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A STUDY OF DOUBLE SCATTERING EFFECTS§ IN ANTIPROTON-DEUTERON ANNIHILATION*

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ABSTRACT

The double scattering process in the deuteron is investigated for the reaction $\bar{p}d \to p_s$ + mesons. About 30% of the apparent $\bar{p}n$ annihilations are involved in double scattering. A model which describes the properties of protons emerging from apparent $\bar{p}n$ annihilations is presented.

DATA

The data came from a 150,000 triad exposure taken at the Brookhaven National Laboratory 31-inch deuterium filled bubble chamber using an antiproton beam of momenta from 1.09 to 1.43 GeV/c. The sample used in this study contained events in which the antiproton appears to interact with the neutron and produce 3 or 5 charged secondaries. These events will have either 3, 4, 5 or 6 outgoing tracks and are referred to as 3, 4, 5 or 6 prong events respectively. All the 3 and 5 prong events were measured. These correspond to the case where the spectator proton does not have enough momentum to produce a visible track. The 4 and 6 prong topologies contain events from both antiproton-proton as well as antiproton-neutron interactions. Therefore, a 4 or 6 prong event was measured only if it had a positive track with an ionization equal to or greater than the ionization of the incident antiproton. A total of 121,399 events were measured. Kinematic fits were then performed on the data. About 40,000 even prong events had π-K-p ambiguities involving the mass

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interpretation of the positive tracks. Therefore, an ionization scan was performed on this sample to determine which of the positive tracks, if any, was a proton. Even prong events without a proton were not used in this analysis. Also, events due to the reactions $\bar{p}d \rightarrow p_s\bar{p}p\pi^-$, $\bar{p}d \rightarrow p_sK^+K^-\pi^-$, or $\bar{p}d \rightarrow p_sK^+K^-2\pi^-\pi^+$ were not used. Further details of the event selection procedure are described elsewhere[1]. The sample of $\bar{p}d \rightarrow p_s$ + mesons used in the analysis contains 58,167 3 or 4 prong events and 25,398 5 or 6 prong events.

EVIDENCE FOR DOUBLE SCATTERING

Figure 1(A) shows the deuteron wave function prediction for the internal Fermi momentum distribution of the deuteron. The prediction was made from the Reid soft core wave function.[2] The momentum distributions of protons emerging from apparent $\bar{p}n$ annihilations in a deuteron target are shown in Figure 1(B-C). If the idea that the deuteron breakup occurs spontaneously when the incident particle interacts with one of the nucleons is indeed correct, the momentum distribution of the spectator nucleon should follow the curve in Figure 1(A). This process will be referred to as single scattering. To compare the momentum distributions of protons emerging from $\bar{p}n$ annihilations to the impulse approximation prediction, the fact that low momentum protons are not always observable in the bubble chamber must be considered. It is shown that protons having a momentum between 70 and 130 MeV/c are systematically lost due to a scanning bias.[1] Protons having a momentum less than 70 MeV/c are not able to produce observable tracks in the bubble chamber. By comparing the data to the impulse approximation prediction above 130 MeV/c, one can see that there is a region of excess above 200 MeV/c. This excess appears to be in the form of a broad peak or bump centered at 300 MeV/c. Similarly, this excess is present when the data are compared with other deuteron wave functions.[3-7]

The probability of finding the deuteron with a neutron-proton separation of r is greatest for $r \approx 2$ fm. This probability is given by $\phi^2(r)r^2$, where $\phi(r)$ is the deuteron s-wave radial wave function. Since the nucleon dimensions are of the order of one fm, both nucleons may be involved in a scattering process. Two possible ways the proton could be involved are depicted in Figure 2. The first diagram (called final state interaction or FSI) describes a pion,

