Pion-Deuteron Breakup in the Region of the (3,3) Resonance

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A relativistic Faddeev calculation of the pion-deuteron breakup reactions in the region of the (3,3) resonance has been performed, using as input all the S- and P-wave pion-nucleon and S-wave nucleon-nucleon channels, as well as treating relativistically both the spin and the space variables. Theoretical predictions for the energy dependence of the integrated breakup cross sections, and for the differential cross section of the kinematically complete experiment at 228 MeV, are compared with available data.

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The pion-deuteron system is a basic problem of intermediate-energy physics, since its various reactions can be calculated exactly through the use of relativistic Faddeev equations, and the known properties of the elementary pion-nucleon and nucleon-nucleon subsystems. Thus far, however, the main theoretical and experimental effort has been directed towards the elastic and the pion-absorption channels,[1-7] although recently a great deal of interest in the breakup reactions has been generated by the search for dibaryonic resonances which can decay into a pion and two nucleons.[8,9] There have not been, however, up to now, any three-body calculations of the breakup reactions. Thus, this is the first attempt to describe the breakup channels, using standard relativistic three-body theories.

In a previous Letter,[1] I calculated the pion-deuteron elastic scattering cross section, using as input the six S- and P-wave pion-nucleon channels and the two S-wave nucleon-nucleon channels, as well as treating relativistically both the space and the spin variables by means of Wick's three-body helicity formalism.[3,10] The theoretical results agreed quite well with the experimental data in the resonance region except at 256 MeV, where there was a big discrepancy at large angles. However, by using new data and taking into account the effect of the nucleon-nucleon short-range repulsion, I found later that the discrepancy at 256 MeV can be essentially removed.[2] The effect of the pion-absorption channel in pion-deuteron scattering has been included by Fayard, Lamot, and Mizutani,[5] who found that it is not very important in the resonance region except perhaps at 256 MeV.

In this Letter, the same relativistic three-body model of Refs. 1–3 is applied to calculate the breakup reactions in the region of the (3, 3) resonance. In order to represent the six S- and P-wave pion-nucleon channels, I used separable T matrices normalized to the experimental phase shifts as described in Refs. 1–3, except that for the vertex function $g(p)=p^l/(\alpha^2+p^2)$, $l=0,1$, I used a range $\alpha=1$ GeV/c, which is consistent with other theoretical and experimental results.[11-13] Since the amplitude describing the P_{11} channel does not have a pole at an invariant mass corresponding to the mass of the nucleon, this model does not include the effect of pion absorption. In

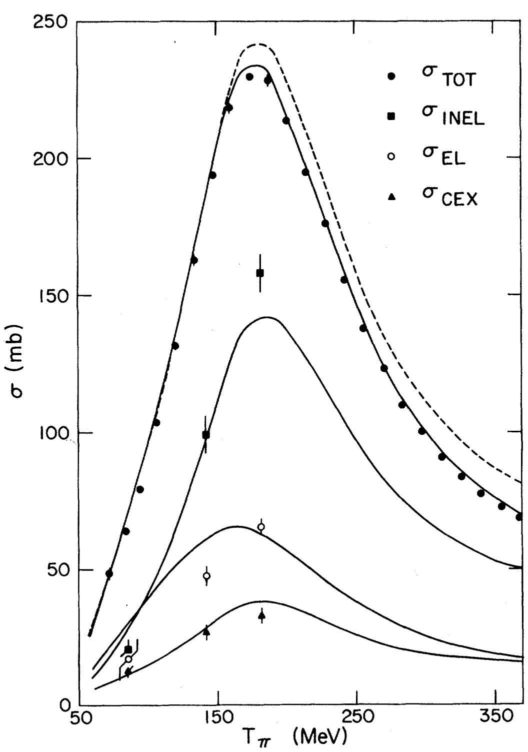

FIG. 1. Energy dependence of the integrated cross sections for the total (σ_{TOT}), inelastic (σ_{INEL}), elastic (σ_{EL}), and charge-exchange (σ_{CEX}) reactions, as a function of the incident kinetic energy of the pion. The dashed line is the sum of the elastic plus the two breakup cross sections.

the case of the nucleon-nucleon channels, I used $^1S_0$ and $^3S_1$ relativistic Yamaguchi models, which were obtained by applying the prescription of minimal relativity[14] to the standard forms.[15] For the deuteron wave function, the wave function of Moravcsik[16] was used, which has a D-state probability of 6.7%. I solved the relativistic Faddeev equations along the real axis, by means of Padé approximants for all values of total angular momentum $J<6$ and by use of the impulse approximation for the remaining values up to $J=14$.

