ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ

Дубна

E1-98-319

FRAGMENTATION OF TENSOR POLARIZED DEUTERONS INTO CUMULATIVE PIONS

Submitted to «Physics Letters B»

1998

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To study the deuteron core structure, a number of experiments in a GeV region including the polarization ones, have been performed in the last two decades. The nucleon momentum distributions in a deuteron, extracted from the deuteron breakup [1] and *ed*- inelastic scattering [2], are in good agreement with each other confirming that both hadron and electron probes give reliable information on the deuteron structure. These data were reproduced rather well by the relativistic impulse approximation (IA) calculations using conventional deuteron wave functions (DWF) [3, 4] at internal momenta up to $k = 0.25$ GeV/c [5]. In the higher momentum region, however, a marked deviation from the calculations was observed. Taking into account additional mechanisms to IA [6, 7] gives a satisfactory description of the momentum distribution data.

A deviation from IA was also observed in the data on the tensor analyzing power T_{20} for deuteron inclusive breakup with the emission of the proton at a zero angle [8, 9, 10] and for *dp*- backward elastic scattering [11, 12] as shown in Fig.1. The same values of T_{20} are assumed in both reactions since one nucleon exchange mechanism is to be dominant in both of them. However, the data for these reactions disagree in a high momentum region. Furthermore, the *dp*-backward data demonstrate a strong oscillation structure in the region $k > 0.3$ GeV/c. The experimental data over all internal momentum region cannot be described by . the calculations taking account of additional mechanisms to IA [6, 13] or considering additional components to the DWF due to relativistic effects [14, 15, 16, 17]. On the other hand, the behavior of T_{20} at high nucleon momenta is explained by the models incorporating the non-nucleonic degrees of freedom in the deuteron [18, 19]. These theoretical investigations give different explanations to the data on different reactions, in particular in a high momentum region, based on different pictures of the deuteron core structure and nucleon correlations at short distances. It is desirable to have a global picture which could explain the data.

The deuteron fragmentation into cumulative hadrons is one of the suitable reactions to study the deuteron core structure. Cumulative hadrons are those produced in a nuclear reaction beyond the kinematic limit of free nucleon-nucleon collisions. [20] [21]. The simplest model used to describe their production is a direct mechanism, where a nucleon with a high momentum in the projectile, for instance in the deuteron, collides against a nucleon in the target nucleus and produces a cumulative hadron (e.g. $NN \to NN\pi$) [22]. The fea-

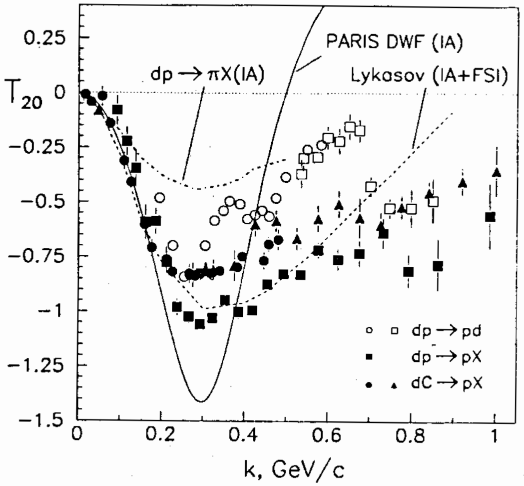

Fig.1. The experimental data for the reactions induced by tensor polarized deutrons in GeV region: the T_{20} data for deuteron breakup $dA \to pX$ on the hydrogen and carbon targets [8, 9, 10]; and the T_{20} data for backward elastic $dp \to pd$ [11, 12]. The solid curve is the IA calculation with the Paris DWF [3] for both breakup and backward elastic scattering, and the dashed curve is the calculation [6] taking account of final state interactions for breakup at 9GeV/c. The direct mechanism IA-prediction for $dC \to \pi(0^\circ)X$ [23] is also shown (dot-dashed curve).

tures of cumulative reactions reflect the nuclear structure at small distances where short range nucleon correlations take place. In case of the deuteron, spin observables in the fragmentation of deuterons into cumulative hadrons allow one to extract information on the deuteron core spin structure.

In order to compare the data on cumulative hadrons obtained under different kinematic conditions, the cumulative variable x_c ("cumulative number") [20] [23] is often used in the literature. For the reaction of cumulative pion production, $A + B \to \pi + X$, it is expressed as

$$x_c = \frac{(p_B p_\pi) - (m_\pi^2/2)}{(p_A p_B) - m_N^2 - (p_A p_\pi)}, \qquad (1)$$

where p_A, p_B are the four-momenta per nucleon for projectile and target nuclei, respectively, p_h is the four-momentum of the produced pion, m_N and m_π are

the nucleon and pion masses. In its meaning, the cumulative number, x_c, is a minimum target mass (measured in nucleon mass units) in the rest frame of a fragmenting nucleus needed to obey the 4-momentum conservation law for particle production in nucleon-nucleus collision. Hence, its range is up to A, the mass number of the fragmenting nucleus. When the hadron with x_c larger than 1 is produced, it is assigned to a cumulative hadron. The backward elastic scattering $dp \to pd$ is the special case of cumulative reactions when $x_c = 2$. In the framework of the direct mechanism, the cumulative hadron is produced by a nucleon with a high internal momentum k in the fragmenting nucleus. Hence, the minimum momentum of the nucleon, k_{min}, which is wanted for cumulative hadron production can be related to x_c: k_{min} increases from 0 as x_c increases from 1. In this paper, the data on the tensor analyzing power T_{20} at the fragmentation of deuterons into cumulative pions are presented vs the variables x_c and k_{min}.

