Reactions Induced by Heavy Ions," Commissariat à l'Energie Atomique Report (unpublished), p, 26.

[7]R. A. Chatwin, J. S. Eck, D. Robson, and A. Richter, Phys. Rev. C 1, 795 (1970).

[8]E. H. Auerbach *et al.*, Phys. Rev. Lett. 30, 1078 (1973).

[9]J. G. Cramer, private communication.

[10]K. Kemper, private communication.

Backward $\bar{p}p$ Charge Exchange from 1 to 3 GeV/c*

J. Storer,† D. Cutts,‡ M. L. Good, P. D. Grannis, D. Green,§ Y. Y. Lee,‖ and R. Pittman¶
State University of New York, Stony Brook, New York, 11790

and

A. Benvenuti, G. C. Fischer,** and D. D. Reeder
University of Wisconsin, Madison, Wisconsin 53706

(Received 13 March 1974)

We have measured the differential cross section for $\bar{p}p \to \bar{n}n$ near 180° in the center of mass for incident $\bar{p}$ momenta between 1 and 3 GeV/c. A backward peak is observed at all energies, whose slope increases with increasing momentum. The s dependence shows some departure from smooth behavior. The magnitude of backward charge-exchange scattering is comparable to backward elastic scattering and thus rules out a diffractive interpretation of the s-dependent structure.

We report here a measurement of the differential cross section, $d\sigma/du$, for the reaction $\bar{p}p \to \bar{n}n$ near 180° in the center of mass (c.m.) for $\bar{p}$ momenta between 1 and 3 GeV/c. These data are a part of larger study of $\bar{p}p$ charge exchange; details of the apparatus and method, together with results on the reaction cross section, are available elsewhere.[1] Our aims in this study have included the study of high-mass meson states formed in $\bar{N}N$ collisions; such states have been suggested in previous experiments.[1-5] Further interest has been generated by the results[6,7] on backward $\bar{p}p$ elastic scattering in which rather pronounced s-dependent structure was observed. The suggestion has been advanced[6] that this structure could be secondary diffraction minima passing through the $\theta_{\text{c.m.}} = 180°$ region as energy is varied. Backward $\bar{p}p$ charge exchange is free from such diffractive contributions.

The experimental problems in studying backward $\bar{p}p$ charge exchange are first to isolate the reaction and second to distinguish scattering near 180° from the kinematically identical scattering near 0°. The apparatus is shown in Fig. 1. The incident $\bar{p}$ beam passed through three 12-in. hydrogen target segments; the targets were completely surrounded, apart from a beam entrance hole, by a set of counters A_c whose purpose was to veto events with charged secondaries. Outside A_c were two sets of scintillator and heavy metal arrays, S and A_γ. The arrays S, located to either side of the target and covering about half the azimuth, consisted of five scintillator planes sandwiching 1-in. iron layers. The remaining solid angle was covered by the lead-sandwich A_γ counters. An iron-scintillator hodoscope, F, permitting x-y definition to within a 4-in. square was located at a variable distance downstream from the target. Arrays S and A_γ detected the γ's produced in final states containing π^0's. In addition, S distinguished $\bar{n}$ from n by requiring elements of at least four of the five planes to count. F was used for a fraction of the events to record the forward-going n or $\bar{n}$.

An event triggered the apparatus when a $\bar{p}$ entered the target and no charges emerged. Further preselection was made off-line by requiring a count in those two planes of S whose photomultiplers were at opposite ends, thus permitting determination of the time and the spatial location of the interaction in S. The charge-exchange events were selected from this sample by requiring that the measured time of the pulse in S was greater than 10 nsec later than the expected time for a γ produced in the target. A sample time spectrum is shown in Fig. 2. A check of the purity of the remaining events was made for that subset which included a count in F; for this subset, the coplanarity of the two observed tracks was found to be consistent, within the resolution of

