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Presented on the International Symposium
"DUBNA DEUTRON-93"
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Hungarian Academy of Sciences
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December 20, 1993

Presented on the International Symposium
"DUBNA DEUTRON-93"
Dubna, 14-18 September, 1993

HU ISSN 0368 5330

Abstract

The $^{1}H(d,2p)n$ deuteron breakup reaction was measured at 2 GeV deuteron energy in a kinematically complete experiment. Five-fold differential cross sections are given in a wide range of the kinematic variables. The transition matrix elements $|A|^2$ are obtained and compared with the model predictions including the impulse approximation (IA) and NN rescatterings. The marked deviation from the theory was established depending on the value of the four-momentum transfer t_{24} in the scattering process. At low t_{24} the $|A|^2$ are in good agreement with the IA while large discrepancies were found above internal momentum $q \approx$ 200 MeV/c when the four momentum transfer was large.

1 Introduction

The wave function of the deuteron has been the subject of many investigations, in order to get information about the bound two-nucleon system at low as well as at high values of the internal momentum. Three kinds of experiments were usually performed in these studies: kinematically complete measurements of the deuteron breakup reaction induced by electrons and protons and the A(d,p)X type inclusive experiments detecting the breakup products in the interaction of deuterons with different target nuclei. The bombarding energies varied from several hundreds MeV up to 7.4 GeV. Recently we have investigated the ^{1}H(d,2p)n breakup reaction in a kinematically complete, exclusive experiment at Saclay using 2 GeV vector and tensor polarized deuterons, continuing by this the series of the experiments of such kind [1-5]. The aim of the experiment was to study the structure of the deuteron wave function at large internal momenta by investigating polarization phenomena under definite kinematic conditions and analyzing them in the frame of IA. It was found that the measured asymmetries and polarizations at low q values were in accordance with the predictions of the IA, at higher internal momenta, however, significant deviations have been observed. Although the measurement was planned to investigate first of all polarization effects, valuable information was obtained also about the variation of the cross section itself in a rather extended range of the kinematic variables.

The results of the experiment concerning polarization have been reported elsewhere [6] and in the present paper the unpolarized cross section results will be presented and discussed.

2 Experiment and data handling

In this work the deuteron breakup reaction

$$d + p \rightarrow p + p + n \qquad (1)$$

has been investigated in a kinematically complete (exclusive) experiment. To specify the particles involved in the reaction we will use the symbols and subscripts as follows:

$$(1) + (2) \rightarrow (3) + (4) + (5) \;. \qquad (2)$$

The experiment has been performed in the Laboratoire National Saturne at Saclay. Vector and tensor polarized deuterons (particle 1) accelerated to $T_1 = 2$ GeV kinetic energy by the synchrotron SATURNE were directed to a liquid hydrogen target. The two scattered protons (particles 3 and 4) were detected by the magnetic spectrometer SPES IV [7] and by a large angular acceptance recoil spectrometer (RS), respectively.

SPES-IV angle was fixed at $\theta_{30} = 18.3°$, five central momentum settings (p_{30} = 1.6, 1.7, 1.8, 1.9, 2.0 GeV/c) were studied. The RS was positioned at

$\theta_{40} = -57.0°$ ($-53° < \theta_4 < -61°$ and $-5.8° < \varphi_4 < 5.8°$) and provided angular ($\delta\theta_4 = 0.3°$), time-of-flight t_4 ($\delta t_4 = 1$ nsec) and amplitude (from ΔE and E scintillators) informations.

The combination of the measured values ($\vec{p}_3$, θ_4 and φ_4) defines 3-body kinematics. The correlations between $E - t_4$ and $t_4^{meas} - t_4^{rec}$ were used to select events of the reaction from the background.

The following software cuts were also applied: $\frac{\delta p}{p} < \pm 2.5$ %, $\delta\theta_3 < \pm 0.15°$, $\delta\varphi_3 < \pm 1.1°$, $T_4 > 70$ MeV. After the filtering procedure about 23% of the triggered events remained as true ones. The combined efficiency of the detectors and of the data processing was about 80%. The number of true events was obtained with about 25% systematic error. The background measured with empty target cell was $\sim 2 - 3$ %.

3 Experimental results

The two dimensional distributions of the events in the $[\Theta_4, t_4]$ coordinate plane are shown in Fig. 1 measured at the five p_{30} momenta. The distributions are concentrated along curves defined by the kinematics of the reaction. At $p_{30} =$ 1.6 and 1.7 GeV/c only the events with high T_4 (low t_4) are within the energy and angular acceptances of the RS, while at higher p_{30}-s the spectra are accepted up to the kinematic limits of the reaction.