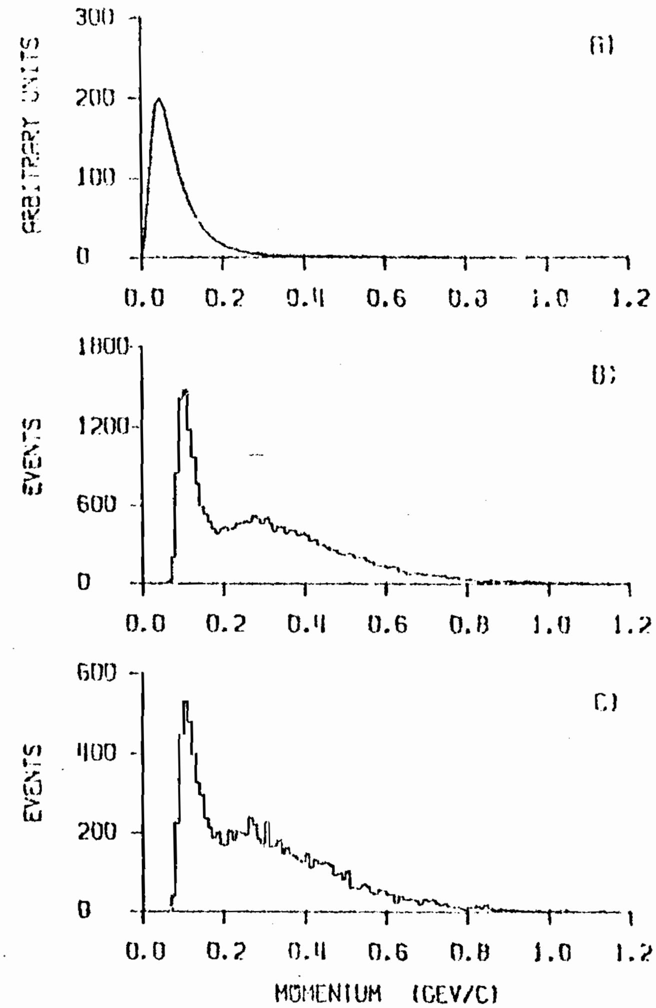

Figure 1. Spectator Momentum Distribution

(A) Reid soft core deuteron wave function
(B) Four prong data
(C) Six prong data

from the $\bar{p}n$ annihilation, interacting with the proton. The second diagram (called initial state interaction or ISI) describes the antiproton elastically scattering from the proton before $\bar{p}n$ annihilation takes place. To determine the presence of FSI and ISI, one must look for features characteristic of these processes.

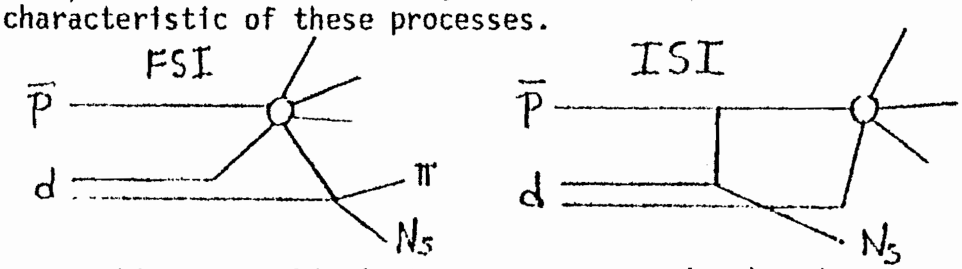

Figure 2. Final State Interaction (FSI) and Initial State Interaction (ISI)

Since FSI results when a pion scatters from the spectator nucleon, production of the $\Delta(1236)$ resonance is expected. Figure 3 shows the π^+p_S and π^-p_S invariant mass distributions. For comparison, the π^-p_S distribution is normalized to the π^+p_S distribution. Only events with spectator momenta above 190 MeV/c were used in the plot. By comparison, one observes a peak in the π^+p_S mass distribution characteristic of the $\Delta(1236)$ resonance. Both π^- and π^+ may scatter from the proton. However, since the π^-p cross section is smaller than the π^+p cross section in the $\Delta(1236)$ mass range, the peak in the π^-p_S mass distribution will not be as apparent as the π^+p_S peak. In addition, there is one more π^- than π^+ in an event, therefore assuming only one pion scatters from the proton, the peak in the π^-p_S mass distribution will have more background than the peak in the π^+p_S mass distribution.

ISI results when the antiproton elastically scatters from one constituent nucleon before annihilation by the other. This elastic scattering imparts a transverse momentum to the spectator nucleon. Therefore, the distribution of the cosine of the laboratory angle between the beam and spectator nucleon should show a bump characteristic of elastic scattering. Fig. 4 shows the cosine distribution for the spectator proton for three spectator momentum ranges. The first range $p < 190$ MeV/c appears to be smooth. A peak at cos (θ) between 0.2 and 0.4 is seen for spectator momenta in the range 190-350 MeV/c. This peak is also observed for spectator momentum greater than 350 MeV/c.