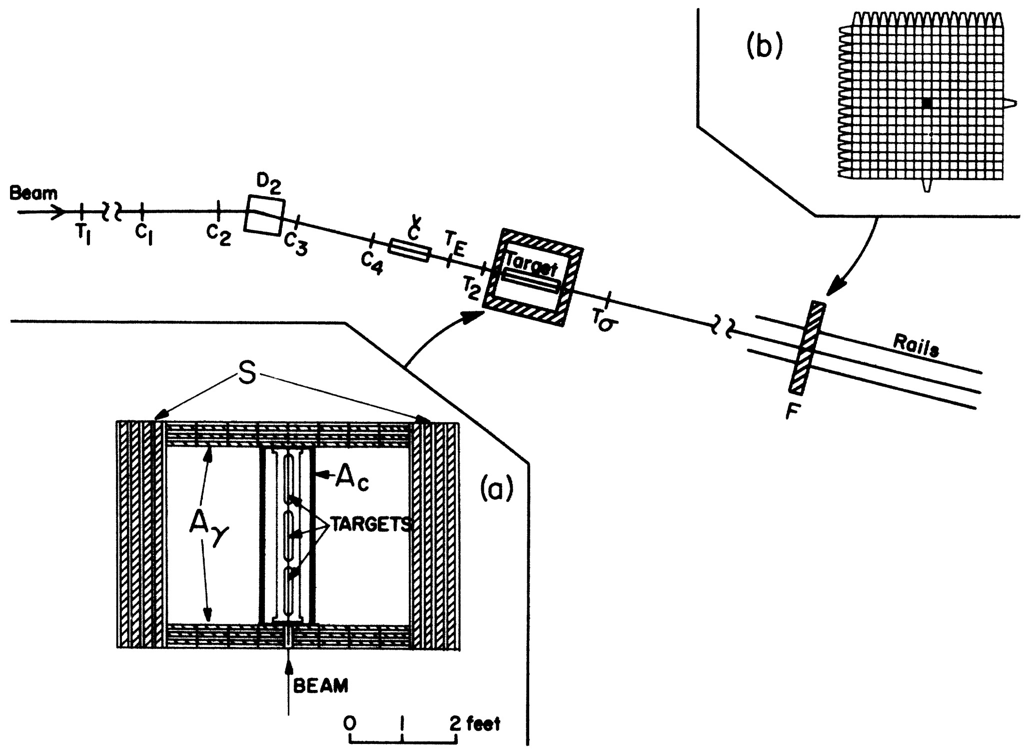

FIG. 1. Schematic layout of the experiment. Scintillators T_1, T_E, T_2 defined the beam, Čerenkov $\check{C}$ identified π's, and proportional wire chambers $C_1 - C_4$ measured the horizontal coordinate before and after magnet D_2. Inset (a) shows the target region (top view). Scintillator box A_c surrounded the three target segments. A_γ was a lead-scintillator array. Hodoscope S was five planes of scintillator separated by steel sheets. Scintillator T_σ was used to monitor beam transmission. Hodoscope F contained six planes of scintillator and steel and moved along the beam axis. Inset (b) shows the subdivision of F into a 17×17 array perpendicular to the beam direction.

the apparatus, with no γ contamination.

The separation of backward-scattering events

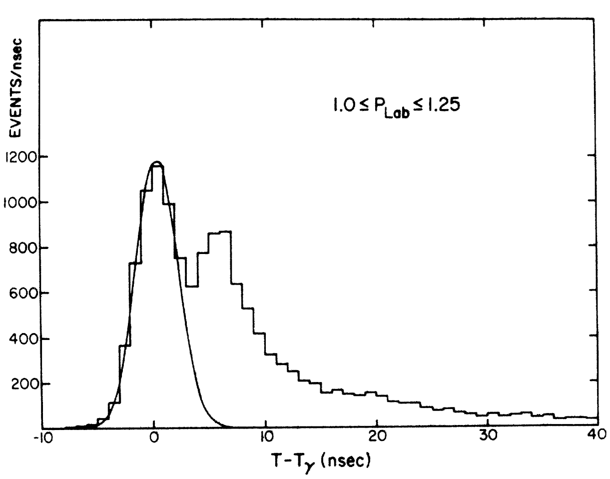

FIG. 2. Distribution of events versus $T - T_\gamma$, where T is the observed time of flight between incident $\bar{p}$ and count in S and T_γ is the expected time of flight for γ. The solid line is a fit to the γ peak. Good charge-exchange events were required to have $T - T_\gamma > 10$ nsec.

