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Observation of the d^* Effect in the $\bar{p}d \to p\bar{p}\pi^+\pi^-n$ Reaction at 5.55 GeV/c

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This experiment is based on 150 000 photographs, taken at the Zero Gradient Synchrotron with the 30-in. bubble chamber. We present results on a subsample of $p_s\bar{p}\pi^+\pi^-n$ events in which the protons stopping in the chamber do not show the characteristic nucleon-spectator behavior. The selection procedure for this sample is discussed. A strong low-mass $p_s n\pi^+$ enhancement at 2.2 GeV/c^2 is observed. This bump is not considered as a real resonance and is interpreted as having the same origin as the 2.2-GeV/c^2 $d\pi$ enhancement observed, for instance, in the $\bar{p}d \to \bar{p}d\pi^+\pi^-$ reaction at the same energy.

I. INTRODUCTION

In this paper we present results on a subsample of events belonging to the $\bar{p}d \to p_s\bar{p}\pi^+\pi^-n$ channel. Throughout this work p_s will denote a proton stopping in the chamber while the symbol N_{sp} is reserved for a real nucleon spectator. The present data were extracted from a $\bar{p}$ exposure made at the Zero Gradient Synchrotron with the 30-in. deuterium-filled bubble chamber. The 150 000 photographs were scanned twice for four-pronged events with at least one positive track stopping in the chamber. In this way we obtained an enriched sample of events with a proton spectator in the final state. Excluding that part of the events having the p_s laboratory momentum for $p_p \gtrsim 0.28$ GeV/c, we should, in principle, be left with a $p_{sp}\bar{p}\pi^+\pi^-n$ sample, allowing the study of the $\bar{p}n \to \bar{p}\pi^+\pi^-n$ reaction. As shown in Ref. 1, this method does not give satisfactory results for the $\bar{p}d \to p_s\bar{p}\pi^+\pi^-n$ channel. For this reaction there is an important fraction of events having outgoing stopping protons which cannot be considered as proton spectators. These events will be studied in this work. Further experimental details on the present experiment can be found in Refs. 2 and 3.

II. SELECTION OF EVENTS CONTRIBUTING TO THE d^* EFFECT

Each event fitting the $\bar{p}d \to p_s\bar{p}\pi^+\pi^-n$ hypothesis was taken as a candidate for this reaction if there was compatibility between the calculated and observed bubble densities of the tracks. After resolving the ambiguity problems between the competitive hypotheses as described elsewhere[1] and applying further cuts on the missing mass squared and the χ^2 probability, we obtained 1239 events. For this sample we show in Fig. 1(a) the scatter

