Comparison of Isobar Production in pp and $\bar{p}n$ Interactions at 2.8 GeV/c*

T. C. BACON, F. M. BOMSE, T. B. COCHRAN, W. J. FICKINGER, E. R. GOZA, H. W. K. HOPKINS, AND E. O. SALANT
Vanderbilt University, Nashville, Tennessee

(Received 24 March 1967)

The reactions $pp \to N^{*++}(1238)n$ and $\bar{p}n \to \bar{N}^{*--}(1238)p$ at 2.8 GeV/c incident laboratory momentum are analyzed with the Brookhaven National Laboratory 20-in. bubble chamber. Isobar and anti-isobar production differential cross sections and decay angular distributions are compared with the predictions of an absorptive single-pion-exchange model. The absolute values, shapes, and ratios of the cross sections are in good agreement with the theory when the absorptive parameters γ_1 and γ_2 are 0.033 and 0.016 for the $\bar{p}n$ reaction, and 0.057 and 0.019, respectively, for the pp reaction.

THE observed peripherality of reactions producing quasi-two-body final states in particle collisions at high energies indicates the importance of single-particle-exchange mechanisms. Experimental results for a variety of reactions are in general agreement with the predictions of a single-pion-exchange model in which effects of absorption due to competing interaction channels in the initial and final states are included.[1] A comparison of isobar and anti-isobar production in pp and $\bar{p}n$ collisions provides a further test of this model in that it includes the added absorptive effects of the annihilation channels in the $\bar{p}n$ reaction. For, while the absorption reduces cross sections of both pp and $\bar{p}n$ reactions leading to quasi-two-body final states, the model predicts a stronger absorption of low partial waves for the $\bar{p}n$ than for the pp interactions; in consequence, anti-isobar production shows a more collimated forward differential cross section and an additional reduction of total cross section over that for isobar production. Since the isospins of the two reactions reported here differ only in the sign of the third component, the two channels can be compared directly.

In this paper we present an analysis of 1302 events of the type $pp \to p\pi^+n$ and 944 events of the type $\bar{p}n(p) \to \bar{p}\pi^-p(p)$, where (p) represents the spectator proton of the deuteron. An account of the pp reaction at 2.8 GeV/c has been published[2]; the data are presented here in a form suitable for comparison with the predictions of the absorptive one-pion-exchange model. The $\bar{p}n$ sample was obtained from approximately 15 000 three- and four-prong events observed in the deuterium-filled 20-in. bubble chamber exposed to 2.8-GeV/c antiprotons at the Brookhaven alternating gradient synchrotron. We shall discuss only those events with at least one proton of momentum less than 200 MeV/c, a range in which the impulse approximation appears valid by comparison of the proton momentum distribution with that predicted by the Hulthén wave function.[3] For the purpose of analysis the proton with lower momentum was chosen as the "spectator." Total cross sections have been computed using all events.

In Figs. 1(a) and 1(b) are shown the distributions of the $\bar{p}\pi^-$ and $p\pi^+$ effective masses evaluated from the fitted variables. Both histograms have been fitted by the least-squares method to a Breit-Wigner resonance form with mass-dependent width, together with a phase-space background. The curves have the form

$$\frac{d\sigma}{dM} \propto P(M)\left[(1-f)+\frac{fM\Gamma(M)}{q[(M^2-M_0^2)^2+M_0^2\Gamma^2]}\right],$$

where

$$\Gamma(M)=\Gamma_0\left(\frac{q}{q_0}\right)^3\left(\frac{2.2m_\pi^2+q_0^2}{2.2m_\pi^2+q^2}\right)$$

and $P(M)$ is the phase space; $P(M)$ does not take into account any anisotropies in the decays of the resonances. The term $(1-f)$ is the fraction of background, M_0 and Γ_0 are the intrinsic mass and width of the resonance, q is the three-momentum of either isobar decay product in the isobar rest frame, and q_0 is the value of q for $M=M_0$. The form of $d\sigma/dM$ is a phenomenological expression discussed by Jackson.[4] The distribution of events outside the resonant channel is assumed to follow phase space, an assumption justified by the relatively small $N^*(1238)$ production observed in the $n\pi^+$ and $p\pi^-$ systems. A 15-MeV resolution has been folded into the fits. The fitted parameters are given on the figures, and the fitted background is shown by the lower curves. The N^{*++} fitted width is considerably less than the accepted value of 120 MeV.[5]

In Figs. 1(c) and 1(d) are shown differential cross sections for isobar and anti-isobar production as a func-

* This work was supported in part by a grant from the National Science Foundation, which is gratefully acknowledged. Computing for this experiment was done at the U. S. Army Computing Center at Redstone Arsenal, Huntsville, Alabama.