Figure 1 shows the present results for the energy dependence of the integrated inelastic ($\pi^\pm + d \to \pi^\pm + p + n$) and charge-exchange ($\pi^- + d \to \pi^0 + n + n$ or $\pi^+ + d \to \pi^0 + p + p$) cross sections, as well as, for comparison, the elastic and total cross sections. I should point out that while the data for the total cross section are of very good quality,[17] this is not the case for the elastic and the two breakup cross sections,[18-20] where the data can only be used to give an idea of the relative sizes of the various cross sections, which as we see are in good agreement with those of the present calculation. The dashed line is the sum of

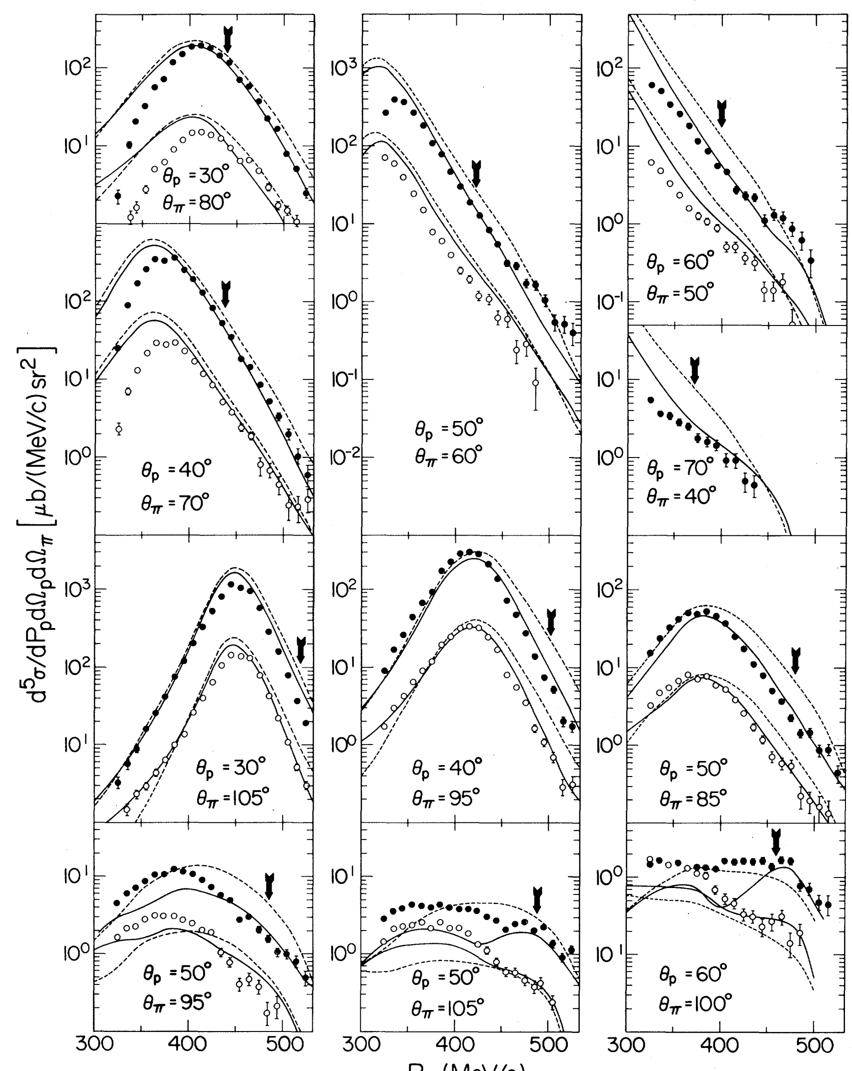

FIG. 2. Differential cross sections for the inelastic scattering reactions $\pi^\pm + d \to \pi^\pm + p + n$ at $T_\pi = 228$ MeV, for several values of the pion and proton angles, as a function of the proton momentum. The solid lines are the results of the full three-body calculation, and the dashed lines the results of the impulse approximation. The solid circles represent π^+ data and the open circles π^- data. The arrows indicate the points at which the invariant mass of the pion-proton subsystem is equal to the mass of the delta.

the calculated elastic plus breakup cross sections, which should be equal to the total cross section, since the pion-absorption channel was not included. The discrepancy seen at the higher energies is a consequence of the fact that this model satisfies three-body unitarity only approximately, because of the inconsistent treatment of the nucleon-nucleon interaction, since the Moravcsik deuteron wave function has short-range repulsion and a D-state component, while the simple Yamaguchi T matrix does not have any of these features. I like to keep this inconsistent treatment, however, since I have found that in order to give a good description of the total cross section as well as of the differential cross sections for the inelastic reactions at 228 MeV, it is important to have a realistic deuteron wave function. We can use, however, the unitarity condition to test the numerical accuracy of the code, by repeating the calculation of Fig. 1 with a simple Yamaguchi deuteron wave function that is consistent with the nucleon-nucleon T matrix, in which case it is found that the total cross section and the sum of the elastic plus breakup cross sections agree with each other to within 3%, which is the numerical accuracy of the code.