The five-fold differential cross section was calculated as:

$$\frac{d^5\sigma}{dp_3 d\Omega_3 d\Omega_4} = C_{exp} \frac{N_p(\Theta_4)}{\Delta p_3 \Delta\Theta_3 \Delta\varphi_3 \Delta\varphi_4 \Delta\Theta_4}, \tag{3}$$

with $C_{exp} = 1/n_B n_T \epsilon$. The factor n_B is the beam intensity, n_T is the number of target nuclei per unit area and the factor ϵ contains the inefficiency of the detectors and of the data filtering process.

The quantity $N_p(\Theta_4)$ is the number of protons detected by RS at Θ_4 in the bin $\Delta\Theta_4$. This number was obtained from the two dimensional $N_p(\Theta_4, t_4)$ spectra by summing the events at Θ_4 along the t_4 direction and subtracting the background. Practically this was done by fitting the data with a Gaussian superimposed on a linear function. This procedure was effective through the whole angular range in the case of the p_{30}=1.6 and 1.7 GeV/c spectra, while at higher momenta the back-bending of the spectra at the kinematic limits allowed unambiguous determination of the cross section only below an arbitrarily chosen maximum angle.

According to the general theory of reactions with multiparticle final states the cross section (3) is in direct relation with the transition matrix element $|A|^2$ of the reaction through the kinematic factor :

$$\frac{d^5\sigma}{dp_3 d\Theta_3 d\varphi_3 d\varphi_4 d\Theta_4} = \frac{p_3^2 p_4^2}{32(2\pi)^5 m_2 p_1 E_3 (p_4 E_5 - E_4 p_5 \cos\Theta_{45})} |A|^2 . \tag{4}$$

In this expression Θ_{45} is the angle between the directions of p_4 and p_5, respectively in the horizontal plane. (Note: in order to match the experimental layout, these formulae are related — in an unconventional way — to a spherical coordinate system with its axis perpendicular to the horizontal plane and the notations: Θ_i for azimuthal and $(90^\circ - \varphi)$ for polar angles were used respectively.)

The transition matrix elements calculated according to (4) are displayed in Figs. 2 as the function of T_4 along with the model predictions.

4 Discussion and conclusions

The experimental results will be discussed in this Section on the basis of the model including IA and NN rescatterings . The initial goal of the experiment, based on *a priori* assumed dominance of IA (see Fig. 3), was to deduce the *dnp*-vertex D_{dnp} in dependence on the mass of the virtual nucleon $t_{15} = (p_5 - p_1)^2$ or, what is the same, on the internal momentum $\vec{q}$ of nucleon in *dnp*-vertex $t_{15} = m_d^2 + m^2 - 2m_d\sqrt{m^2 + q^2}$. Note, that the graph at Fig. 3 represents the pole term in the invariant amplitude A caused by one nucleon exchange

$$A = \frac{M_{NN}(s_{34}, t_{24}, t_{15}) D_{dnp}(t_{15})}{t_{15} - m^2} + B \ , \tag{5}$$

where the NN amplitude M_{NN} depends on the virtual nucleon mass t_{15}. The background B was approximated in our approach by graphs described shortly in the appendix. Evidently that one could hope to extract D_{dnp} from $|A|^2$ only neglecting the background B (still being left with the off-shell problem for the NN amplitude). It is more or less justified near the nucleon pole and seems to be risked at large distance from it.

The intervals in t_{15} at different p_3 were achieved in the experiment by the variation of the other momentum transfer $t_{24} = (p_4 - p_2)^2$, directly related to the kinetic energy of the proton detected in RS $t_{24} = -2mT_4$. The Figs. 2 show measured $|A|^2$ at five values of p_3 =1.6, 1.7, 1.8, 1.9 and 2.0 GeV/c along with the corresponding values of $t_{15} - m^2$ (last figure) in dependence on T_4. It is seen from the last figure that at each p_3 we have the nearest to the pole position at $T_{40} \approx 0.15$ GeV, which moves away from the nucleon pole when increasing p_3. Going to the right as well as to the left from T_{40} also increases the distance from the pole and in the second case it happens even more quickly. The experimental points at Figs. 2 demonstrate in fact the evident deviation from the pole contribution (dashed line) only at large T_4 for each p_3, what is confirmed at least qualitatively by calculated background (solid line). The experimental points at $T_4 \leq 0.2$ GeV for p_3 =1.8, 1.9 and 2.0 GeV/c do not confirm the noticeable deviations from IA predicted by the model.