[1] See, for example, J. D. Jackson [Rev. Mod. Phys. 37, 484 (1965)] and J. D. Jackson, J. T. Donahue, K. Gottfried, R. Keyser, and B. E. Y. Svensson [Phys. Rev. 139, B428 (1965)] in which experimental results on several different quasi-two-body reactions are compared with the predictions of an absorptive single-particle-exchange model.

[2] W. J. Fickinger, E. Pickup, D. K. Robinson, and E. O. Salant, Phys. Rev. 125, 2082 (1962).

[3] See, for example, T. C. Bacon, H. W. K. Hopkins, D. K. Robinson, E. O. Salant, A. Engler, H. E. Fisk, C. M. Meltzer, and J. Westgard, Phys. Rev. 139, B1420 (1965), Fig. 2.

[4] J. D. Jackson, Nuovo Cimento 34, 1644 (1964).

[5] A. H. Rosenfeld, A. Barbaro-Galtieri, W. H. Barkas, P. L. Bastien, J. Kirz, and M. Ross, Rev. Mod. Phys. 39, 1 (1967).

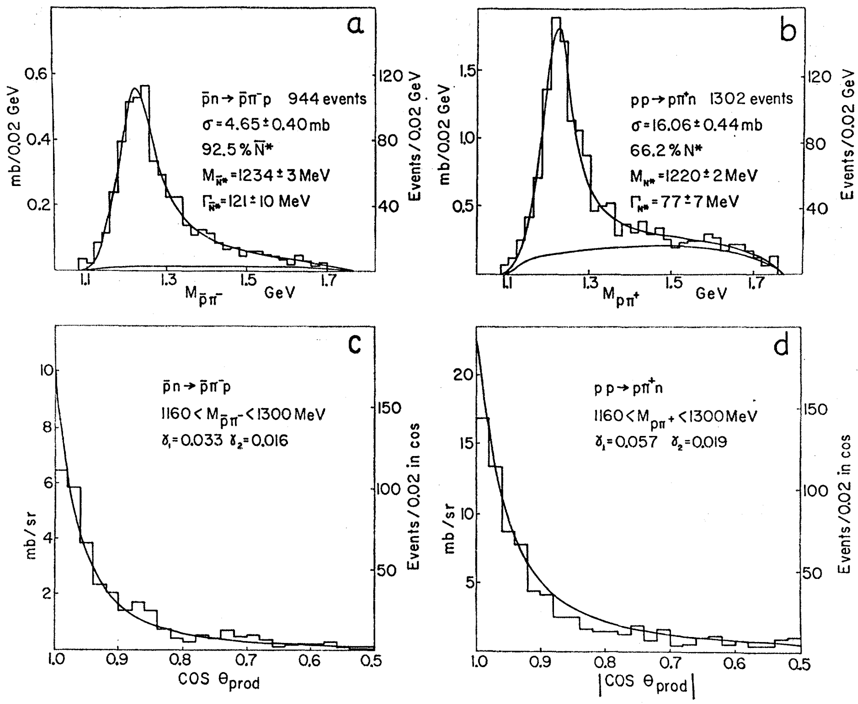

FIG. 1 (a) and (b). Effective-mass distributions for the $\bar{p}\pi^-$ and $p\pi^+$ systems. The upper curves are fitted Breit-Wigner forms with phase-space background. The lower curves are the fitted phase-space contributions. (c) and (d). Production angular distributions for isobar events. The curves are the absolute predictions of an absorptive one-pion-exchange model for the quoted values of γ_1 and γ_2.

