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DEUTERON BREAKUP REACTION AT MEDIUM ENERGIES

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Secondary effects in deuteron breakup reactions are re-examined for processes $p\vec{D} \to ppn$ with a proton detected at 180°. The calculation includes double-scattering and final-state-interaction corrections to a plane-wave impulse approximation. The method used here incorporates both the energy-conserving and the principal-value part of the free nucleon propagator. The two nucleon Paris deuteron wave function /6/ and the available nucleon-nucleon elastic scattering data /5/ have been used as an input. The results are compared with the inclusive $H(\vec{d}, p)X$ cross sections and the tensor asymmetry T_{20} data /1/ at a 1.25 and 2.1 GeV deuteron kinetic energy.

The investigation has been performed at the Laboratory of High Energies, JINR.

Развал дейтрона при промежуточных энергиях

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Рассматриваются вторичные эффекты для развала дейтрона в процессах $p\vec{D} \to ppn$ с измерением протонов на 180°. Расчеты проведены с учетом двойного перерассеяния и взаимодействия в конечном состоянии как поправки к импульсному приближению с плоскими волнами. Представленный метод учитывает одновременно энергосохраняющую часть и полюсную часть свободного нуклонного пропагатора. Были использованы двухнуклонная парижская волновая функция дейтрона /6/ и имеющиеся данные /5/ по нуклон-нуклонному рассеянию. Результаты сравниваются с инклюзивными сечениями $H(\vec{d}, p)X$ и тензорной асимметрией T_{20} /1/ при кинетической энергии дейтрона 1,25 и 2,1 ГэВ/с.

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I. Introduction

The investigation of the processes of deuteron breakup on nucleons at medium and high energies can give nontrivial information about the deuteron structure. It is believed that the detection of protons from the deuteron in the forbidden kinematic region for the interaction on free nucleons can improve our knowledge on nuclear physics at small distances. In a first approximation the deuteron breakup at medium and high energy is a relatively simple process in which one of the nucleons of the deuteron interacts with a probe (e.g., a proton) and the other proceeds largely undisturbed. This simple picture presented by a plane-wave impulse approximation (PWIA) needs to be corrected for the effects such as multiple scattering, final-state interaction (FSI) and also for other possible contributions or mechanisms which occurrence can have a sufficient influence on the experimentally measured characteristics. For the deuteron breakup, FSI and double scattering are small and can be in principle calculated, and thus they offer interesting grounds for various theoretical models. There exists now a considerable amount of deuteron data for energies ranging from a few hundreds MeV to several GeV. In this paper we consider the process $p\vec{D} \to ppn$ with a proton detected at 180°. This reaction canal dominated in deuteron breakup processes induced on the proton probe especially in the region when one approaches the kinematic limit which is the maximum laboratory proton momentum for a given incoming energy. The aim of our study is to estimate the final-state interaction (FSI) and the double-scattering (GDS) effects. The calculation results are compared with the measured inclusive cross sections and the tensor asymmetry T_{20} for deuteron breakup at 1.25 and 2.1 GeV/1/.

II. Theoretical Formulation

In this section we present the formalism for the calculation of the inelastic scattering of a proton from a deuteron target

$$P_1 + \vec{D} \to P_3' + N_1' + N_2' \qquad (1)$$

incorporating the multiple-scattering expansion in addition to the single-scattering contribution of the PWIA. The calculation is performed in the rest frame of the deuteron using non-relativistic wave functions. The transformation of the NN amplitudes to this frame and kinematics are treated relativistically.

We call the projectile proton particle No.1 and the target nucleon particles Nos.2 and 3. We call the nucleons in the final state 1′, 2′, 3′ having in mind that particle 3′ detected in the backward hemisphere is a proton. For the polarized deuteron the differential cross section for pure M states (M = -1, 0, 1) in reaction (1) reads

$$d\sigma_{if}(M) = \frac{(2\pi)^4}{2v_{in}} \sum_{spins} |T_{if}^M|^2 \delta^4(k_i - k_f)\, d\vec{k}_1' d\vec{k}_2' d\vec{k}_3' \qquad (2)$$