Of course we need additional checking up of experimental data as well as our model to understand the situation and if it would be confirmed the hope would appear that we have found the kinematic conditions under which the background of IA is suppressed up to the deuteron internal momemta $q \approx 0.4$ GeV/c.

Support of the Hungarian Academy of Sciences under grants OTKA I/1 No. 1239 and OTKA I/3 No. 1817 is gratefully acknowledged.

A Appendix: Model

We [8] take the amplitude of the breakup reaction as the sum

$$M = M_{ONE} + M_{DS} + M_{\Delta} \ . \tag{6}$$

Amplitudes M_{ONE}, M_{DS} and M_{Δ} correspond to the graphs a, b and c shown in Fig. 4.

The amplitudes M_{NN} and $M_{\pi d\to NN}$ are taken to satisfy the Pauli principle. Thus the term corresponding to the diagram a is antisymmetric with respect to the interchange of the first and the second nucleons and the diagrams b and c are with respect to the second and the third nucleons. To make the amplitude (6) fully antisymmetric the two more sets of the diagrams with cyclic permutated nucleons at the final state had been added to the pictured ones. These diagrams are denoted in the above picture as (123→231) and (123→312).

We have used the NN amplitudes obtained in the energy-dependent phase shift analysis (PSA) by Arndt et al. [9]. Following Everett [10] we have taken the NN amplitudes out of the loop integral, corresponding to the triangle diagram b, at some optimum Fermi momentum. However in the case of the energy of the final nucleon's pair less than 400 MeV we used the form factor f for the corresponding half off shell NN amplitude $M^{off} = fM^{on}$, M^{on} being taken out of the loop integral. The threshold form factor related to the $^1S_3$ -wave function of the deuteron was taken and integrated along with dnp vertex and two propagators. The real part of the resulting integral is connected with the allowing the intermediate nucleon with the momentum p_f to be off shell.

We have calculated the amplitude $M_{\pi d\to NN}$ taking into account the one-loop diagrams with the $N\Delta$ as intermediate state and the diagrams with the πN intermediate scattering in the S, P and D waves parametrized by their phase shifts. To avoid the double counting we have excluded however the one nucleon exchange diagram, which already contributes to ONE term in (6), and the P_{11}-wave (the nucleon pole in the πN amplitude is a part of the DS term). Finally, the ρ-exchange is taken into account in the $\pi d \to NN$ amplitude. The details are given in the appendix of the paper by Laget [11].

