Pion-Deuteron Elastic Scatterng for Momenta from 408 to 600 MeV/c

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The differential cross section for elastic scattering of pions from deuterium has been measured for momenta of 408, 441, 539, and 600 MeV/c. The measurements confirm the energy dependence of a pronounced minimum around 100°, previously observed with lower-precision experiments. Our results are compared to calculations including effects of excitation of dibaryon resonances in the deuteron.

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There is a growing body of evidence indicating that dibaryon resonances, whose nature is still controversial, may play a significant role in the pion-deuteron system. The most direct evidence for dibaryon states was the observation of structure in the total cross section for proton-proton scattering with the spins of both protons parallel to the beam direction.[1] This was interpreted in terms of diproton states in $^3F_3$ and $^1D_2$ waves.[2] Structure in the cross section for pion photoproduction on deuterium[3] has also been interpreted as evidence for the formation of dibaryon resonance states. For pion-deuteron backward scattering an enhancement was observed at around 700 MeV/c[4] and cited as evidence for the effects of such a resonance. Gabathuler *et al.*[5] observed a broad minimum around 100° in the differential cross section for πd scattering at 370 MeV/c and interpreted it in terms of the vanishing of the dominant P-wave part of the pion-nucleon cross section in this angular region. In a later paper we reported measurements of πd elastic scattering[6] in the range of momentum from 343 to 637 MeV/c, which showed that the minimum became more pronounced at 441 MeV/c (both deeper and narrower) and persisted out to 637 MeV/c where, however, with rather limited data, it seemed to be shallower. Attempts to fit the data with Faddeev calculations, multiple scattering, or Glauber methods (all of which used standard N-N potentials) were notably unsuccessful in reproducing the deep minimum. By including dibaryon states Kanai *et al.*[7] were able to reproduce the minimum and obtain rather satisfactory fits. Thus it is natural to speculate that πd elastic scattering may be very sensitive to the existence of dibaryons. The statistical accuracy of the early experiments on πd elastic scattering was only about 10%–30%, and verification of the structure of the cross section with higher precision was required. Such measurements were reported recently by Gabathuler *et al.*[8] for momenta up to 408 MeV/c. Even more recently, Bolger *et al.*[9] have reported measurements of the angular distribution of the vector analyzing power (iT_{11}) at 245 and 370 MeV/c. At the lower momentum, conventional Faddeev calculations fit their data, but at the higher momentum they are in disagreement. The inclusion of dibaryon effects, however, results in excellent agreement with the data. In this paper we present new measurements that extend the accurate data on the πd differential scattering cross section to the momentum range from 408 to 600 MeV/c, and compare the results to calculations incorporating dibaryon formation.

The P^3 pion beam at the Clinton P. Anderson Meson Facility was tuned for a momentum resolution of 1% and focused on a liquid-deuterium target. The experiment was designed to measure elastic scattering events by detecting and identifying the recoil deuterons. The scattered pions were detected in a counter telescope consisting of three multiwire chambers followed by two scintillation detectors, $S3$ and $S4$. A magnetic spectrometer consisting of a single dipole magnet, multiwire chambers, and two scintillation counters, $S1$ and $S2$, was used to measure the angle, momentum, and time-of-flight (TOF) of the recoil deuteron in coincidence with the scattered pion. From the TOF the velocity of the particle could be determined. With the velocity and momentum the mass could be calculated for particle identification. Breakup of the deuterons in the spectrometer was negligible at all energies for this experiment and the mass resolution was excellent. The TOF was calculated by taking the difference of the times of the signals at $S1$ and $S3$ and correcting for the transit time of the pion from the target to $S3$. The momentum acceptance of the spectrometer was constant over the region used in our measurements, and extended to very low momenta. The effective angular acceptance in pion scattering angle for the two-arm apparatus was ±2.5%. The data were binned according to this full acceptance.

The pion flux was monitored by two ionization chambers, a two-counter telescope set to detect pions scattered through an angle of 170° from the target, and a pair of telescopes each consisting of two 5-mm-diam plastic scintillators, located upstream of the target to detect decay muons emerging at an angle of 5° to the beam. The two ionization chambers agreed to within 3% except at forward deuteron angles where the downstream one was blocked by the spectrometer. The front ionization chamber agreed with the $\pi\mu$ decay monitors to 3%. The scattering monitor agreed with the front ionization chamber to 5% at each beam and target setting. The monitors were calibrated by filling the target with liquid hydrogen and measuring the cross section for scattering of pions on protons. The data were normalized to the phase-shift analyses of Höhler *et al.*[10] for πp scattering.