In summary, properties of protons emerging from apparent $\bar{p}n$-like annihilation can not be described by a simple impulse model. The discrepancies can be seen in the spectator momentum distribution, the invariant mass of the $\pi^+ p_S$ and $\pi^- p_S$ systems, and the cosine of the angle between the spectator proton and the beam. These distributions show features characteristic of double scattering.

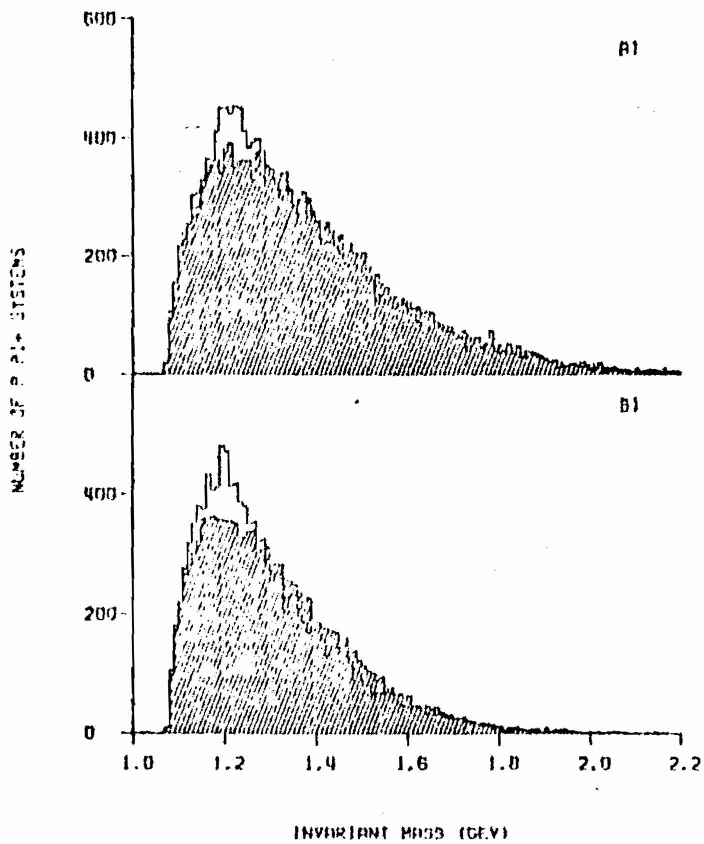

Figure 3. Invariant Mass Distributions of $\pi^+ p_S$ (unshaded) and $\pi^- p_S$ (shaded) Systems for 4 prong events (A) and 6 prong events (B) The $\pi^- p_S$ distribution has been normalized to the $\pi^+ p_S$ distribution.

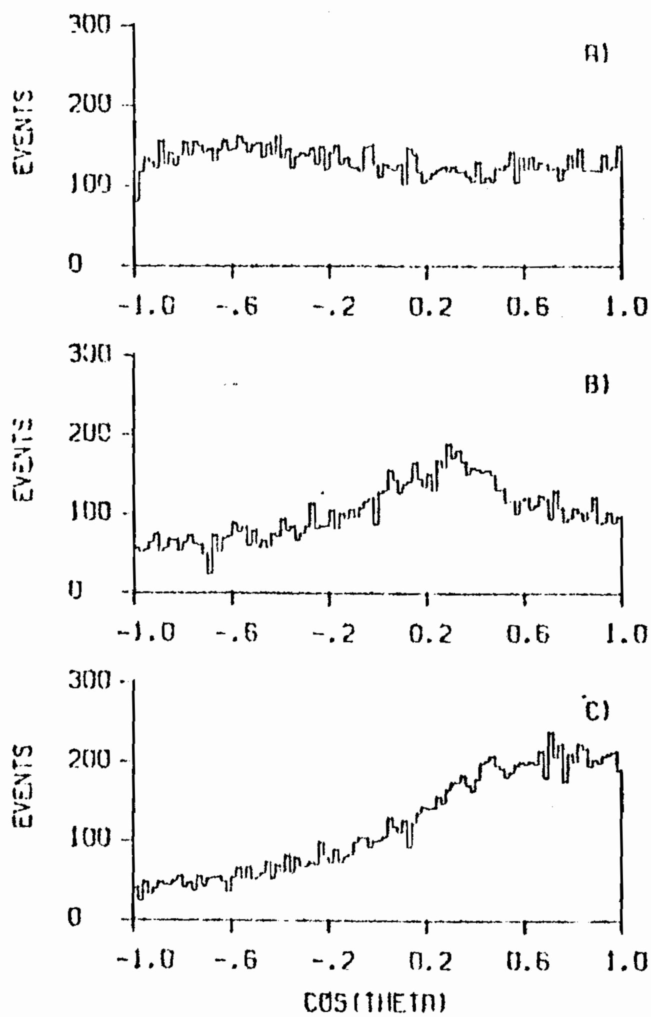

Figure 4. Laboratory Cosine Distribution of Protons:

A) $p < 190$ MeV/c
B) $190 \leq p \leq 350$ MeV/c
C) $p > 350$ MeV/c

FINAL STATE INTERACTION

Effects which are attributed to FSI have been observed in other data.[8-9] However, a complete and detailed description of the FSI process has not been attempted. In this section, a model describing FSI in the reaction $\bar{p}d \to p_S$ + pions is developed.

The probability that a pion from the annihilation will interact with the spectator depends on the neutron-proton separation. This probability is greater for small values of n-p separation. By Fourier transform, the internal Fermi momentum of the deuteron will be larger for smaller values of the neutron-proton separation. Therefore, FSI will have a greater probability to occur if the internal Fermi momentum of the deuteron is large. To incorporate this feature in the model, the following amplitude for FSI was assumed:

$$F(r) = Cf_{\pi N} \frac{\phi(r)}{r} \qquad (1)$$

Here, $\phi(r)$ is the radial deuteron wave function and $f_{\pi N}$ is the πN scattering amplitude. C is a normalization constant. The factor 1/r, which can be thought of as the amplitude for a spherical wave of pions, takes account of the fact that FSI has a greater chance to occur if r is small. To obtain the momentum space representation of F(r), the Fourier transform was used:

$$G(p) = C'f_{\pi N} \int \frac{\phi(r)}{r} e^{-ip.r} d^3r \qquad (2)$$

$$= C'f_{\pi N} \, g(p), \qquad (3)$$

where p is the internal Fermi momentum and C' is a constant. In performing the integral over r, it was assumed that $f_{\pi N}$ could be taken outside the integration. This assumption is valid because $f_{\pi N}$ does not explicitly depend on r. Then, the probability for FSI, expressed in momentum space, is given by:

$$P(p) = 4\pi C'^2 \sigma_{\pi N} \, g^2(p) p^2. \qquad (4)$$

FSI is dominated by πN elastic or charge exchange scattering. This dominance is caused by two factors. First, a large fraction of the pions produced by the annihilation are below threshold for pion production. Second, the πN cross sections are largest in the region below the pion production threshold. Therefore, only elastic or two body charge exchange scattering will be considered.

To describe the effects of FSI, $\bar{p}n$ and $\bar{p}p$ annihilation events were generated using the Monte Carlo event generating program SAGE.[10] The proton and neutron were assumed to have equal but opposite momentum values given by the momentum distribution $\phi^2(p)p^2$. The generated event was weighted by the flux factor to account for the Fermi motion of the target. Since annihilations in the momentum range examined here usually produce less than eight pions, annihilations producing up to seven pions were considered. The probability that one of the pions resulting from the annihilation will scatter from the remaining nucleon depends on the pion-nucleon invariant mass. The cross section ($\sigma_{\pi N}$) and angular distribution of pions in the double scattering process are given by the phase shift analysis of Donnachie, Kirsopp and Lovelace.[11] For each type of annihilation, the fractional amount of FSI for the following three categories was determined:

1) $\bar{p}p$ annihilations having a $\bar{p}n$ topology due to charge exchange scattering FSI

2) $\bar{p}n$ annihilations having a $\bar{p}p$ topology due to charge exchange scattering FSI

3) $\bar{p}n$ annihilations having a $\bar{p}n$ topology and involving elastic scattering FSI.