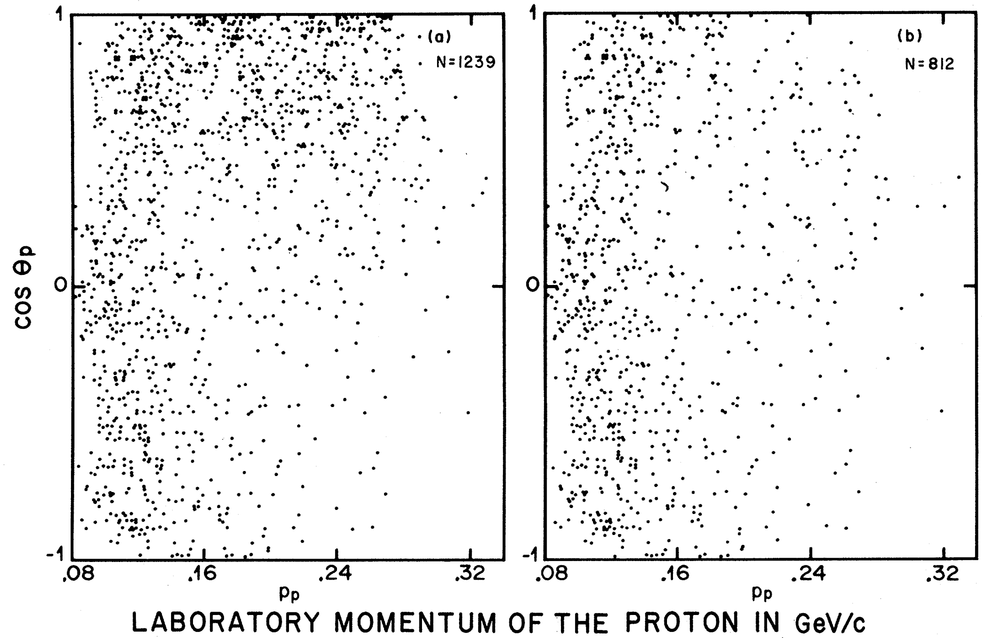

FIG. 1. Scatter plots of the laboratory momentum of the proton versus the cosine of its laboratory emission angle (a) for all the events identified as belonging to the $\bar{p}d \to p_s \bar{p}\pi^+\pi^- n$ reaction and (b) for the events which remain after extracting the 427 events as described in the text.

plot of the laboratory momentum of the proton p_p versus the cosine of its laboratory emission angle θ_p. On this figure, one observes an accumulation of events in the $\cos\theta_p > 0$ region. The projections of this plot on the p_p and $\cos\theta_p$ axes do not show the expected spectator-nucleon behavior for the outgoing p_s; i.e., (a) the p_p distribution does not follow the Hulthén prediction, and (b) the deviation from isotropy for the $\cos\theta_p$ distribution is too significant to be accounted for by flux-factor corrections.[2] The removal of 264 events for which the neutron has a smaller laboratory momentum than the proton ($p_n < p_p$) reduces the accumulation of events seen in Fig. 1(a). However, a Monte Carlo calculation shows that the number of 264 events is too large to be explained by the presence of the $\bar{p}d \to n_{sp} p\pi^+\bar{p}\pi^-$ reaction. This calculation predicts at most a contamination of ~80 $n_{sp} p\pi^+\bar{p}\pi^-$ events in the $\bar{p}d \to p_s \bar{p}\pi^+\pi^- n$ reaction if one assumes the equality of the $\bar{p}d \to p_{sp} \bar{p}\pi^+\pi^- n$ and $\bar{p}d \to n_{sp} p\pi^+\bar{p}\pi^-$ cross sections. In the following we will interpret the observed accumulation in Fig. 1(a) (due to the 264 removed events and those which still remain) as being due mainly to the same d^* effect as observed in the same experiment for the $\bar{p}d \to \bar{p}d\pi^+\pi^-$ reaction.[3] This interpretation is based primarily on the fact that for the 264 events, one observes a strong bump in the $M_{p_s n\pi^+}$ mass [shaded area of Fig. 2(a)] with a central value (~2.2 GeV/c^2) and a width (Γ ~0.2 GeV/c^2) similar to the $M_{d\pi^+}$ enhancement (hereafter called d^*) seen in the $\bar{p}d \to \bar{p}d\pi^+\pi^-$ reaction. That the $M_{p_s n\pi^+}$ and the $M_{d\pi^+}$ bumps have the same origin is also suggested by the mechanism used for successfully describing the $M_{d\pi}$ enhancement. The low-mass $M_{d\pi^+}$ bump was interpreted by means of a $d\pi^+$ final state interaction treated as elastic scattering or by means of a Reggeized π exchange which scatters off the deuteron.[3,4] From the presence of such a $\pi d \to \pi d$ process, one expects to observe a 2.2-GeV/c^2 $M_{d\pi}$ enhancement. This is because the general features of the $\pi d \to \pi d$ scattering can be described by the first-order impulse approximation, i.e., in terms of πN elastic scattering. The strong πN δ_{33} phase shift will then produce a bump in the elastic πN cross section at 1.236 GeV/c^2 which corresponds to an enhancement in the πd cross section around $M_{d\pi}$~2.2 GeV/c^2, the sum of the Δ and N masses.[4] If such a mechanism is responsible for the $d\pi$ enhancement, it could also produce a bump in the $M_{pn\pi^+}$ mass distribution for the reaction under study. In this case, however, the outgoing deuteron and the π^+ are assumed to interact in such a way that the deuteron does not remain bound.