Two methods were used to extract the elastic data. The first method was to make a scatter plot of momentum versus TOF, in which the elastic events stood out as a very strong signal above the background. Cuts were made in momentum and TOF to extract the elastic data. The background was measured by counting the events in a region in the neighborhood surrounding the elastic data. The second method was to use the TOF and momentum to calculate the mass, which was then displayed as a frequency distribution with distinct peaks corresponding to proton and deuteron mass. The background in the neighborhood of the mass peak was fitted to a straight line and subtracted from the peak. The two methods agreed within the statistical errors. The same procedure was used for the πd and πp elastic scattering data.

Recent measurements of Gabathuler *et al.*[8] for pion momentum of 408 MeV/c are compared to our results in Fig. 1. The agreement is excellent. As an internal consistency check some measurements were made at the three lower momenta with a negative-pion beam. Within statistical er-

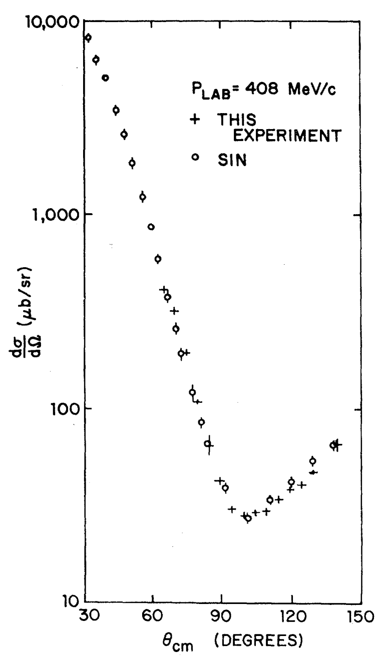

FIG. 1. Differential cross section for πd elastic scattering at P_{lab} = 408 MeV/c. Our data are compared to the data of Gabathuler *et al*. (Ref. 8).

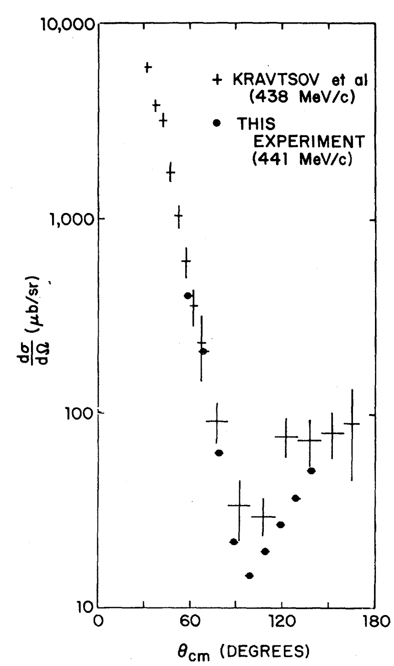

FIG. 2. Differential cross section for $\pi^+ d$ at 441 MeV/c measured in this experiment, compared with measurements at 438 MeV/c for $\pi^- d$ by Kravtsov *et al*. (Ref. 11).

rors our measurements for π^+ and π^- scattering agree, which is consistent with charge symmetry. An additional check using charge symmetry can be obtained by comparing our data at 441 MeV/c with measurements of Kravtsov *et al.*[11] using 438-MeV/c negative pions. As seen in Fig. 2, the agreement is acceptable given the rather large errors of Ref. 11.

The cross sections at all four momenta are shown in Fig. 3. The errors are statistical only. In addition there is an overall normalization uncertainty at each energy which we estimate to be of the order of 7%. The minimum near 100° is the dominant feature. The new data show a smoother and more consistent behavior than do those of our earlier work,[6] but are in agreement within the much larger errors of that experiment. The minimum is less pronounced at 600 MeV/c than at the lower energies. The recent measurements from Schweizerisches Institut für Nuklearforschung[8] as well as older data[12] show little or no evidence of the minimum at momenta below 350 MeV/c.

In Fig. 3, the calculations of Kanai *et al.*[7] are compared to our measurements. These calculations use a nonresonance background calculated from a Glauber model along with a dibaryon resonance term that accounts for excitation of a dibaryon resonance with a mass of 2.22 GeV/c and a spin and parity assignment of 3^-. The interference between the Glauber background (which has no deep minimum) and the dibaryon term results in a minimum around 100°. At forward angles, where the background Glauber part dominates, the agreement between calculation and experiment is good. However, the measured cross sections exhibit even deeper minima than the calculations.