To compare the model to the data, only the Monte Carlo events in categories 1 or 3 were used. The category 2 events are not present in the measured sample. The Monte Carlo events were used to predict the spectator momentum distribution, the π^+p_s invariant mass distribution, and the cos (θ) distribution. These three distributions were generated for three or four prong and five or six prong topologies by combining the Monte Carlo events of the appropriate reactions. To combine the Monte Carlo events, the number of events in the distribution from the ith reaction is given by:

$$N_i \propto \sum_j P_j(p)\,\sigma_i \qquad (5)$$

Here σ_i is the cross section for the ith $\bar{p}$N reaction. In addition, the cos (θ) and invariant mass distributions contain only the events with proton momentum greater than or equal to 190 MeV/c. The values of σ_i were obtained elsewhere.[1,12-16] Values for σ_i involving multi-π° production were calculated using the Fermi statistical model.[17,18]

INITIAL STATE INTERACTION

It is possible for the incident antiproton to elastically scatter from the proton before the $\bar{p}$n annihilation takes place. This process will be referred to as initial state interaction or ISI. ISI will tend to give the proton a momentum in a direction transverse to the beam direction similar to that in elastic scattering. Therefore, ISI must explain the bump in the cos (θ) distribution. The momentum transfer between the antiproton and the proton is given by $d\sigma/dt = (d\sigma/dt)_0 e^{At}$. In the momentum range used here $A = 17.5\ (\mathrm{GeV/c})^{-2}$ and the total $\bar{p}$p elastic cross section is 42 mb.[19,20]

Monte Carlo events for ISI were generated for $\bar{p}$n annihilations producing up to seven pions. The Fermi momentum distribution of the deuteron was given by $\phi^2(p)p^2$. The probability of double scattering was assumed to be proportional to $g^2(p)p^2$. This distribution was used to account for the fact that small pn separations have a greater chance to result in a double scattering. The ISI Monte Carlo events were combined into three or four prong and five or six prong groups. This was done by requiring the number of Monte Carlo events in the group from each $\bar{p}$n reaction to be proportional to the cross section for that reaction. Then, the events in each group were used to produce distributions of spectator momentum, $M(\pi^+p_s)$, and cos (θ).

FITS TO THE DATA

To determine how well the data can be described by FSI and ISI, fits were made to the data using the spectator distribution, the invariant mass distribution $M(\pi^+p_s)$, and the cos (θ) distribution. Only the events with spectator momentum greater than 190 MeV/c were included in the cos (θ) and invariant mass distributions. In this region the data are dominated by the FSI and ISI processes. This region is used so the $\Delta(1236)$ signal in the π^+p_S invariant mass distribution can be enhanced. Since the π^+p_S scattering is elastic, the invariant mass is not modified. Only by selecting a sample of events in which the π^+ scatters from the spectator proton, can the $\Delta(1236)$ signal in the invariant mass distribution be observed.

Also the spectator momentum, cos (θ), and invariant mass distributions were calculated for single scattering events. However, because FSI and ISI are more probable when the internal Fermi momentum of the deuteron is high, the shape of the single scattering spectator distribution is modified from the usual $\phi^2(p)p^2$. Spectator protons with a momentum distribution given by $\phi^2(p)p^2$ were generated and then randomly selected, using a probability proportional to $g^2(p)p^2$, to be involved in double scattering. The fractional amount of double scattering was required to be consistent with the amount of double scattering in the data. The modified single scattering spectator proton momentum distribution is given by the momentum distribution of the protons not involved in double scattering. These distributions are shown in Figures 5(D) and 6(D). These figures show that there is no single scattering above 190 MeV/c. Figures 5(E-F) and 6(E-F) show how the invariant mass and cosine distributions for single scattering events with spectator momentum greater than 190 MeV/c would appear if there were no double scattering.

Fits were made to the data using the double scattering distributions. The fits were made by assuming that the data distributions are sums of the Monte Carlo distributions, shown in Figures 5(G-L) and 6(G-L), for the FSI and ISI contribution. That is, the data distributions were assumed to be given by:

$$F(P) = B\, F_{FSI}(p) + D\, F_{ISI}(p), \qquad (6)$$

$$C(\cos\theta) = B\, C_{FSI}(\cos\theta) + D\, C_{ISI}(\cos\theta), \qquad (7)$$

and $$M(\pi^+p_S) = B\, M_{FSI}(\pi^+p_S) + D\, M_{ISI}(\pi^+p_S). \qquad (8)$$

The subscript FSI and ISI stand for final state interaction and initial state interaction respectively. To perform the fits, the integrals of the Monte Carlo events in the fitted region were required to be unity. Then, the values of B and D are equal to the number of FSI and ISI events in the fitted region. Figures 5(A-C) and 6(A-C) show that the data are well described by the model. The results of these fits are summarized in Table 1.