v_{in} is the velocity of incoming proton and T_{if} represents the corresponding three-nucleon T matrix element. The factor 1/2 in (2) represents averaging over initial proton spin. When describing characteristics of inclusive data, we have to perform integration over $\vec{k}_2'$. The invariant inclusive cross section and the tensor asymmetry T_{20} are then written in the form

$$\rho = [\rho(1) + \rho(0) + \rho(-1)]/3 \qquad (3)$$

$$T_{20} = \frac{1}{\sqrt{2}} \cdot \frac{\rho(1) + \rho(-1) - 2\rho(0)}{\rho(1) + \rho(0) + \rho(-1)} \qquad (4)$$

$$\rho(M) = E_3' \frac{d\sigma_{if}}{d\vec{k}_3'}(M)$$

$$\rho = \frac{(2\pi)^4}{6} \frac{E_1 E_3'}{k_1} \sum_{\substack{M\mu_1 \\ \mu_1'\mu_2'\mu_3'}} \int d\vec{k}_1' \delta(E_i - E_f) |T^{M\mu_1}_{\mu_1'\mu_2'\mu_3'}(\vec{k}_1', \vec{k}_2', \vec{k}_3')|^2, \qquad (5)$$

where M, μ_1, μ_1', μ_2', μ_3' are the deuteron and nucleon spin projections, respectively. When writing the amplitude of process (1), antisymmetrization of the states must be taken into account

$$\boldsymbol{T}_{A(f,i)} \equiv \langle A(f) | \boldsymbol{T} | A(i) \rangle = \delta(\vec{k}_f - \vec{k}_i) \cdot T_{A(f,i)} \qquad (6)$$

which after summing over all final states leads to the appearance of the additional factor 1/2 evaluating the cross section in (5). This means that we cannot perform superfluous summing over the states which correspond to the permutation of identical nucleons. Assuming that nuclear interaction is mainly mediated by two-body forces and following an earlier work of Faddeev [2] and Wallace [3], we write expression (6) in the form:

$$\langle A(f) | \boldsymbol{T} | A(i) \rangle = \langle A(f) | V | A(\psi_{in}) \rangle = \frac{1}{\sqrt{2}} \sum_P \delta_P \langle P(f) | V | \psi_1 \rangle . \qquad (7)$$

Here V is the potential of the three-nucleon system, $V = V_a + V_b + V_c$, and $|A(\psi_{in})>$ is the outgoing scattering state of the system which originates from the initial state $|A(i)>$. The initial state $|\phi_1>$ is the product of the free nucleon state $|p_1>$ and the deuteron wave function $|D_{23}>$ which is antisymmetrized and normalized to unity. Following Faddeev [2], we write the scattering state for the three identical nucleons in the form

$$|A(\psi_{in})> = [\,|\psi_1> + |\psi_2> + |\psi_3>]/\sqrt{3}$$

where the $|\psi_j>$ satisfies the coupled equations

$$\begin{aligned}
|\psi_1> &= |\phi_1> + G_0 T_a [\,|\psi_2> + |\psi_3>] \\
|\psi_2> &= |\phi_2> + G_0 T_b [\,|\psi_3> + |\psi_1>] \qquad (8)\\
|\psi_3> &= |\phi_3> + G_0 T_c [\,|\psi_1> + |\psi_2>]
\end{aligned}$$

G_0 is a free propagator and free-particle two-body transition matrices T_x satisfy the Lippmann-Schwinger equations

$$T_x = V_x(1 + G_0 T_x)\,. \qquad (9)$$

For the specific case of three identical nucleons, the coupled equations (8) degenerate into one equation for the unknown state $|\psi>$. When iterating this equation we obtain the multiple scattering series expansion. In the approximation of the present calculation we neglect the third- and higher-order scattering terms. In addition to the single-scattering contribution (PWIA), we thus include the Glauber double-scattering processes (GDS) as well as corrections to final state interaction (FSI). Using Lippman-Schwinger equation (9) for expression (7) up to the first order of the free propagator, we have:

$$\begin{aligned}
<A(f)|V|A(\psi_{in})> &= \sqrt{3}\,<A(f)|T_a G_0 T_c|\phi_1> + \sqrt{3}\,<A(f)|T_a G_0 T_b|\phi_1> \\
&+ \sqrt{3}\,<A(f)|T_b|\phi_1> + \sqrt{3}\,<A(f)|T_b G_0 T_c|\phi_1> \qquad (10)\\
&+ \sqrt{3}\,<A(f)|T_c|\phi_1> + \sqrt{3}\,<A(f)|T_c G_0 T_b|\phi_1>\,.
\end{aligned}$$

