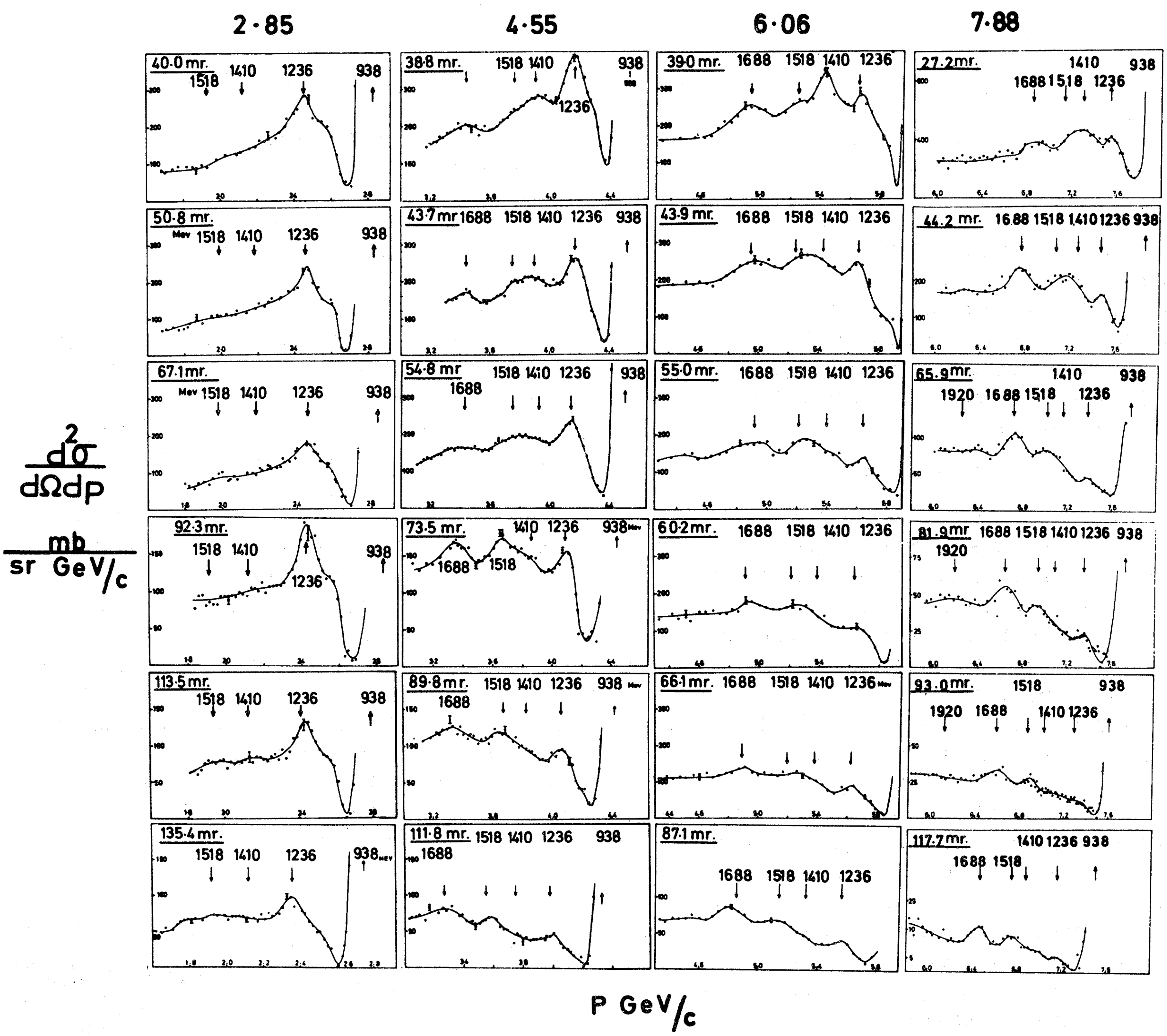

FIG. 2. Differential cross sections for Reaction (1) expressed as $d^2\sigma/d\Omega dp$ in millibarns per steradian per GeV/c, against momentum p (GeV/c) of the scattered protons. Each vertical column refers to the incident momentum in GeV/c shown at the top. The laboratory scattering angle in milliradians is shown in the top left-hand side of each graph. Arrows indicate the expected position of peaks corresponding to the missing masses shown above the arrows.

