Polarization Phenomena in $NN \leftrightarrow D\pi$ Reactions

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Abstract—On the basis of a relativistic approach, $NN \leftrightarrow D\pi$ reactions are analyzed in detail. The coherent sum of one-nucleon-exchange and pion-rescattering diagrams is calculated. It is shown that polarization observables are highly sensitive to off-mass-shell effects within the deuteron and that some of these observables can change sign upon taking these effects into account. The effect of the deuteron $P$ wave is also investigated. The results obtained by calculating a full set of observables are compared with experimental data on the reaction $pp \rightarrow D\pi^+$. © 2001 MAIK "Nauka/Interperiodica".

1. INTRODUCTION

Investigation of the $\pi NN$ system is one of the most important problems in intermediate-energy physics. This may provide deeper insights into nucleon–nucleon interaction at energies above the pion-production threshold. In addition, such an investigation will furnish a basis for calculating more involved processes that occur in multinucleon systems. This is due to an intermediate position that phenomena occurring in pion–deuteron interaction occupy, in what is concerned with complexity, between phenomena characteristic of pion–nucleon interactions and those peculiar to pion–nuclear reactions. Since the deuteron possesses a low binding energy and a large dimension, so that the constituent proton and neutron are offset by a large distance, it can be expected that the amplitude of pion–deuteron scattering is dominated by the contribution from coherent scattering on two single nucleons; however, it is necessary, in this pattern, to introduce kinematical corrections for the motion of the nucleons and corrections for the binding energy. By way of example, we indicate that, by comparing the total cross section for elastic pion–deuteron scattering at a primary-pion energy $\omega$, $\sigma_{\pi D}(\omega)$, with the sum of the relevant cross sections, $\sigma_{\pi p}(\omega) + \sigma_{\pi n}(\omega)$, for scattering on free nucleons, one can see that this approximation, the simplest possible one indeed, yields an astonishingly accurate result over the entire range of laboratory pion energies from the threshold to 1 GeV. In general, additional terms stemming from rescattering on two nucleons are small, provided that leading terms are not suppressed.

This is not so only for pion-production and pion-absorption processes, for which it is not obvious that the description in terms of pion–nucleon amplitudes would be sufficient. Among these, we would like to mention the pion-absorption process proceeding through the channel $\pi D \rightarrow NN$, which is related to the inverse reaction $NN \rightarrow D\pi$ by the detailed-balance principle. All these processes can be considered as prototypes of pion production and absorption in nuclei and, for this reason alone, have been the subject of keen interest both for experimentalists and theorists over the last five decades. The point is that the structure of the deuteron has been well understood, whence it follows that the pion–deuteron system is an ideal laboratory for studying the mechanisms of pion–nucleus interactions under controllable conditions. What is of importance in pion absorption on nuclei is its kinematics that is indeed unusual on the nuclear scale: the energy transfer from the incident pion to the nucleus involved is low, while the corresponding momentum transfer is high. By way of example, we indicate that, in the absorption of a pion at rest, its mass $\mu$ is shared among the final nucleons in equal fractions; therefore, the kinetic energy of each of these nucleons in the deuteron laboratory frame is equal to half the pion mass $(T = \mu/2)$. Hence, the relative momentum of the nucleons is $p = \sqrt{m\mu} = 360$ MeV/c, which corresponds to inelastic distances of about $1/\sqrt{m\mu} \approx 0.6$ fm. This is a large quantity in relation to the characteristic scale that the binding energy $e_D$ specifies for the inelastic nucleon–nucleon momentum: $e_D = \sqrt{2m\muD} \approx 45$ MeV/c. Although the absorption process is allowed, the required relative momentum differs significantly from momenta easily accessible in the deuteron. Such a distinction is peculiar to pion absorption or production both in the deuteron and in more complex nuclei. The requirement that the momentum transfer between the two nucleons involved be high renders the pion-absorption process highly sensitive to the dynamics of the $\pi NN$ system at relatively small distances.
Because of unusual pion-production kinematics, high momentum transfers must occur in the $NN$ system. Therefore, it is necessary to introduce mechanisms that optimize the momentum transfer between the nucleons immediately prior to and after a pion-production event. The simplest approach consists in assuming that a pion is produced on a single nucleon, in which case the characteristic absolute value of the momentum carried away must be selected in the momentum distribution of the deuteron nucleon involved. Herein lies the reason behind the smallness of the amplitude in the impulse approximation: it is impossible to compensate effectively for so large a difference in momentum only owing to the momentum distribution in the deuteron. As a result, the one-nucleon-exchange mechanism is suppressed, so that there must exist a mechanism that ensures better balance. Obviously, the next step consists in exploring rescattering processes where a pion is produced on one nucleon and is then scattered on the second one.