In order to show the importance of the rescattering terms in the cross sections of Fig. 1, Table I compares the results for $T_\pi = 142$ MeV using the impulse approximation and using the full three-body calculation. We see that the charge-exchange cross section changes little between the two calculations, although the inelastic cross section decreases by about 30% and the elastic by about 10%, while the total cross section increases by about 15%. We also notice, by comparing σ_{TOT} with $\sigma_{CEX} + \sigma_{INEL} + \sigma_{EL}$, that the impulse approximation violates unitarity by about 40%.

A new set of high-quality data for the breakup reactions $\pi^\pm + d \to \pi^\pm + p + n$ has been measured recently by Hoftiezer *et al.* in a kinematically complete experiment at $T_\pi = 228$ MeV, in which they detected the pion and the proton at fixed angles, and measured the momentum of the proton.[8] I compare in Fig. 2 the theoretical predictions for this experiment, where both the results of the full three-body calculation (solid lines) as well as those of the impulse approximation (dashed lines) are presented. We see that overall the theory is in good agreement with the data, although there are some regions where serious discrepancies remain. It is worth mentioning that the dominant diagram of these results is the term in the impulse approximation where the pion scatters from the proton with the neutron acting as spectator, which determines the positions of the maxima, since they correspond to the configurations in which the relative momentum between the proton and the neutron inside the deuteron is lowest. I have indicated, by means of an arrow, the position where the invariant mass of the pion-proton subsystem is equal to the mass of the delta, which as we see is the place where the theory works well in all cases. Thus, this model, which is based on the isobar approximation for the two-body subsystems, works well if the dominant pion-nucleon amplitude corresponds exactly to an isobar state. The points to the right of the arrow correspond to a pion-proton invariant mass smaller than the mass of the delta, and we see that the theory also works well in these cases. The points to the left of the arrow, on the other hand, correspond to a pion-proton invariant mass larger than the mass of the delta, and here the theory works well in some cases but not in others, so that the theory overestimates the cross section of the five angle pairs in the upper two rows, while it underestimates the ones of the fourth row. The results of the third row, however, which constitute a transition region between the two previous cases, are the ones best described by the theory.

I conclude by saying that the results of these calculations show that it is possible to explain

TABLE I. Comparison of the cross sections of Fig. 1 for $T_\pi = 142$ MeV calculated by using the impulse approximation and by using the full three-body calculation. All the cross sections are given in millibarns.

	σ_{CEX}	σ_{INEL}	σ_{EL}	σ_{TOT}	$\sigma_{CEX}+\sigma_{INEL}+\sigma_{EL}$
Impulse approximation	29.3	133.7	67.9	163.2	230.9
Three-body calculation	28.6	97.9	60.5	187.5	187.0

the pion-deuteron breakup reactions by using the same relativistic three-body theory which has worked well in explaining the elastic cross sections. However, in the case of the kinematically complete experiment at 228 MeV, if the invariant mass of the pion-proton subsystem is larger than the mass of the delta, some discrepancies still remain which cannot be explained by the theory.

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Intense Coherent Submillimeter Radiation in Electron Storage Rings

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Energetic electron bunches in storage rings produce pulsed bursts of *incoherent* synchrotron radiation. It is pointed out that they should also produce a roughly comparable power output of *coherent* radio-frequency radiation. Thus electron storage rings might additionally serve as pulsar simulators, producing a similar spectrum of coherent emission, the properties and modification of which could be studied in the laboratory. A spontaneous bunching of electrons (artificially bunched here) might be evidenced as "superbunching."

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In electron storage rings, small (~ 1 cm) bunches of ~ 10^{11} electrons circulate at high energies (several gigaelectronvolts) around relatively small (~ 12 m radius) rings. The resultant synchrotron radiation then extends into the several-kilovolt x-ray region and provides a valuable source of such radiation [e.g., the Stanford Synchrotron Radiation Laboratory (SSRL)]. Moreover, this radiation is pulsed, because the electrons are bunched together, and is narrowly beamed, because of the extreme relativistic motion of the electrons.

It has been much less widely noted that the (deliberate) electron bunching has quite a different effect on the low-frequency part of the spectrum. At high frequencies the electrons radiate incoherently since they are more or less randomly located a large number of x-ray wavelengths from one another. But the flux density in the synchrotron spectrum falls rather slowly as one goes to low frequencies (essentially as $\omega^{1/3}$) and remains substantial even at wavelengths as long as the size of the bunch. For example, going from x-ray wavelengths (~ 10^{-8} cm) to the bunch size (~ 1 cm) reduces the flux density by less than 10^3. In contrast, once the bunch is less than about a wavelength in size, all the electrons radiate coherently. That is to say, the "bunch" might