Table 1

Summary of Fits

	3-4 Prong	5-6 Prong
Total events	58167	25398
Events in Fitted Region	15891	6188
FSI Events in Fit	12395±758	4383±307
ISI Events in Fit	3072±240	1629±184
Total FSI Events	15474±946	5504+385
Total ISI Events	4376±341	2317±262
Fractional amount of FSI	.266±018	.217±0.15
Fractional amount of ISI	.053±.004	.064±.007

Since there are no single scattering events above 190 MeV/c, the amount of single scattering can not be found by using these fits. However, since there are events in the data having visible spectators with momenta values below 190 MeV/c, it is of interest to see how well these events can be described. Therefore, the number of events in the modified single scattering momentum distribution, N_{SS}, plus the total number of FSI and ISI events, $N_{FSI} + N_{ISI}$ was required to be equal to the total number of events in the data, N_d. The resulting normalization gives excellent agreement with the data in the 130-190 MeV/c regions of the spectator momentum distribution (see Figures 5(A) and 6(A)). Because of elastic charge exchange scattering, FSI can interchange characteristics of the "$\bar{p}p$" and "$\bar{p}n$" topologies. This effect occurs when a pion from the annihilation scatters, via a charge exchange process, from the spectator nucleon. Since "$\bar{p}p$" or "$\bar{p}n$" topologies are characterized by the presence of a spectator neutron (n_s) or proton(p_s) respectively, charge