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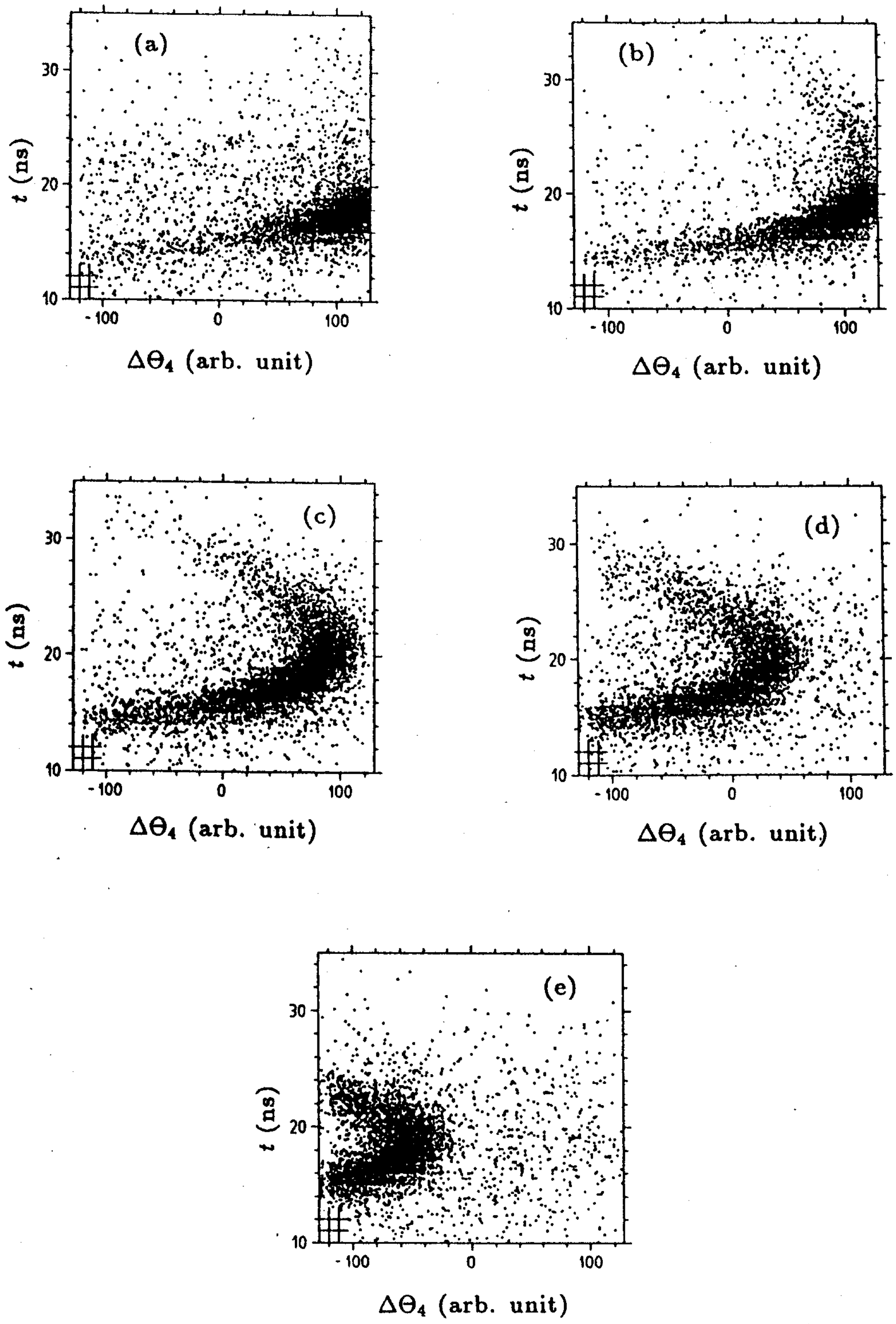

Figure 1: Two dimensional spectra of the measured events in the $[t_4, \Theta_4]$ coordinate plane. (a) p_3 = 1.6 GeV/c (b) p_3 = 1.7 GeV/c (c) p_3 = 1.8 GeV/c (d) p_3 = 1.9 GeV/c (e) p_3 = 2.0 GeV/c