The shaded part of Fig. 2(a) does not contain all the $p_s \bar{p}\pi^+\pi^- n$ events which can contribute to the $M_{p_s n\pi^+}$ bump because we have not considered those having $p_p < p_n$. Part of these $p_p < p_n$ events can be taken for the present analysis assuming that the neutron and proton resulting from the virtual $\pi d \to \pi pn$ process have similar laboratory momen-

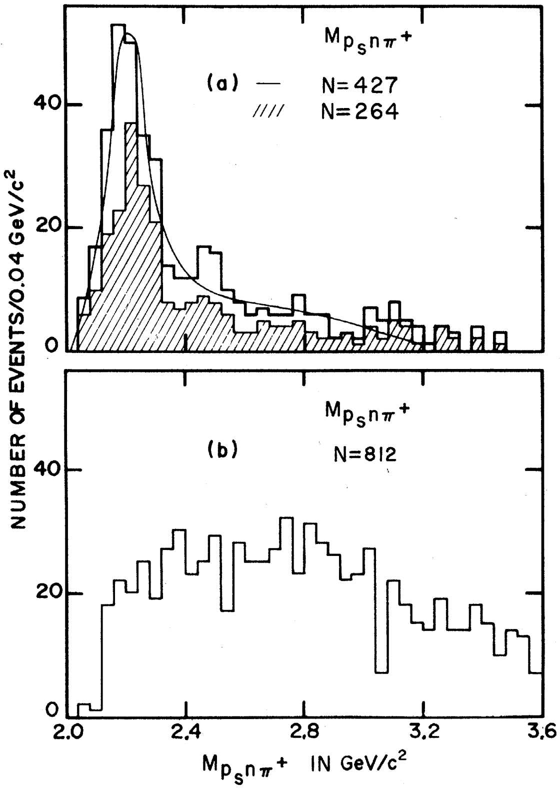

FIG. 2. (a) The M_{p_s} distribution for the 427 selected events. The curve is obtained by fitting the data as described in the text. The shaded area shows the $M_{p_s n\pi^+}$ distribution for the events having $p_n < p_p$. (b) The $M_{p_s n\pi^+}$ distribution for the 812 events which are left after extracting the sample of 427 events.

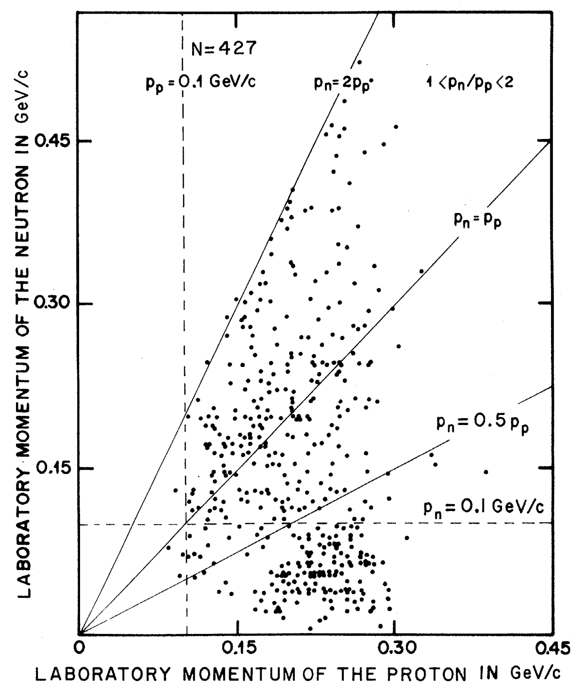

FIG. 3. The p_n versus p_p scatter plot for the 427 events. The lines defined by $p_n = 0.5p_p$ and $p_n = 2p_p$ are symmetric with respect to the $p_n = p_p$ line; similarly for the lines $p_n = 0.1$ GeV/c and $p_p = 0.1$ GeV/c.