The state $<f|$ which describes a free motion of the three nucleons after reaction (1) is the product of single nucleon states. When evaluating amplitudes (10), the approximation [1, 3] is often used which includes only impulse terms and the energy-conserving parts of double-

scattering terms connected with decomposition:

$$G_0 = P[1/(E - H_0)] - i\pi\delta(E - H_0) . \tag{11}$$

It is hoped that in the deuteron breakup the principal-value part cancels the higher-order scattering terms similar to the case of elastic pD scattering. We proceed here in a different way exploring the method of evaluating the nucleon nucleon wave functions in energy continuum. So we include in our calculations the whole propagator G_0 and expansion (10) up to its first order. Using the Lippmann-Schwinger equation for the NN wave functions and extracting its plane wave part

$$(1 + G_0^- T_x^-) f = \psi_x^- = f + \varphi_x^- \tag{12}$$

expression (10) can be rewritten to the form

$$<A(f) | V | A(\psi_{in})> = \sqrt{3} <A(f) | T_b | \phi_1> + \sqrt{3} <A(f) | T_c | \phi_1>$$

$$+ \sqrt{3} <A(\varphi_a^-) | T_b | \phi_1> + \sqrt{3} <A(\varphi_a^-) | T_c | \phi_1> \tag{13}$$

$$+ \sqrt{3} <A(\varphi_c^-) | T_b | \phi_1> + \sqrt{3} <A(\varphi_b^-) | T_c | \phi_1> .$$

Taking into account the symmetry in indices a, b, c, one can get expression (13) in a more explicit form. We divide it into three parts which describe the plane-wave contribution, final-state part and Glauber double-scattering corrections of our approximation. For the particle with momentum k_3' detected as a proton we have:

$$T_{A(f,i)} = T_0 + T_{FSI} + T_{GDS} \tag{14}$$

$$T_0 = 2 \cdot {}_a<p_1'| \; {}_{bc}<\Phi_0(n_2' p_3') | T_{ab} | \phi_1> + 2 \cdot {}_a<p_2'| \; {}_{bc}<\Phi_0(p_3' n_1') | T_{ab} | \phi_1>$$

$$T_{FSI} = 2 \cdot {}_a<p_1'| \; {}_{bc}<\Phi^-(n_2' p_3') | T_{ab} | \phi_1> + 2 \cdot {}_a<p_2'| \; {}_{bc}<\Phi^-(p_3' n_1') | T_{ab} | \phi_1>$$

$$T_{GDS} = 2 \cdot {}_b<p_1'| \; {}_{ca}<\Phi^-(n_2' p_3') | T_{ab} | \phi_1> + 2 \cdot {}_b<n_1'| \; {}_{ca}<\Phi^-(p_2' p_3') | T_{ab} | \phi_1>$$

$$+ 2 \cdot {}_b<p_2'| \; {}_{ca}<\Phi^-(p_3' n_1') | T_{ab} | \phi_1> + 2 \cdot {}_b<n_2'| \; {}_{ca}<\Phi^-(p_3' p_1') | T_{ab} | \phi_1>$$

$$+ 2 \cdot {}_b<p_3'| \; {}_{ca}<\Phi^-(p_1' n_2') | T_{ab} | \phi_1> + 2 \cdot {}_b<p_3'| \; {}_{ca}<\Phi^-(n_1' p_2') | T_{ab} | \phi_1> .$$

The other terms are either zero or cancel each other. Here indices i,j,k label the momenta, spins and isospins of nucleons. Indices a, b, c determine the action of the two nucleon operators on the appropriate states. The NN wave functions $\langle \Phi_0(N_i' N_j') + \Phi^-(N_i' N_j') |$ are antisymmetrized and normalized to the delta functions[4]. These functions describe a full interaction between nucleon pairs with final momenta $\vec{k}_i'$ and $\vec{k}_j'$. In formula (14) we refer only to a strong interaction ignoring an electromagnetic one, and hence the operator T_{ab} does not depend on isospin.