from this purified sample of charge-exchange events used the properties of the S arrays. The probability of a slow neutron interacting and being seen in any one scintillator plane is about 7%; thus the probability of a slow neutron (from $\bar{p}p \to \bar{n}n$ near 0°) interacting in four or five planes is negligibly small. Slow $\bar{n}$'s (from $\bar{p}p \to \bar{n}n$ near 180°) annihilate in the iron or plastic giving several energetic charges. In some cases, fewer than five planes are struck as a result of the stopping of charged pions, neutrals among the annihilation products, or loss of annihilation products at the edge of the detector. We have demanded that at least four planes show counts in order to identify an event as backward charge exchange. To examine the effectiveness of this requirement, we have analyzed all those charge-exchange events which showed counts in both F and S. From them we extracted two classes: (a) those with small showers (one or two squares) in F, and (b) those with large showers (seven or eight squares). Class (a) contains an enriched sample of n's in F (hence backward scattering),

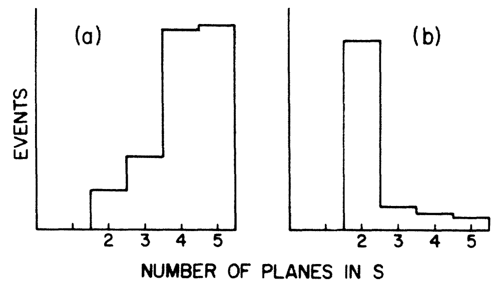

FIG. 3. Distribution of events with both F and S counts versus number of planes of S struck. (a) Small shower in F (one or two squares); (b) large shower in F (seven or eight squares).

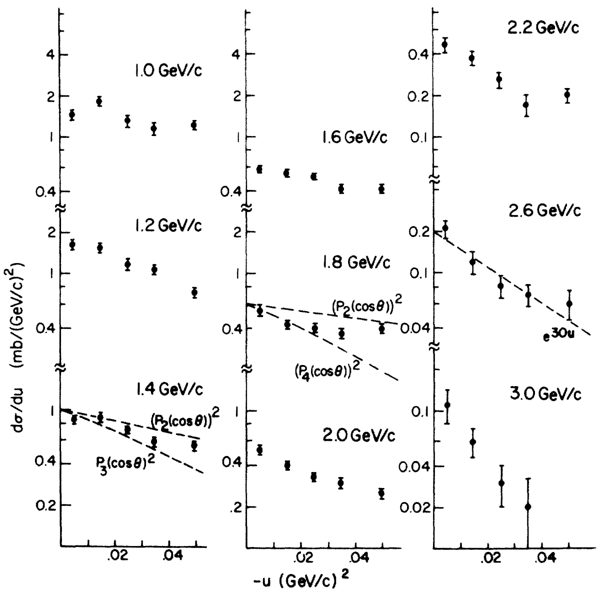

FIG. 4. Differential cross section for $\bar{p}p\to\bar{n}n$ versus u. The dashed lines are representive functions normalized to the data for reference.

and class (b) contains mostly $\bar{n}$'s in F (forward scattering). For these two classes we compare the number of planes struck in S. The results are shown in Fig. 3. The striking difference in the two classes is apparent. Making the extreme assumption that all class-(a) events are backward scattering and all class-(b) events are forward scattering leads to the upper limit on the contamination in our backward sample of 1.5% due to forward charge exchange.