tion of $\cos\theta_{\text{prod}}$ where θ_{prod} is the angle between the incident $\bar{p}(p)$ and outgoing $\bar{N}^{*--}(N^{*++})$ in the over-all $\bar{p}n(pp)$ center-of-mass system. For these and all subsequent distributions we have selected events for which 1160 MeV$\leq M_{\bar{p}\pi^-}(M_{p\pi^+})\leq$1300 MeV. Since fewer than 10% of the events have $\cos\theta_{\text{prod}}<0.5$, these distributions are plotted over the interval $0.5<\cos\theta_{\text{prod}}\leq 1.0$. In the pp reaction, isobars are produced symmetrically with equal probability in the forward and backward directions (t and u channels). Consequently, the differential cross section in Fig. 1(d) has been folded about $\cos\theta_{\text{prod}}=0$. The calculated production angle in the $\bar{p}n$

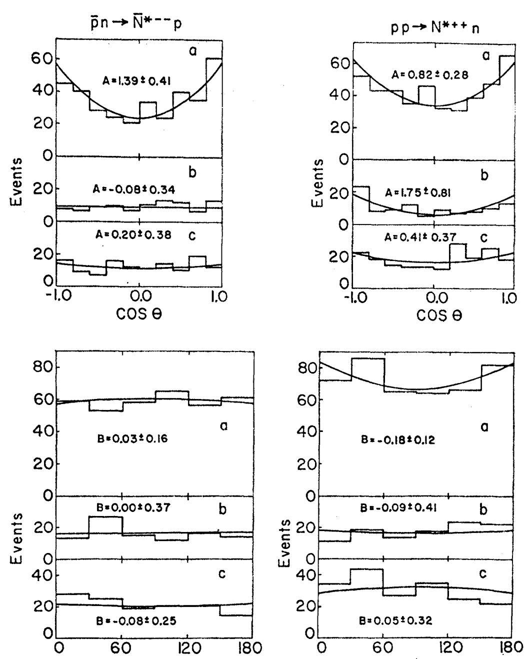

FIG. 2. Isobar decay angular distributions fitted to $N_1(1+A\times\cos^2\theta)$ or $N_2(1+B\sin^2\phi)$ for three regions of $\cos\theta_{\text{prod}}$: (a) $1.0\geq\cos\theta_{\text{prod}}>0.9$, (b) $0.9\geq\cos\theta_{\text{prod}}>0.8$, (c) $0.8\geq\cos\theta_{\text{prod}}>0.0$.

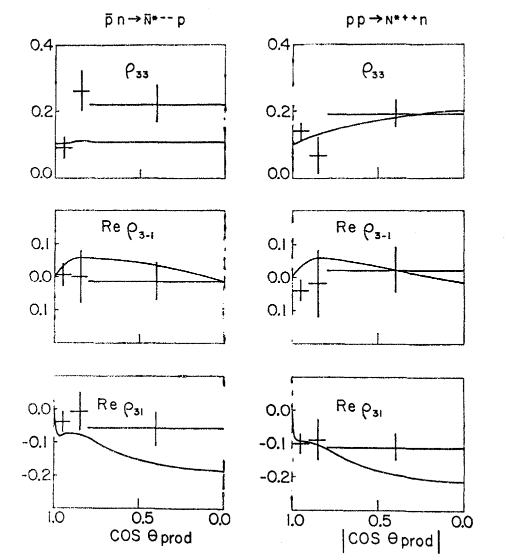

FIG. 3. Spin-density matrix elements for isobar decay as a function of production angle compared to the predictions of an absorptive one-pion-exchange model.

interaction depends on which of the two final-state protons is identified as the recoil. For $\cos\theta_{\text{prod}} > 0.98$ the identification is ambiguous because the laboratory momenta of the recoil and spectator protons are comparable. Moreover, when the target neutron is moving approximately opposite to the beam in the laboratory, it is possible for the spectator and recoil protons to produce invisibly short tracks in the bubble chamber. Such events are, therefore, missing from the extreme forward end of the experimental distribution. A Monte Carlo simulation of the experiment indicates that at least some of the forward loss can be accounted for by this type of scanning bias.