(3) The data are consistent with the existence of an isobar of mass around 1410 MeV which is produced strongly at small angles, but whose production decreases rapidly with increasing angle, and therefore becomes masked by the neighboring 1518 isobar. The actual mass and width of this isobar requires a more quantitative analysis of the data, as does the detailed s and t dependence of the isobar cross sections.

The spectra in Fig. 2 are plotted in the form of $d\sigma^2/d\Omega dp$ against p, the momentum of the inelastically scattered proton in Reaction (1). In order to obtain quantitative information when X is a resonant system, it is necessary to separate the individual distributions from one another and from the nonresonant background.

The following graphical procedure has been adopted for evaluating the differential cross sections of Reaction (1), where X is taken as one of the various isobars:

(i) Since the mass (1236 ± 0.4 MeV) and width (120.0 ± 1.5 MeV) of the $N^*(1236)$ are accurately known,[8] a peak corresponding to this mass and width was fitted to the experimental data. The area of the peak was measured to give the differential cross section $d\sigma/d\Omega$ for the reaction

$$p + p \to p + N^*(1236). \tag{2}$$

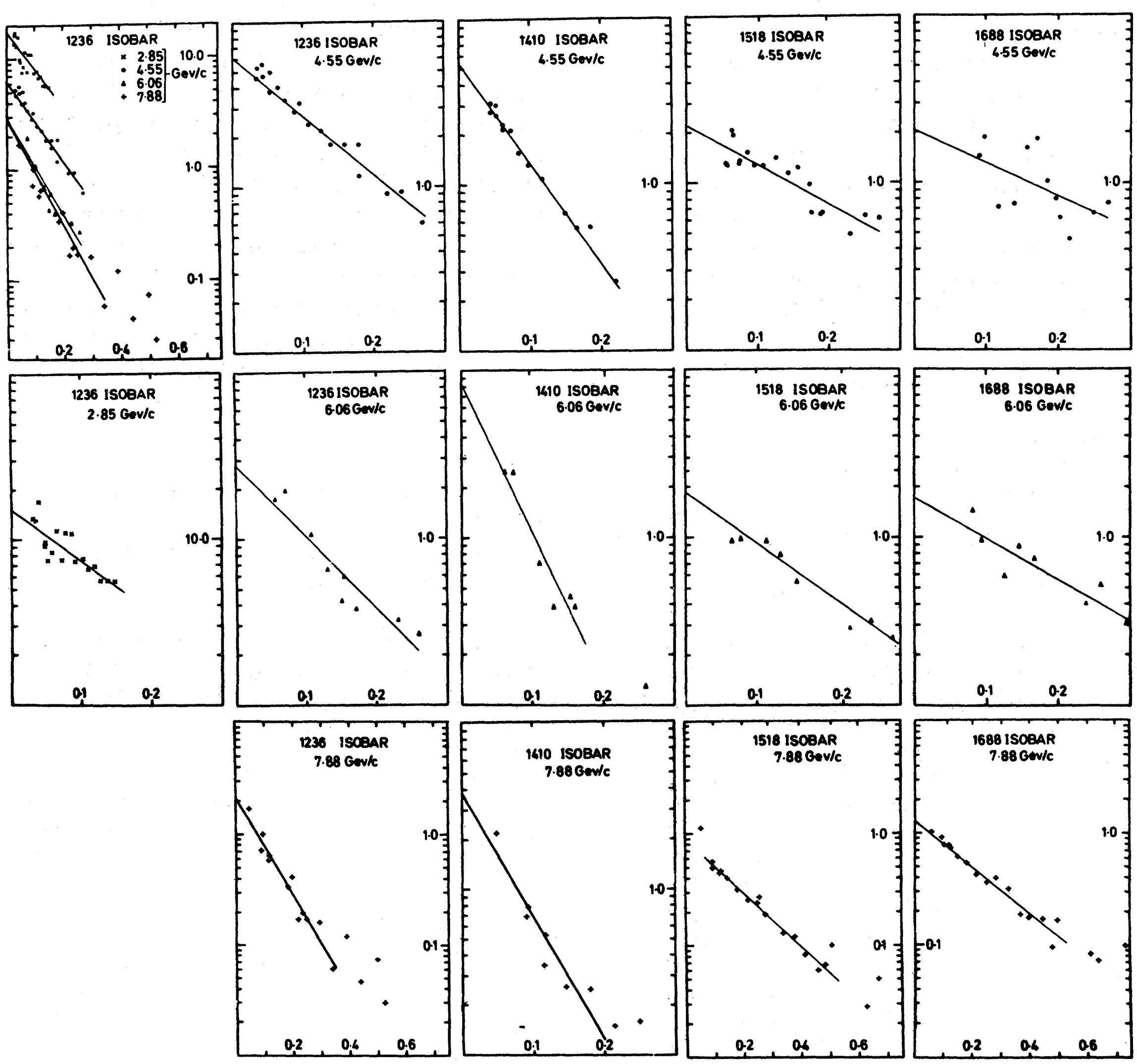

FIG. 3. Differential cross sections for the reaction $p + p \to p + N^*$ expressed as $d\sigma/d|t|$ in millibarns per GeV^2 against $|t|$, the modulus of the squared four-momentum transfer in GeV^2. The lines indicated are fits to the expression $d\sigma/d|t| = Ae^{-b|t|}$. The values of A and b and the $|t|$ range used are indicated in Table I.

(ii) There was no significant structure in the inelastic spectrum corresponding to mass values >1688 MeV. A smooth curve was extrapolated from the high-mass region to the region of the $N^*(1688)$. A subtraction of this extrapolated background from the experimental data gave a peak consistent with a mass assignment of 1688 MeV and width ~120 MeV. With these values the differential cross sections have been extracted for the reaction

$$p+p\rightarrow p+N^*(1688). \tag{3}$$