Various corrections must be applied to obtain the differential cross sections. The most sensitive of these is the $\bar{n}$ detection efficiency. In order to record a good event, the $\bar{n}$ must escape from the target and A_c without interacting and nullifying the trigger. Further, it must annihilate in S and produce the four-plane signature. These corrections have been calculated using assumed $\bar{n}$ cross sections. In the heavy nuclei we have taken $\sigma=\pi(R+\lambda)^2$, where R is the nuclear radius and λ is the de Broglie wavelength; for hydrogen we use $\sigma(\bar{n}p)=86/\beta_{\rm lab}$. The hydrogen cross section is an extrapolation of $\sigma(\bar{p}p)$ from data above 350 MeV/c,[3,8] with the matrix elements for $\bar{N}N$ scattering assumed constant over the region $0\leq T_{\rm c.m.}\leq 32$ MeV.[9] We have checked that the hydrogen cross section assumed is reasonable by studying the number of events observed as a function of $\bar{n}$ path length in hydrogen[10]; this study rules out the possibility of large cross sections at low momenta. Inclusion of the geometric efficiency of S and the small effect due to some annihilations striking fewer than four planes has been made with a simple Monte Carlo program. The resulting detection probability for observing an $\bar{n}$ directed toward S is between 0.4 and 0.5; the geometric efficiency of the detector is about 0.5.

Other, more straightforward, corrections to the data include the attenuation of incident $\bar{p}$'s in the target, veto of trigger or event selection due to accidental counts in A_c or A_γ, neutron interactions in hydrogen, A_c, and A_γ, and accidental counts in the S array satisfying the $\bar{n}$ requirements. This latter effect is attributed to γ showers from unrelated events and contributes uniformly in time of flight and thus primarily at small u. Statistical errors from these sources are included in the data. Finally, small corrections are applied for target-empty events and loss of events in the logic due to electrical noise in the experimental hall.

Representative differential cross sections are shown in Fig. 4 for $|u|<0.06$ (GeV/c)^2; this limit is imposed by the cut required to safely eliminate events with γ's. The overall normalization uncertainty of the experiment is ±30% and is due primarily to the uncertainly in $\bar{n}$ detection efficiency. The primary features of the data include (a) a backward peak at all energies studied; (b) a significant increase in the slope of this peak between 1 and 3 GeV/c. The s dependence of the 180° cross section is shown in Fig. 5, together with the corresponding backward $\bar{p}p$ elastic cross sections.[6] Our data indicate a factor of 10 decrease in $d\sigma/du$ between 1 and 3 GeV/c with a broad flat region between 1.4 and 2.1 GeV/c. The fact that backward elastic and charge-exchange

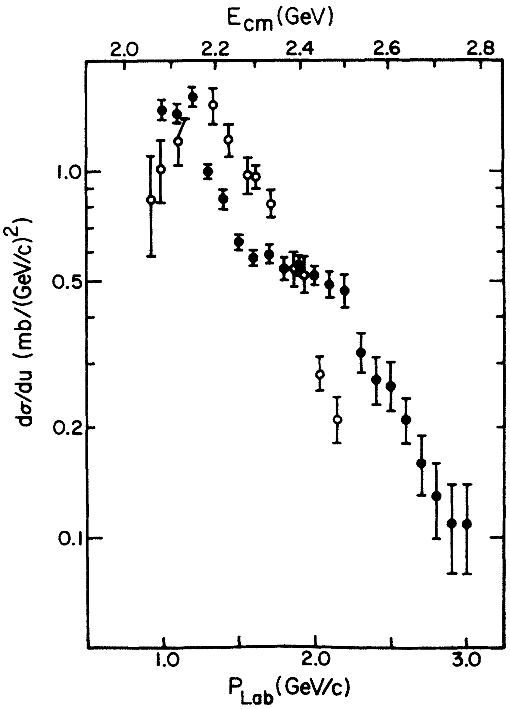

FIG. 5. Differential cross section for $\bar{N}N \to \bar{N}N$ near the backward direction versus p_{lab}. Closed circles, data from this experiment for $\bar{p}p \to \bar{n}n$ in the interval $0 \leq |u| \leq 0.01$ (GeV/c)^2. Open circles, data from Ref. 6 for $\bar{p}p \to \bar{p}p$ in the interval $-1.00 \leq \cos\theta_{c.m.} \leq -0.98$.