In Figs. 1(c) and 1(d) the solid curves are the predictions of an absorptive one-pion-exchange model.[6] The absorptive parameters γ_1 and γ_2 which best fit our data and which affect both the total cross sections and the shapes of the curves are given on the figures. The $NN^*\pi$ coupling constant used in the calculations is based on an assumed N^* width of 120 MeV,[6] to which the predicted cross sections are directly proportional. The measured total cross section for the reaction $\bar{p}n \rightarrow \bar{N}^{*--}p$ is 3.79 ± 0.17 mb. This cross section becomes $4.25_{-0.21}^{+0.49}$ mb when a multiplicative correction of $1.12_{-0.02}^{+0.12}$ for the shielding of the neutron by the proton is introduced.[7] We estimate that this cross section may still be low by as much as 2% because of the possible loss in the forward direction discussed above. The disproportionate increase in the uncertainty in this cross section results from the large theoretical uncertainty in the shielding correction itself. In the interval $0.5 < \cos\theta_{\text{prod}} \leq 1.0$, the measured cross section is $3.92_{-0.19}^{+0.45}$ mb which may be low by as much as 3% because of events missing in the forward direction; the theoretical value over this range is 3.72 mb. For the reaction $pp \rightarrow N^{*++}n$, the measured total cross section is 10.63 ± 0.29 mb. In the interval $0.5 < \cos\theta_{\text{prod}} \leq 1.0$, the measured cross section is 9.80 ± 0.25 mb and the theoretical value over this range is 11.69 mb. The ratio of the cross sections $R = \bar{N}^{*--}/N^{*++}$ is measured to be $0.40_{-0.05}^{+0.02}$. The theoretical ratio is independent of the $NN^*\pi$ coupling constant and depends only on absorptive effects; the values predicted for noninterfering t and u channels are $R = 0.50$ without absorption, and $R = 0.33$ with absorption.[6]

The anti-isobar (isobar) decay angular distributions are shown in Fig. 2. We have calculated these decay angular distributions for three different regions of $\cos\theta_{\text{prod}}$. The distributions are given in terms of $\cos\theta$ and ϕ, where θ is the angle between the incident $\bar{p}(p)$ and outgoing $\bar{p}(p)$, and ϕ is the Treiman-Yang angle, both calculated in the anti-isobar (isobar) rest frame. The curves shown are least-squares fits to the experimental distributions. These curves have been constrained to the forms $N_1(1 + A\cos^2\theta)$ and $N_2(1 + B\sin^2\phi)$, N_1 and N_2 being normalization constants. The fitted parameters are shown on the figure. These parameters have been used to calculate the spin-density matrix elements of the anti-isobar and isobar, which are compared with the one-pion-exchange absorption-model predictions[6] in Fig. 3. The values of ρ_{33} and $\text{Re}\rho_{3,-1}$ have been calculated from the equations $\rho_{33} = (3 - A)/(12 + 4A)$ and $\text{Re}\rho_{3,-1} = (-\sqrt{3}B)/(4B + 8)$. The values of the third matrix element $\text{Re}\rho_{31}$ are determined from $\text{Re}\rho_{31} = -1.08\langle\sin 2\theta \cos\phi\rangle_{\text{av}}$. The one-pion-exchange model without absorption predicts $\rho_{33} = 0$ [i.e., $W(\theta) \propto 1 + 3 \times \cos^2\theta$] for all $\cos\theta_{\text{prod}}$. In the range $\cos\theta_{\text{prod}} > 0.9$, the absorption model predicts $\rho_{33} \approx 0.1$ [or $W(\theta) \propto 1 + 1.3 \times \cos^2\theta$] for both $\bar{p}n$ and pp. The experimental values of ρ_{33} in the region $\cos\theta_{\text{prod}} > 0.9$ are 0.09 ± 0.03 for the $\bar{N}^{*--}$, and 0.14 ± 0.03 for the N^{*++}, in good agreement with the prediction of the absorption model. At smaller values of $\cos\theta_{\text{prod}}$ the data are in fair agreement with the theory.

We would like to thank the operating crews of the alternating gradient synchrotron and the 20-in. bubble chamber, and our scanning and measuring staff for their cooperation. We also gratefully acknowledge the loan of some scanning and measuring equipment by Brookhaven National Laboratory. We are indebted to J. D. Jackson and G. E. Hite for their comments and discussions, and D. K. Robinson for his compilation of the pp data.

[6] J. D. Jackson, G. E. Hite, and B. E. Y. Svensson (private communications).

[7] V. Franco and R. J. Glauber, Phys. Rev. 142, 1195 (1966).