(iii) The total background left after the removal of the contributions from the $N^*(1236)$ and $N^*(1688)$ from the spectra was smoothly continued under the remaining structure and subtracted. At large momentum transfers a single peak remains consistent with the known mass (1518 MeV) and width (120 MeV) of the $N^*(1518)$. At low momentum transfers the predominant peak corresponds to a mass of about 1410 MeV, and at intermediate momentum transfers a wide peak is observed whose position varies with momentum transfer between 1518 and 1410 MeV. Using the accepted values of mass and width of the $N^*(1518)$, the differential cross section of the reaction

$$p+p\rightarrow p+N^*(1518) \tag{4}$$

was evaluated.

(iv) The remaining structure is consistent with the reaction

$$p+p\rightarrow p+N^*(1410), \tag{5}$$

where the N^* has a rapidly varying angular distribution, a mass of 1410 ± 15 MeV, and a width of 125 ± 20 MeV. The uncertainty in the width depends somewhat on the fitting procedure and has been estimated from two sets of fits.

There is evidence for an N^* of mass about 1410 MeV in the $T=\frac{1}{2}$ total elastic π-p cross sections and in the π^--p mass spectrum in the final state of the reaction $\pi^-+p\rightarrow\pi^++\pi^-+\pi^-+p$,[9] in K^--p collisions,[10] and in p-p collisions.[5-7] Phase-shift analyses of pion-nucleon scattering[11-15] indicate that the only phase shift which shows any marked variation in this energy region is the P_{11}. By considering the position of fastest variation of the real part of this phase shift with energy, a resonant mass value of about 1400 MeV is suggested.

The variation with t of the differential cross sections for the various Reactions (2)-(5) are shown in Fig. 3. During the fitting procedure outlined above, estimates were made of the uncertainties to be assigned to these cross sections. These turned out to be in the region ±20 to ±30%. In addition, there is a ±13% uncertainty in the absolute scale of the cross sections which arises from the uncertainties in the calibration of the ion chamber. The data have been fitted using the expression

$$\frac{d\sigma}{d|t|}=Ae^{-b|t|}, \tag{6}$$

and the resulting values of A and b are listed in Table I.