tum distributions. In other words we admit that the events due to the d^* effect are distributed symmetrically around the $p_n/p_p = 1$ line in the region of the p_n, p_p scatter plot free of scanning losses (Fig. 3). This is, of course, a simplified picture because the Clebsch-Gordan coefficients needed for coupling the π^+p and π^+n isospin states are not equal. Therefore, in terms of the first-order impulse approximation, the $\pi^+p \to \pi^+p$ and $\pi^+n \to \pi^+n$ interactions used for describing the $\pi^+d \to \pi^+pn$ process contribute with different weights to this reaction and may lead to different p and n laboratory momentum distributions. If we assume, however, the above-mentioned symmetry, we may extract 163 additional events which are in the $\cos\theta_p > 0$ region and which fulfill the $1 < p_n/p_p < 2$ condition. The reason for this selection will be explained below, although the real justification comes from the fact that we are left with a $p_{sp}\bar{p}\pi^+\pi^-n$ sample where the p_{sp} now show the expected nucleon-spectator behavior. As the momentum threshold detection of p_s is $p_p \gtrsim 0.1$ GeV/c, nearly all the d^* events having $p_p < p_n$ and $\cos\theta_p > 0$ must lie in the $1 < p_n/p_p < 2$ region. This can be seen in Fig. 3 by examining the symmetry of the region defined by the conditions $1 < p_n/p_p < 2$ and $p_p > 0.1$ GeV/c, with respect to the $p_n/p_p = 1$ line. This reflected region contains practically all the $p_n < p_p$ events for which $p_n > 0.1$ GeV/c. This justifies the choice of the $1 < p_n/p_p < 2$ condition. The $\cos\theta_p > 0$ condition was taken because it is in this region that the accumulation of events has been seen in Fig. 1(a). Moreover, a calculation shows also that the nucleons which contribute to the d^* effect have a tendency to go forward in the laboratory system. In Fig. 1(b) we present the $(\cos\theta_p, p_p)$ scatter plot obtained this time by excluding the 163 events in addition to the 264 for which $p_n < p_p$. As can be seen from this figure the accumulation seen previously disappears. The $\cos\theta_p$ and p_p distributions (not shown) for the 812 remaining events agree now in a satisfactory way with the predictions obtained from the impulse approximation. Moreover, the 163 events chosen in the way described above contribute mainly to the 2.2-GeV/c^2 enhancement [Fig. 2(a)], while for the 812 events no such bump appears in the $M_{p_s n\pi^+}$ distribution [(Fig. 2(b)]. All this justifies, *a posteriori*, the way of selecting our $264 + 163 = 427$ events, although a small contamination of events with a real nucleon spectator is certainly present in this sample. An upper limit of this contamination can be

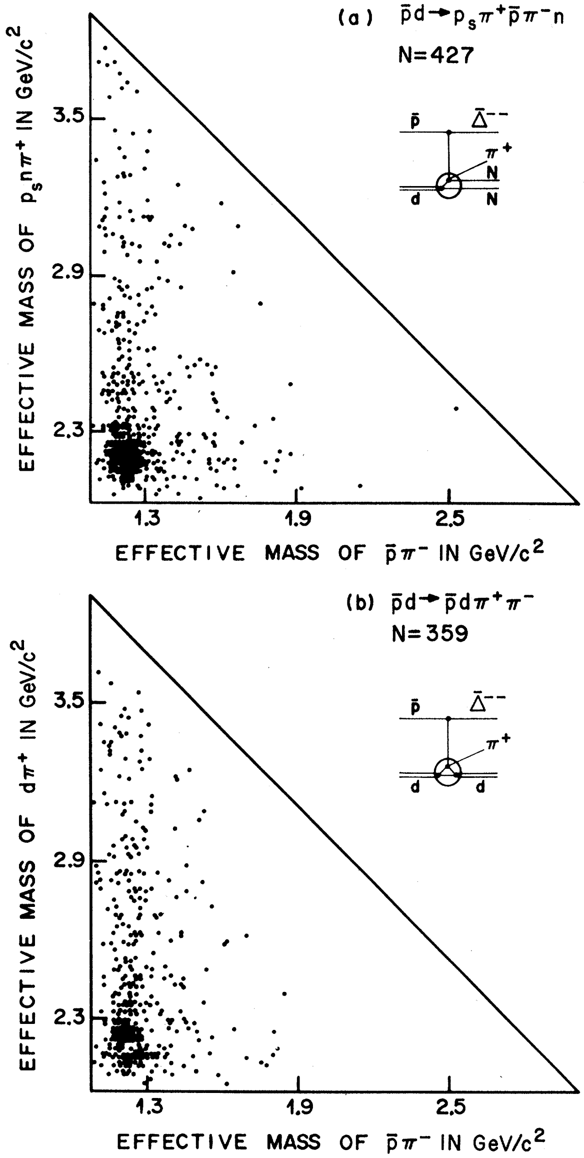

Fig. 4. Comparison between the triangle plots of (a) $M_{pn\pi^+}$ versus $M_{\bar{p}\pi^-}$ (this work) and (b) $M_{d\pi^+}$ versus $M_{\bar{p}\pi^-}$ (Ref. 3). The diagram in which the exchanged π scatters off the deuteron represents the assumed production mechanism yielding the $M_{p_s n\pi^+}$ and $M_{d\pi^+}$ enhancements.

given by counting the number of events which do not contribute to the $M_{p_s n\pi^+}$ bump, which is about 160.