The terms representing the plane-wave impulse approximation (PWIA) make a main contribution to our amplitudes. As in all the interval of momentum $\vec{k}_3'$ of detected cumulative proton there exists the factor of smallness which is the deuteron wave function of arguments $\vec{k}_1'$ or $\vec{k}_2'$ with respect to that of argument $\vec{k}_3'$, the spectator mechanism plays a dominant role here. In this approximation the cross section and the tensor asymmetry T_{20} can be expressed as a simple combination of the deuteron S and D states. In this case for the PWIA amplitude in (14) we can write:

$$T_0 \doteq -\sum_{\mu_2} T_{\mu_1'\mu_2' \mu_1\mu_2}(N_1' N_2', pn; \vec{k}_1 - \vec{k}_1') \, \Phi^M_{\mu_2\mu_3'}(\vec{k}_3') \, . \tag{15}$$

Here $\Phi^M_{\mu_2\mu_3'}$ denotes the deuteron wave function with the spin projection M and with the nucleon spin projections μ_2, μ_3'. In our calculations we evaluate the NN amplitudes T at energy ϵ which corresponds to the collision of the projectile with the nucleon from the deuteron at rest. In reality this is not the case because that energy varies and depends on an internal motion of the struck nucleon. The corrections for this motion are tightly connected with the off-energy shell problem and require further investigations.

The diagrammatic view of the plane-wave terms as well as the other terms in (14) describing FSI and GDS corrections is presented in fig.5. Studying these diagrams and the underlying kinematics, we have to keep in mind that the method of employing the NN wave functions in energy continuum is limited with respect to a relative energy of that NN pair. We find the wave functions describing the final-state interaction of a nucleon pair as solutions of the Schrödinger equation with a potential and with appropriate asymptotics. We write these functions as a sum over orbital momenta. Higher J-terms of such a decomposition have very small contributions to the measured experimental spectra especially in the region forbidden for free NN kinematics.

This corresponds to our ideas that if we measure protons in this kinematic region, we test small distances in the deuteron which are connected with small orbital momenta. In our paper we have used the potentials [7,8] which include central, spin orbital and tensor forces and can describe the NN scattering data in the appropriate energy region.

Evidently, Schrödinger formalism for energy higher than, say, 350-400 MeV cannot be reasonably applied. On the other hand, we make a convenient assumption that the correlations of a NN pair with higher relative momenta are weaker than for that with smaller ones. So, we neglect residual interactions of the detected proton with the forward fast moving particle with respect to those between slow nucleons. Under this assumption for the FSI and GDS terms in (14) we write:

$$T_{FSI} = - \sum_{\bar{\mu}_j \mu_2} T_{\mu_1' \bar{\mu}_j \, \mu_1 \mu_2} (\vec{k}_d) \cdot {}_{\bar{\mu}_j} R^{M}_{\mu_2} (\vec{k}_d, \vec{k}_f, \mu_2', \mu_3', T' = 0) \qquad (16)$$

$$T_{GDS} = \sum_{\bar{\mu}_k \mu_2} T_{\bar{\mu}_k \mu_1' \, \mu_1 \mu_2} (\vec{k}_1') \cdot \frac{1}{2} [{}_{\bar{\mu}_k} R^{M}_{\mu_2} (\vec{k}_d, \vec{k}_f, \mu_2', \mu_3', T' = 0) +$$

$$+ {}_{\bar{\mu}_k} R^{M}_{\mu_2} (\vec{k}_d, \vec{k}_f, \mu_2', \mu_3', T' = 1)] . \qquad (17)$$

Of particular physical interest in the present formalism is quantity R used in (16)-(17) which can be in principle measured in the experiment. This quantity can be interpreted in a model-dependent way. In the model used it corrects the deuteron wave function in (15). It represents the overlap integral of the deuteron wave function and the part of the NN wave function responsible for residual interactions.

$${}_{\bar{\mu}_j} R^{M}_{\mu_2} (\vec{k}_d, \vec{k}_f, \mu_2', \mu_3', T') =$$

$$= \int d\vec{r} \, e^{-i \vec{k}_d \vec{r} / 2} \, \Phi^{-*}_{\bar{\mu}_j \mu_k} (\vec{r}; \vec{k}_f, \mu_2', \mu_3', T') \, \Phi^{M}_{\mu_2 \mu_k} (\vec{r}) . \qquad (18)$$

The function Φ^- describes the residual interaction of the NN pair with isospin T', relative momentum $\vec{k}_f$ and the total momentum $\vec{k}_d$. The magnetic quantum numbers $\bar{\mu}_j$, μ_k and μ_2', μ_3' are nucleon spin projections before and after interaction.