The total cross section for the production of the various isobars was calculated by inte-

Table I. The parameters A and b, and σ_T. The $|t|$ range quoted in the third column is that over which the expression $Ae^{-b|t|}$ has been fitted, and does not necessarily include all the data (see Fig. 3). The normalization uncertainty of ±13% is included in the quoted error on σ_T, but not in those on A and b which are just fitting errors.

p_0 (GeV/c)	N^*	$\|t\|$ (GeV^2)	A (mb/GeV^2)	b (GeV^{-2})	σ_T (mb)
2.85	1236	0.031-0.16	15.0 ± 1.6	6.9 ± 1.2	3.8 ± 0.6
4.55	1236	0.034-0.27	6.9 ± 0.7	8.9 ± 0.9	1.5 ± 0.2
6.06	1236	0.056-0.26	2.8 ± 0.5	10.0 ± 1.0	0.6 ± 0.1
7.88	1236	0.046-0.34	2.1 ± 0.3	9.9 ± 0.6	0.41 ± 0.06
4.55	1410	0.044-0.22	5.5 ± 0.8	14.0 ± 1.3	0.63 ± 0.08
6.06	1410	0.061-0.16	8.8 ± 2.9	20.7 ± 2.7	0.65 ± 0.18
7.88	1410	0.048-0.145	5.9 ± 2.5	22.1 ± 4.1	0.45 ± 0.09
4.55	1518	0.057-0.27	2.2 ± 0.2	5.4 ± 0.8	0.68 ± 0.08
6.06	1518	0.065-0.29	1.8 ± 0.4	7.1 ± 1.1	0.45 ± 0.09
7.88	1518	0.092-0.484	0.9 ± 0.1	5.3 ± 0.5	0.31 ± 0.05
4.55	1688	0.091-0.27	2.1 ± 0.5	4.6 ± 1.3	0.7 ± 0.1
6.06	1688	0.081-0.30	1.8 ± 0.5	5.6 ± 1.3	0.5 ± 0.1
7.88	1688	0.058-0.5	1.3 ± 0.2	4.8 ± 0.4	0.46 ± 0.09

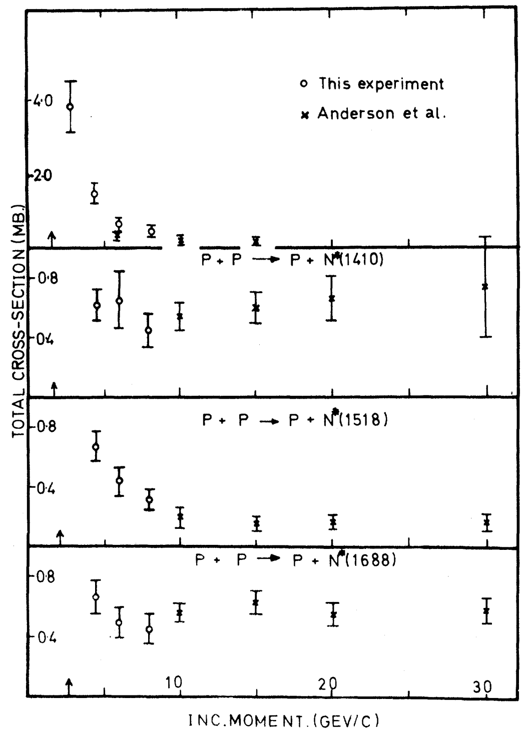

FIG. 4. Total cross sections for the reaction $p+p \rightarrow p+N^*$ expressed as millibarns against incident momentum in GeV/c.

grating Eq. (6) between the maximum and minimum physically allowed values of $|t|$ and multiplying by 2 in order to include the backward hemisphere in the center-of-mass system. The results are given in Table I, and are shown as a function of incident momentum in Fig. 4, together with the data of Anderson et al.[7] for higher incident momenta. The errors shown have been calculated from the error matrix of the least squares fit to expression (6) and the 13% uncertainty in the absolute scale, the latter being the major contribution. Clear s dependence is seen from the $N^*(1236)$ and the $N^*(1518)$ at the lowest incident momenta.

We are grateful to the members of the Nimrod Division who operated the accelerator and provided many of the necessary services, and to I. L. Watkins who assisted during the preparation and running of the experiment We also wish to express our thanks to Professor A. Ashmore and F. Capocci, who participated in the early stages of the experiment. Two of us (M.C.M. and D.B.S.) wish to thank the Science Research Council for the award of Research Studentship grants.

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