III. FURTHER DISCUSSION

Additional support of our interpretation of the $M_{p_s n\pi^+}$ enhancement come from the similarity of the triangle plots shown in Fig. 4 and the study of the t_d distributions, t_d being the momentum transfer between the incoming d and the outgoing $p_s n$ system. The triangle plots of $M_{\bar{p}\pi^-}$ versus $M_{p_s n\pi^+}$ and of $M_{\bar{p}\pi^-}$ versus $M_{d\pi^+}$ taken from the $\bar{p}d\to\bar{p}d\pi^+\pi^-$ reaction[3] are presented in Figs. 4(a) and 4(b). One observes here that the $M_{p_s n\pi^+}$ as the $M_{d\pi^+}$ enhancement is associated with $\bar{\Delta}^{--}(1236)$ production. The exchange diagrams shown in this figure represent the assumed production mechanism yielding the $M_{p_s n\pi^+}$ and $M_{d\pi^+}$ enhancements. The t_d distributions obtained either from the sample of 812 or 427 events show an exponential behavior and were fitted with $e^{b_i t_d}$-type functions. Taking scanning losses into account, we obtain the fitted slopes (b_i) presented in Table I. In contrast to $b_1=6.2$ (GeV/c)$^{-2}$, the large b_2 and b_3 values indicate that we are dealing with coherent production yielding, however, to a final state having a broken deuteron.[5]

From the diagrams presented in Figs. 4(a) and 4(b) a rough estimate of the ratio of events contributing to the d^* bump with and without a broken deuteron in the final state can be given by $R=\bar{\sigma}_{\rm in}/\bar{\sigma}_{\rm el}$. Here $\bar{\sigma}_{\rm in}$ and $\bar{\sigma}_{\rm el}$ are, respectively, the integrated pion differential $\pi d\to\pi pn$ and $\pi d\to\pi d$ cross sections averaged over an energy interval of $2.04<M_{p_s n\pi^+}<2.50$ GeV/c^2. This interval corresponds approximately to the observed mass range of the $M_{p_s n\pi^+}$ enhancement. We calculate $\bar{\sigma}_{\rm in}$ and $\bar{\sigma}_{\rm el}$ by means of the first-order impulse approximation using the ground-state deuteron form factor deduced from the Hulthén wave function and πN phase shifts as proposed in Refs. 3 and 4; hence $\bar{\sigma}_{\rm in}/\bar{\sigma}_{\rm el}\sim 1.3$. Based on the same experimental material and taking scanning losses into account, one obtains for the $\bar{p}d\to\bar{p}d\pi^+\pi^-$ reaction the corrected number of 232 events which contribute to the $M_{d\pi^+}$ peak[3], while 355 produce the $M_{p_s n\pi^+}$ enhancement. For estimating this latter number we use the assumed symmetry properties of the plot of Fig. 3. We obtain thus an experimental ratio $R\sim 1.5$, the same order of magnitude as $\bar{\sigma}_{\rm in}/\bar{\sigma}_{\rm el}$. Let us note that in the framework of this model, bumps at $M_{pn\pi}=2.2$ GeV/c^2 should be observed in any experiment using deuterons as targets and for which reactions with π exchange in the t channel are present. For meson beams the $M_{pn\pi}$ peak can be partly suppressed because selection rules can forbid π exchange. However, for $\bar{N}N$ or NN interactions, such exchanges seem to contribute in a rather important way to the production, at least

TABLE I. Slopes obtained by fitting the various t distributions with exponential functions.