cross sections are comparable strongly suggests that the structure observed in both does not arise from diffractive phenomena. Interpretation of the structure in terms of s-channel resonance phenomena is possible, though not required. The contributions of suggested resonances near 1.3 and 1.8 GeV/c with reasonable parameters[1,2,4] are comparable (to within a factor of 2) to the magnitude of our cross sections. The shapes of the angular distributions in the 1.4- to 2.1-GeV/c region are also consistent with a resonance interpretation for spins between 2 and 5. Above 2.2 GeV/c, the backward cross section falls with approximately s^{-7} dependence and the slope of the backward peak rapidly increases. This behavior is reminiscent of other reactions for which the allowed exchange quantum numbers are exotic and for which double-exchange mechanisms are believed to dominate.

---

*Research sponsored in part by the U. S. Atomic Energy Commission and the National Science Foundation.

†Present address: Laboratory of Nuclear Studies, Cornell University, Ithaca, N. Y. 14850.

‡Present address: Department of Physics, Brown University, Providence, R. I. 02912.

§Present address: Department of Physics, Carnegie-Mellon University, Pittsburgh, Pa. 15213.

‖Present address: Accelerator Department, Brookhaven National Laboratory, Upton, N. Y. 11973.

¶Present address: Department of Physiology, University of Virginia, Charlottesville, Va. 22901.

**Present address: Rothbury, Mich. 49452.

[1]D. Cutts, M. L. Good, P. D. Grannis, D. Green, Y. Y. Lee, R. Pittman, J. Storer, A. Benvenuti, G. C. Fischer, and D. D. Reeder, to be published.

[2]R. J. Abrams, R. L. Cool, G. Giacomelli, T. F. Kycia, B. A. Leontic, K. K. Li, and D. N. Michael, Phys. Rev. D 1, 1917 (1970).

[3]A. S. Carroll, I-H. Chiang, T. F. Kycia, K. K. Li, P. O. Mazur, D. N. Michael, P. Mockett, D. C. Rahm, and R. Rubinstein, Phys. Rev. Lett. 32, 247 (1974).

[4]J. Alspector, K. J. Cohen, W. C. Harrison, B. Maglich, F. Sannes, D. Van Harlingen, G. Cvijanovich, M. Matin, and J. Oostens, Phys. Rev. Lett. 30, 511 (1973).

[5]G. Chikovani, L. Dubal, M. N. Focacci, W. Kienzle, B. Levrat, B. C. Maglic, M. Martin, C. Nef, P. Schubelin, and J. Seguinot, Phys. Lett. 22, 233 (1966); M. N. Focacci, W. Kienzle, B. Levrat, B. C. Maglic, and M. Martin, Phys. Rev. Lett. 17, 890 (1966).

[6]J. K. Yoh, B. C. Barish, N. Nicholson, J. Pine, A. V. Tollestrup, A. S. Carroll, R. H. Phillips, C. Delorme, F. Lobkowicz, A. C. Melissinos, and Y. Nagashima, Phys. Rev. Lett. 23, 506 (1969).

[7]D. Cline, J. English, D. D. Reeder, R. Terrell, and J. Twitty, Phys. Rev. Lett. 21, 1268 (1968).

[8]U. Amaldi, B. Conforto, G. Fidecaro, H. Steiner, G. Baroni, R. Bizzari, P. Guidoni, V. Rossi, G. Brautti, E. Castelli, M. Ceschia, L. Chersovani, and M. Sessa, Nuovo Cimento 46A, 171 (1966).

[9]Equality of $\sigma(\bar{n}p)$ and $\sigma(\bar{p}p)$ at low energies is based on the measurements of A. J. Apostolakis, G. A. Briggs, N. A. Khan, and J. V. Major, Nuovo Cimento 37, 1364 (1965); C. K. Hinrichs, B. J. Moyer, J. A. Poirer, and P. M. Ogden, Phys. Rev. 127, 617 (1962).

[10]The $\bar{n}$ path length is inferred from knowledge of the incident $\bar{p}$ trajectory, determined by proportional wire chambers in the beam, and the location of the $\bar{n}$ annihilation in S.