From the first observation of the reaction being discussed [1] to the present day, there has been a torrent of experimental investigations and theoretical calculations. According to the first investigations [2–4], it is the excitation of a delta isobar that is the main point in explaining the energy dependence of the reaction cross section. Many analyses were based on the multichannel Schrödinger equation with a separable or a local potential [5–9]—that is, they relied on the nonrelativistic approach. The first attempts at constructing a relativistic description were made in [10–13], where the calculations took into account not only the one-nucleon-exchange pole diagram but also the rescattering diagram. For example, it was demonstrated in [13] that the cross section for the reaction being discussed is dominated by the contribution of the rescattering diagram. However, the calculations there were performed under very restrictive assumptions—in particular, the relevant matrix elements were factorized and the recoil effect was disregarded. A more accurate calculation for the reaction $pp \to D\pi^+$ revealed [14–17] that, in order to achieve agreement with experimental data, it is necessary to take into account diagrams of still higher orders. Nonetheless, a successful description of all polarization observables was not obtained in those studies either. Thus, we can conclude that, although basic bare mechanisms of pion production on a deuteron have been well understood, there are still open questions in what is concerned with detailed qualitative features.

As a matter of fact, an analysis of $NN \to D\pi$ reactions always entails the problem of nucleon off-mass-shell effects within the deuteron. In the present study, we focus primarily on the role of these effects and on the contribution of the $P$-wave component of the deuteron wave function [18, 19]. The problem of an off-mass-shell extrapolation of meson–nucleon vertex functions will be an important point of this discussion, since $NN \to D\pi$ processes provide a sensitive test for such questions. We also explore the sensitivity of polarization observables to these effects and prove that some observables can even change sign.

The ensuing exposition is organized as follows. In Section 2, we discuss in detail the principles underlying our procedure for constructing relativistically invariant amplitudes for $NN \to D\pi$ reactions. Here, we also introduce helicity amplitudes, which are then expanded in terms of partial-wave amplitudes; it is by using these partial-wave amplitudes that we further analyze the reaction being studied. In Section 3, we consider the pole diagram and the rescattering diagram. In Sections 4 and 5, we discuss our results and compare them with available experimental data. The conclusions are formulated in Section 6.

2. GENERAL FORMALISM

2.1. Relativistically Invariant Expansion for the Reaction Amplitude

We begin by considering a basic point of our analysis, a relativistic construction of the $NN \to D\pi$ amplitude with allowance for the requirements of covariance. In general, the $S$-matrix element for the reactions in question, $S_{\sigma_2 \sigma_1}^\beta = \langle \pi D, \text{out} | p_1 p_2, \text{in} \rangle$, is related to the corresponding $M$-matrix element by the equation

$$ S_{\sigma_2 \sigma_1}^\beta = \frac{1}{(2\pi)^2} \frac{m}{E_1 E_2 \omega 2E_D^{\beta}} \times \delta^{(4)}(\pi + D - p_1 - p_2) M_{\sigma_2 \sigma_1}^\beta, $$

where $\pi$ and $D$ are, respectively, the pion and the deuteron momentum, while the indices $\beta, \sigma_1,$ and $\sigma_2$ label the polarization of the deuteron involved and the projections of primary-nucleon spins. The general form of the reaction amplitude is

$$ M_{\sigma_2 \sigma_1}^\beta(s, t, u) = \langle \pi D, \text{out} | p_1 p_2, \text{in} \rangle \xi_{\sigma_2 \sigma_1}^\beta(D) \varphi_{\pi}, $$

where $u_{\sigma_1}^\mu(p_1) \equiv u_1$ and $\bar{v}_{\sigma_2}^\mu(p_2) \equiv \bar{v}_2$ are, respectively, the spinor and the antispinor of primary nucleons having the spin projections $\sigma_1$ and $\sigma_2$ and the