Samples used	Slopes (GeV/c)$^{-2}$	$\lvert t\rvert$ range (GeV/c)^2
812 events	$b_1=\ 6.2\pm0.6$	0.03 – 0.42
427 events	$b_2=14.9\pm0.8$	0.03 – 0.24
222 events in the d^* band	$b_3=16.6\pm1.1$	0.03 – 0.24

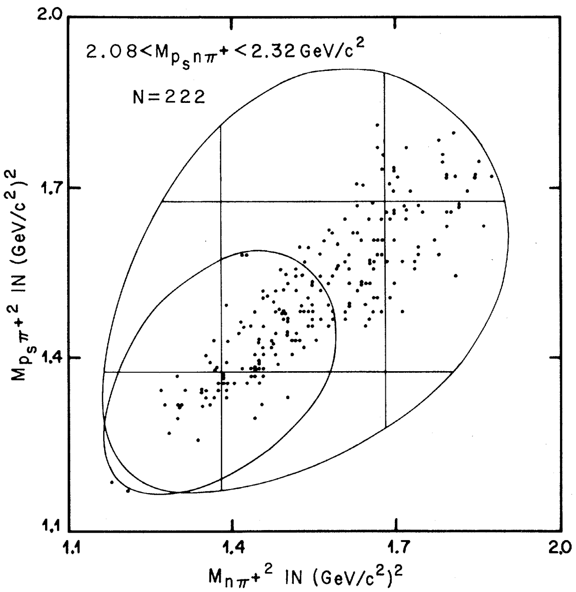

FIG. 5. Dalitz plot for the events in the d^* band. The small and large contours are obtained from the 2.2- and 2.3-GeV/c^2 $M_{p_s n\pi^+}$ values, respectively. The lines represent the bands which correspond to the full Δ^{++} and Δ^+ widths.

for the c.m. energy region considered here.[6,7]

The full curve in Fig. 2(a) represents the fit to the $M_{p_s n\pi^+}$ mass distribution using an incoherent mixture of peripheral phase space and a Breit-Wigner function. This peripheral phase space was obtained by the Monte Carlo method weighting each event by an $e^{b_2 t_d}$ factor. Although we do not interpret the $M_{p_s n\pi^+}$ bump as a real resonance, we use a Breit-Wigner function because it gives a good description of the $M_{p_s n\pi^+}$ and $M_{d\pi^+}$ spectra[3] around 2.2 GeV/c^2. This allows us to obtain the position and width of the peak, i.e., $M_0 = 2.20 \pm 0.01$ GeV/c^2, $\Gamma = 0.15 \pm 0.02$ GeV/c^2, which are nearly equal to the values obtained for the $\bar{p}d \to \bar{p}d\pi^+\pi^-$ reaction ($M_0 = 2.19 \pm 0.01$ GeV/c^2, $\Gamma = 0.18 \pm 0.02$ GeV/c^2) at 5.55 GeV/c.[3]

The Dalitz plot for the events which are in the d^* band (Fig. 5), defined as $2.08 < M_{p_s n\pi^+} < 2.32$ GeV/c^2, shows that most of the events are simultaneously in the Δ^{++} and Δ^+ bands. It is then difficult to see if part of the 2.2-GeV/c^2 $M_{p_s n\pi^+}$ peak can arise from a real resonance decaying into ΔN. In terms of a one-particle or trajectory-exchange model, such a resonance would be emitted at the deuteron vertex in a isospin $I = 1$ state, if one disregards exotic exchange in the t channel. One would then obtain a branching ratio $(d^* \to \Delta^{++}n)/(d^* \to \Delta^+ p) = 9$. As the $\Delta^{++}n$ decay mode should be dominant, we have examined the neutron angular distribution for the events in the d^* band. This angular distribution is given in the ΔN rest frame with respect to the ΔN line of flight defined in the over-all $\bar{p}d$ c.m. system. This distribution is not symmetric as it should be for a real ΔN resonance if one neglects the $d^* \to \Delta(n\pi^+)p$ decay. The asymmetry parameter is found to be $F/B = 198/22$, where F and B are the numbers of neutrons going in the forward and backward hemispheres, respectively. The symmetric part of this distribution gives an upper limit to the number of events (44) for which the interpretation in terms of a ΔN resonance cannot be ruled out. In any case, clear evidence for the existence of such a resonance would be difficult to obtain because one needs reactions with at least two baryons in the final state. The use of NN interactions requires baryon exchange in the t channel and represents then a small contribution with respect to the dominant peripheral nature of the NN interactions.[8]