III. Summary

We have plotted the results of our calculation of the invariant cross sections (5) and the tensor asymmetry T_{20} (4) together with the experimental $\vec{d}p$-breakup data [1] at a deuteron energy of 1.25 and 2.1 GeV. The kinematic limits for the detected proton momenta are 0.3 GeV/c and 0.38 GeV/c, respectively. Our calculation uses the Paris deuteron wave function [6]. The NN amplitudes describing the interaction of the incoming and the first wounded nucleon were taken from [5]. The potentials for the lowest orbital NN canals used to describe residual interactions were taken from [7,8]. We have tested a correct energy behaviour of the corresponding phases.

In the PWIA framework for the reaction canal $p\vec{d} \rightarrow ppn$ we get a relatively good description of the shapes of the invariant cross sections as can be seen in figs.1 and 3. The inclusive T_{20} data are partially reproduced, but for proton momenta $q > 0.18$ GeV/c there exists an evident discrepancy between the PWIA and the data. When switching on our corrections, we see that the final-state interaction plays a more significant role than the Glauber double scattering effects. This is perceived and demonstated in figs.2 and 4. These secondary effects reduce the cross section in the momentum region $q < 0.25$ GeV/c up to 20 %. For higher energy data FSI causes a slight increase of the cross section in the region $q > 0.25$ GeV/c up to about 10 %. The secondary effects have a very large influence on T_{20} at both energies. Though the full description was not achieved, a ditch in its behaviour seems to be filled. The insufficiency in cross section at higher energy for low proton detected momenta can be connected with π-production not included in the calculation. The π threshold at 2.1 GeV is near $q = 0.3$ GeV/c.

To conclude our results, we find that interaction in the final state of the disintegrated deuteron, in particular in canals $^1P_1$, $^3S_1 - {}^3D_1$, $^3D_2$, has in a medium energy region a certain influence on an invariant cross section and corrects substantially the behaviour of the tensor asymmetry T_{20}. We note here that similar conclusions have been made for the inclusive deuteron breakup at higher energies [9] and also for the processes of the deuteron electro-disintegration [10].

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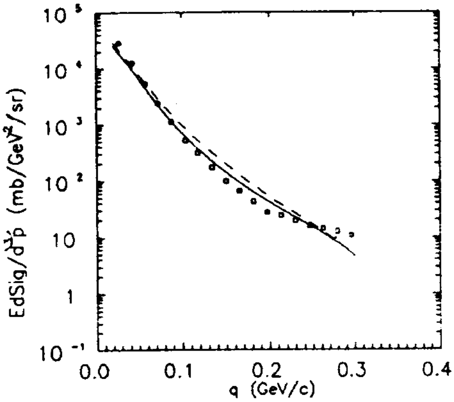

Fig.1. The inclusive H(d, p)X invariant cross section of ref.1 at a deuteron energy of 1.25 GeV plotted versus the proton momentum in the deuteron frame compared with the PWIA and the full calculation results. □□□□ — experimental data, – – – — PWIA, ——— — PWIA + FSI + GDS (S, P, D waves).

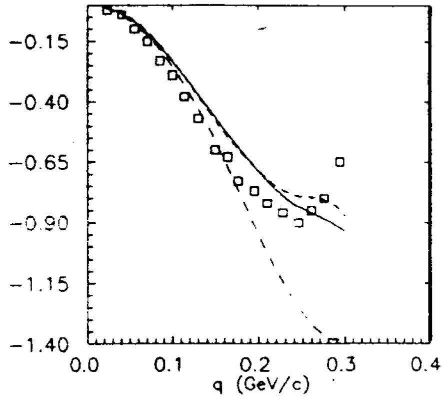

Fig.2. The T_{20}data of ref.1 at 1.25 GeV compared with the PWIA and with the complete calculation. □□□□ — Experimental data, – – – — PWIA, ——— — PWIA + + FSI + GDS (S, P, D waves), ----- — PWIA + FSI.