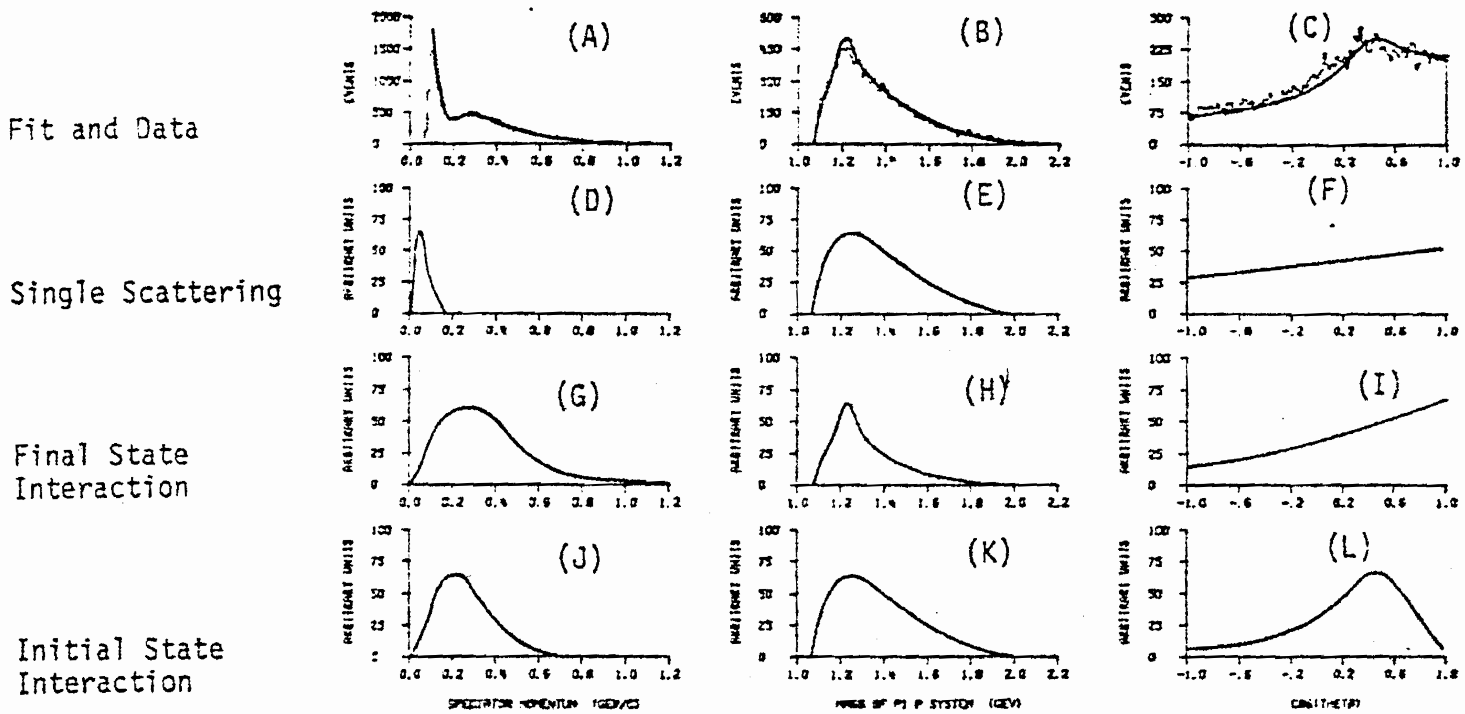

Figure 5. Three and Four Prong Fit and Data

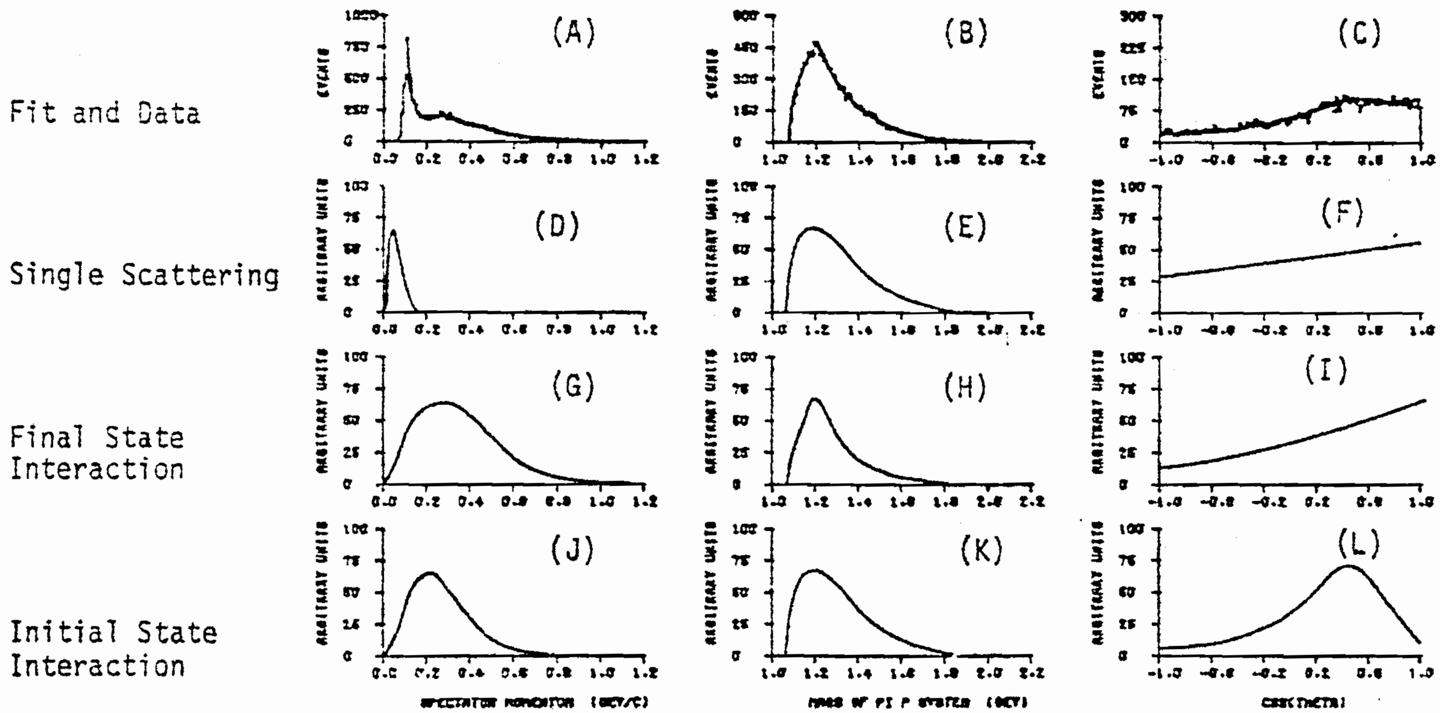

Figure 6. Five and Six Prong Fit and Data

exchange FSI will interchange these topologies. Table 2 shows the amount of topology interchange predicted by the model.