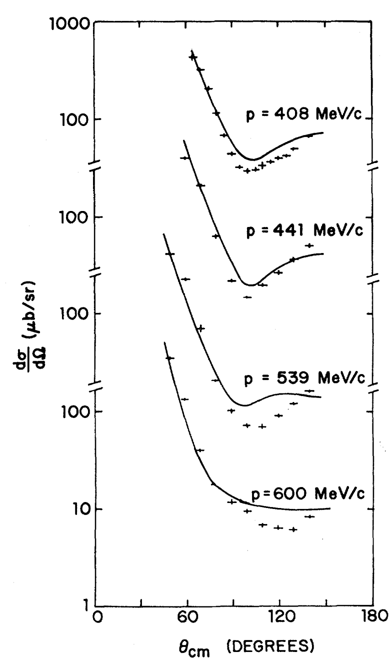

FIG. 3. Differential cross section for π^+d elastic scattering at 408, 441, 539, and 600 MeV/c. The solid lines are the calculation of Kanai *et al*. (Ref. 7). Note the breaks in the vertical scale.

The minimum at 100° may be related to true pion absorption rather than to dibaryon excitation. Rinat and Thomas[13,14] used a set of relativistic equations to couple the πd and $N\Delta$ systems and obtained a minimum for momenta up to 370 MeV/c. They found that true absorption was an important effect. Blankleider[15] used a unified approach to NN and πd scattering as well as πd absorption. His results for πd elastic scattering match the data very well up to 370 MeV/c. Without absorption the backward angle cross section is rather flat with angle but the minimum is obtained when absorption terms are added.

Interpretation of the structure of the differential cross section in terms of dibaryon resonances requires additional theoretical work, but these new data are consistent with existing predictions of models incorporating dibaryon effects. The spin dependent measurements of Bolger *et al.* (Ref. 9) should be extended to the energies studied in this experiment to see if a consistent picture of dibaryon effects in the deuteron can be obtained.

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Ejectile Polarization in Heavy-Ion Reactions

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Using the transmission method we have measured the circular polarization, P_γ, of γ rays from excited projectilelike fragments in the reaction $^{16}O+{}^{58}Ni$ at 100 MeV. The polarizations are large with values up to $|P_\gamma| \cong 100\%$. Over the whole Q range, the sign and magnitude of P_γ can be interpreted in terms of matching conditions familiar from direct-reaction analysis, contrasting the statistical character of the associated heavy-fragment excitation.

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Presently, there are two sets of data available concerning nuclear spin polarizations in heavy-ion reactions leading to continuum spectra. They were obtained from measurements of (a) the circular polarization of γ rays from the excited fragments[1] and of (b) the anisotropy of the β decay of ^{12}B ejectiles.[2] Although the two methods should be considered as complementary to each other, it seems that in the case of reactions induced by light heavy-ions to which both methods have been applied the results and their interpretations are somewhat contradictory. The large polarizations of targetlike fragments from $^{16}O+Ni$ deep-inelastic reactions, deduced from the measured γ-ray circular polarization,[3] are in agreement with the prediction of classical macroscopic models involving frictional forces. The application of friction models to this and similar systems was first suggested on the basis of γ-ray multiplicity data[4] and was further established in particle-particle and γ-ray–particle correlation experiments.[5,6] It was shown that excitation energy and transferred spin reach equilibrium values close to the sticking prediction. The multistep character of the underlying reaction mechanism is supported by experimental[6] and theoretical[7] studies.

On the other hand, measurements of the spin polarization of the ^{12}B ejectiles from $(X, {}^{12}B)$ transfer reactions on various targets ($X={}^{14}N, {}^{13}C, {}^{19}F$) seem to reveal a dominantly one-step character of the reaction mechanism, even in cases with large mass transfer and energy loss.[8] In the high-energy part of the ejectile spectra distorted-wave analyses agree quantitatively with the data,[8,9] whereas in the lower-energy part the ^{12}B polarizations are small in contradiction to both distorted-wave Born approximation (DWBA) and naive friction model expectations. Clearly, what is needed in this situation are data from experiments sensitive to the individual polarizations of *both* fragments.

In this Letter we report on a measurement of the circular polarization of discrete γ-ray lines from excited ejectiles in the reaction $^{16}O+{}^{58}Ni$ at 100 MeV. For this system, the polarization of the targetlike fragments is already known[3] and is remeasured in this experiment with use of a different technique. Thus it serves as basis for a study of polarization correlations between the two reaction partners.

We have applied the transmission method[10] which permits the measurement of the circular polarization of γ rays as a function of γ-ray en-