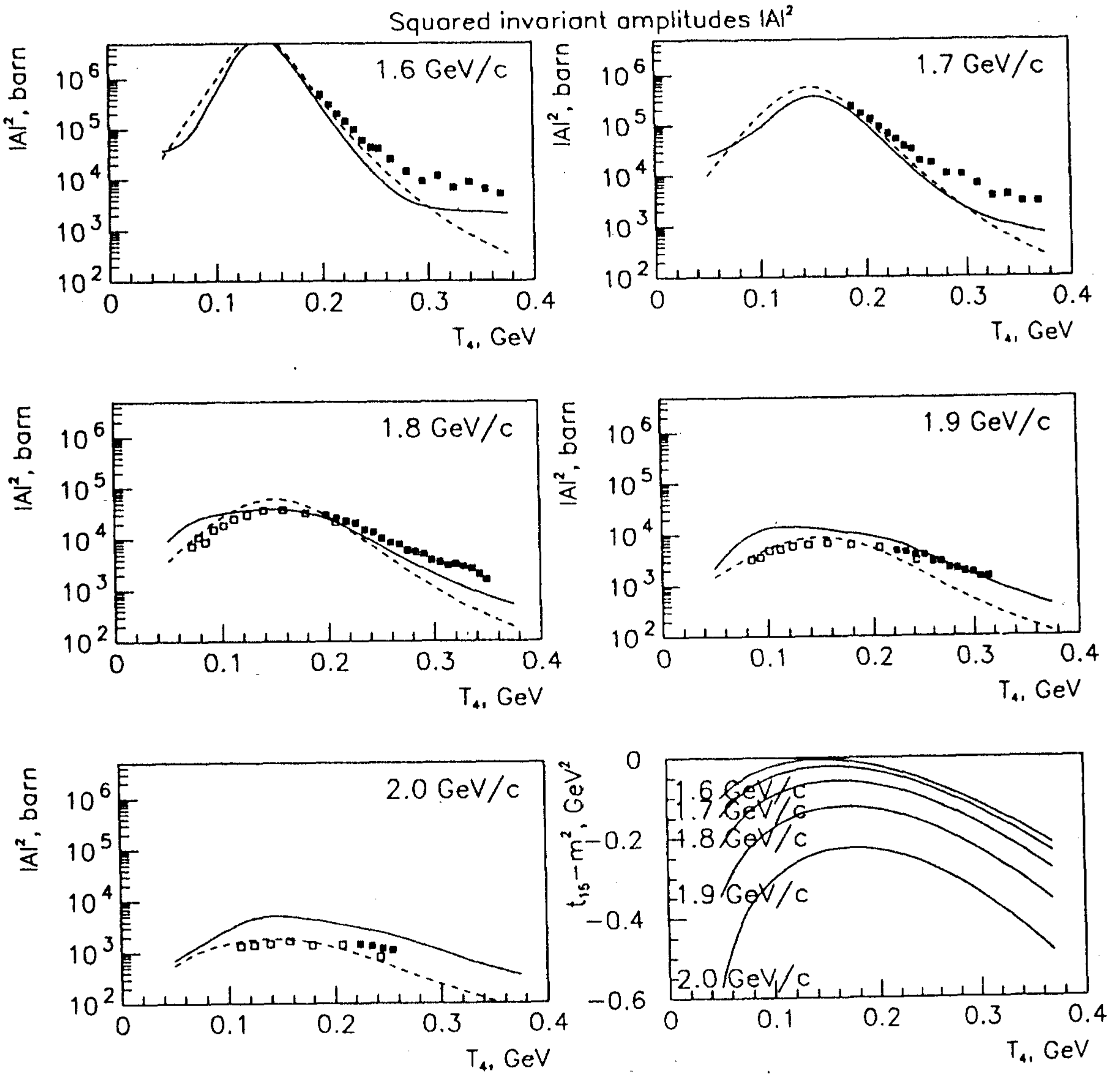

Figure 2: Transition matrix elements (squares) calculated according equ. (4) at $p_3 = 1.6, 1.7, 1.8, 1.9$, and 2.0 GeV/c, and virtual nucleon mass (last figure). The curves are theoretical calculations: the pole contribution (dashed line) and the background (solid line)

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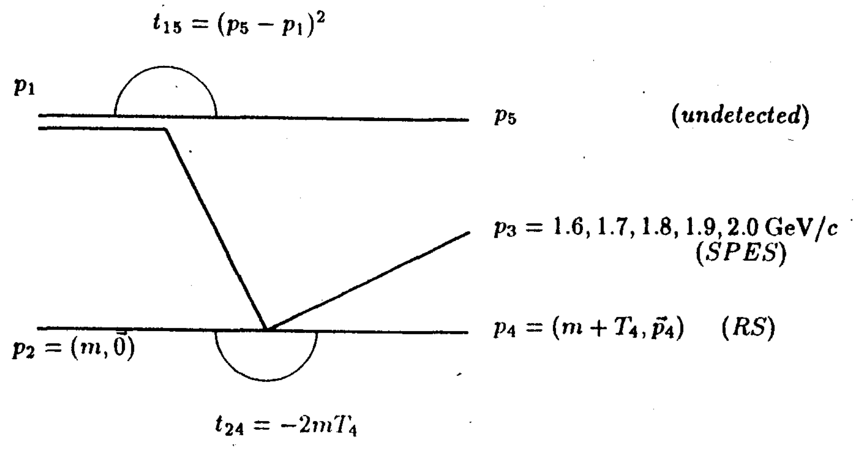

Figure 3: IA mechanism

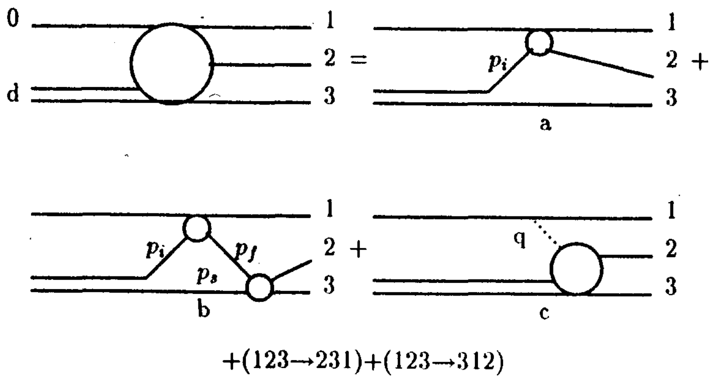

Figure 4: ^{1}H(d,2p)n breakup reaction. Feynman graphs taken into account

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