Table 2

Topology Interchange Effect

	3-4 Prong	5-6 Prong
Fractional amount of fake $\bar{p}n$ events in the data	.069	.041
Fractional amount of $\bar{p}n$ annihilations having a $\bar{p}p$ topology	.095	.062

CONSIDERATIONS OF POSSIBLE ΔΔ STATES IN THE DEUTERON

In most cases, the deuteron is well known to be a bound neutron-proton system. However, it is possible for the deuteron to exist as a virtual ΔΔ state for a fraction of the time. This virtual state must have the same quantum numbers of the deuteron. This conjecture was used to describe the magnetic moment of the deuteron.[21-22] Two possible states, which have been the subject of both theoretical and experimental work[21-30] are the $\Delta^{++}\Delta^{-}$ and $\Delta^{+}\Delta^{o}$ states. Previous experimental works attempt to detect the ΔΔ state by observing backward spectator $\Delta(\Delta_s)$ produced in deuteron break-up reactions.[26-30] To establish the existence of the ΔΔ state in such a direct manner, one must be certain that the observed Δ signal corresponds to spectator Δ_s because there are other mechanisms, such as FSI, which can produce a Δ. This is done by examining kinematic regions which have as little background as possible. Since the existence of ΔΔ states implies the existence of a spectator Δ, one expects to observe Δ_s in the backward direction. Previous experimental studies[26-30] make use of this fact since the background from other processes is expected to be smaller in the backward direction. In this work double scattering models are used to predict the angular distribution. An increase over this background would require existence of ΔΔ states.

To establish the existence of a possible $\Delta\Delta$ state, a set of Δ_S^{++} candidates is defined. The π^+p_S mass is required to be in a range 1180-1300 MeV. The momentum of the proton was required to be greater than 190 MeV/c. Figure 7 shows the distribution of the cosine of the laboratory angle between the beam and the π^+p system. The data appears to be well described by the double scattering model. In particular, no excess of backward π^+p systems is observed. The $\Delta\Delta$ state is not needed to describe the distribution examined here.

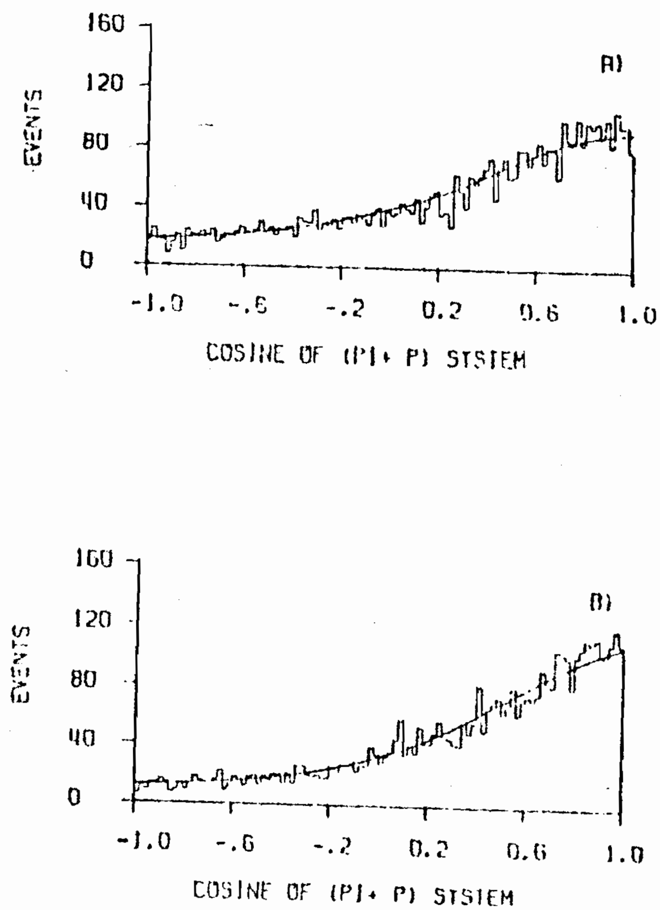

Figure 7. Cosine of the laboratory angle between the beam and π^+p_S system. (A) 4 prong events, (B) 6 prong events

CONCLUSIONS

The characteristics of protons emerging from apparent $\bar{p}n$ annihilations are well described by the double scattering model presented here. Since a sizeable fraction (about 30%) of the events involve double scattering, the process must be considered in $\bar{p}d$ annihilations. In particular, it is important to consider the effect of double scattering on the spectator nucleon. In addition to an excess of high momentum spectators, double scattering causes a topological interchange. These effects are important if the deuteron is used to determine $\bar{p}n$ reaction cross sections. The double scattering model was used to predict the laboratory cosine distribution of Δ. Since this distribution agrees with the data very well, the existence of the $\Delta\Delta$ state is not necessary to describe the data.

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