IV. CONCLUSION

We see that an important part of the events identified as belonging to the $\bar{p}d \to p_s\bar{p}\pi^+\pi^- n$ channel cannot be considered as having a nucleon spectator in the final state. The way of extracting these events (427) is based primarily on the fact that for the $p_s\bar{p}\pi^+\pi^- n$ sample which remains, the p_s show the expected nucleon-spectator behavior. Most of the 427 events selected for the present analysis contribute to a strong 2.2-GeV/c^2 $M_{pn\pi^+}$ enhancement similar to that observed in the $M_{d\pi^+}$ mass spectrum for the $\bar{p}d \to \bar{p}d\pi^+\pi^-$ reaction. We observe also that the distribution of the momentum transfer between the initial deuteron and the outgoing $p_s n$ system shows the characteristic coherent-production feature. We interpret, therefore, the observed $M_{p_s n\pi^+}$ enhancement as being of the same origin as the $M_{d\pi}$ bump, i.e., caused by the π exchanged in the t channel which scatters off the deuteron. This interpretation is supported by the strong similarity between the triangle plots of $M_{\bar{p}\pi^-}$ versus $M_{p_s n\pi^+}$ and $M_{\bar{p}\pi^-}$ versus $M_{d\pi^+}$ obtained from the $\bar{p}d \to \bar{p}d\pi^+\pi^-$ reaction at the same energy. Also, the number of events extracted from the present experiment and contributing to the $M_{p_s n\pi^+}$ and $M_{d\pi^+}$ bumps have the same order of magnitude as predicted by the $\bar{\sigma}_{\rm in}/\bar{\sigma}_{\rm el} \sim 1.3$ ratio. Comparisons between the $\bar{p}d \to p_s\bar{p}\pi^+\pi^- n$ and $pd \to p_s p\pi^+\pi^- n$ reactions at the same energy would be particularly useful to check whether the same amount of d^* is produced for both reactions as predicted by the model used here.

V. ACKNOWLEDGMENTS

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[8]See, for instance, G. Alexander *et al.*, Phys. Rev. 154, B1284 (1967).

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Attempt to Determine the Elastic Proton-Nucleon Cross Section at 83 GeV

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An attempt has been made to measure the proton-nucleon elastic cross section using primary cosmic-ray protons with a mean energy of 83 GeV. A total of 10 m of primary proton tracks has been line-scanned for stars resulting from elastic scatterings on nucleons bound in emulsion nuclei. The probability of detecting an elastic scatter in emulsion is considered using an analysis similar to that of McCusker. Two elasticlike scatters were found, but these can be shown to be random track-intersection coincidences, consistent with the number of proton recoils expected from neutron stars. No elastic scatters in a path length of 10 m have been found. A Monte Carlo analysis, modeled after the suggestions of Goldberger and the calculations performed by Bernardini, has been used to calculate the probability of obtaining an observable proton associated with an elasticlike event in photographic emulsion. This analysis of the detection probability of an elastic scatter indicates that the proton-nucleon elastic cross section at 83 GeV is no greater than 3 mb with 95% probability.

I. INTRODUCTION

Previous Investigations

There have been some previous reports on measurements of the proton-nucleon elastic cross section at cosmic-ray energies. A line scan, in photographic emulsion, of tracks of protons having an average energy 3 TeV has been reported by McCusker *et al.*[1,2] No elastic scatters were detected in a scanned length of 5.9 m. A calculation of the probability of detecting an elastic scatter in emulsion within this path length yielded the proton-nucleon elastic cross section at 3 TeV to be less than 8 mb with 95% probability. A similar analysis by Rybicki[3] yielded three elasticlike events in a path length of 5.8 m for protons with energies above 1 TeV. The collected data, reported by Rybicki, yielded an elastic proton-nucleon cross section of $3.8^{+13}_{-1.5}$ mb at an incident proton energy of approximately 3 TeV.

In the report of McCusker, a calculation was performed to determine the probability of observing a proton resulting from an elasticlike collision of an incident proton with a nucleon in an emulsion nucleus. The probability is calculated that this struck nucleon escapes from the nucleus or is captured, with the excitation energy possibly contributing to observable particles escaping from the nucleus. McCusker's calculations neglected the effect of the Coulomb barrier, charge exchange, Fermi motion of the bound nucleons, and the exclusion principle.

Rybicki's analysis was based on the fraction of