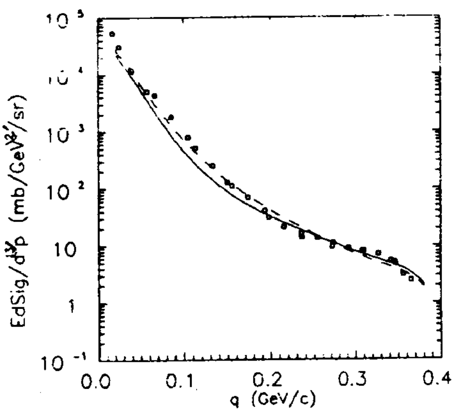

Fig.3. The inclusive H(d,p)X invariant cross section of ref.1 at a deuteron energy of 2.1 GeV, plotted versus the proton momentum in the deuteron frame compared with the PWIA and full calculation results. □□□□ — experimental data, – – – — PWIA, ——— — PWIA + + FSI + GDS (S, P, D waves).

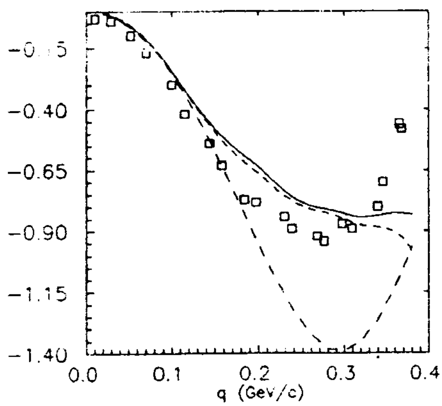

Fig.4. The T_{20} data of ref.1 at 2.1 GeV compared with the PWIA and with the complete calculation. □□□□ — experimental data, – – – — PWIA, ——— – PWIA + + FSI + GDS (S, P, D waves), ----- — PWIA + FSI.

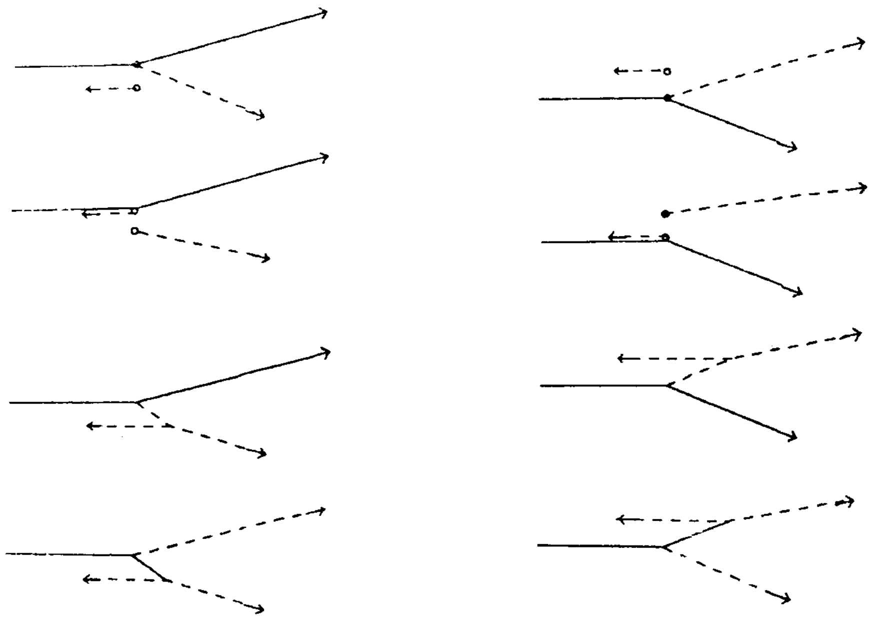

Fig.5. The first and second order diagrams representing the PWIA together with the secondary interactions in the deuteron breakup considered in our analyses. In the calculations we neglect graphs corresponding to residual interactions of the detected proton (momentum $\vec{k}'_3$) with the forward fast moving nucleon (momentum $\vec{k}'_1$) with respect to those concerning the slow forward moving particle (momentum $\vec{k}'_2$). The solid lines represent the projectile proton.

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