The first measurement of T_{20} in cumulative pion production in the forward direction

$$\vec{d} + A \to \pi^\pm(0^\circ) + X \qquad (2)$$

has been performed in our previous experiment [23] using a carbon target. The values of $|T_{20}|$ were found to be about one order smaller than those predicted by the IA calculations. However, it might be due to the nuclear effect of carbon target. Moreover, it was difficult to achieve definite conclusion concerning the sign of T_{20} due to large errors.

Here, we report new data on T_{20} obtained in the fragmentation of deuterons into negative pions on hydrogen, beryllium and carbon targets ($A = 1, 9, 12$) at a zero emission angle over the range of the cumulative variable x_c from 1.08 to 1.76. The values of T_{20} were determined by measuring the ratio of pion yields (N^+/N^-) emitted at forward angles ($\theta_\pi \leq 15mrad$) at different tensor polarizations ($p_{zz}^\pm$) of the deuteron beam:

$$T_{20} = \frac{2\sqrt{2}(\frac{N^+}{N^-} - 1)}{\frac{N^+}{N^-}p_{zz}^- - p_{zz}^+}. \qquad (3)$$

The measurements were carried out with a 9 GeV/c polarized deuteron beam slowly extracted from the Dubna 10 GeV accelerator (Synchrophasotron). The ion source POLARIS [24], operating in the tensor polarization mode, provided three tensor polarization states "+, −, 0" ("0" means the absence of polarization). A series of polarization states was cyclically repeated every three spills. The beam polarization was measured with the two-arm polarimeter ALPHA [25] by detecting dp- elastic scattering at a deuteron momentum of

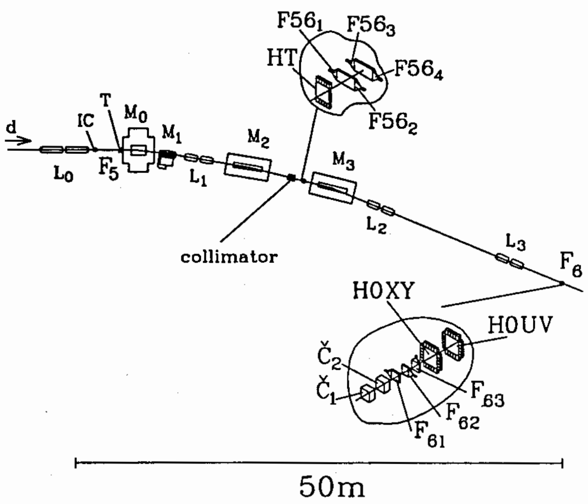

Fig.2. The layout of the setup of the 4V beam line in the Synchrophasotron experimental hall. M_i; bending magnets, L_i; quadrupole magnets, F_i, C_i; scintillation and Cherenkov counters, $HT, H0XY, H0UV$; scintillation hodoscopes, T; target, IC; ionization chamber.

3 GeV/c [26]. The values of tensor polarization for the "+" and "−" states were $p^+_{zz} = 0.643 \pm 0.033(stat) \pm 0.026(syst)$ and $p^-_{zz} = -0.729 \pm 0.024(stat) \pm 0.029(syst)$. To study beam polarization stability for a 5-day run, the beam line polarity was switched periodically to register protons and the T^p_{20} of the deuteron breakup reaction $\vec{d} + C \to p(0^\circ) + X$ was measured (24 times in all). The value of T^p_{20} at $k \sim 0.3 GeV/c$ averaged over the run is shown by a star in Fig.1. It is consistent with the data obtained in other experiments [8] [9]. The analysis of T^p_{20} fluctuations during the run showed that the values of polarization remained stable within ±2% [27].

The deuteron beam intensity was 1.5 to $2.5 \cdot 10^9$ $\vec{d}$/spill. The duration of the beam spill was 0.5 s. The deuterons with a fixed momentum of 9 GeV/c were led to the target T located at focus F5, the starting point of secondary beam line 4V as shown in Fig.2. The position of the beam and its profile (σ_x =4 mm, σ_y=9 mm) at the target point were monitored with the multiwire chambers. The beam intensity was monitored with the ionization chamber IC placed 1 m upstream the target. The magnetic optics of line 4V, consisting of four magnetic dipoles M0-M3 and three quadrupole doublets L1-L3, provided a momentum resolution of $\sigma_p/p = \pm 2.3\%$ and an angular acceptance of $\Delta\Omega = 2.1 \cdot 10^{-4}$ sr. The particles produced in the target were

led to final focus F6 located 42 m downstream the target. The scintillation hodoscopes H0XY and H0UV were used to control the beam size at F6.

The detecting system consists of two counter sets as shown in Fig.2. One set, a scintillation hodoscope HT and counters $F_{56_{1-4}}$, was placed behind the collimator at the intermediate beam focus, and the other, counters $F_{6_{1-3}}$, was 27 m downstream at focus F6. Pions were selected by time of flight (TOF) between the intermediate focus and the focus F6 with a time resolution of σ_{TOF}=0.2ns. To reject background due to the pile-up effect in $F_{56_{1-4}}$, a correlation of two TOF pairs was required. Although events corresponding to pions are only seen in the TOF spectrum, muons from the pions decay should contribute to the peak. Their number was estimated to be no more than 8% [23]. It was confirmed by GEANT simulation [28] that they originate mainly from pions decaying in the final section of beam line 4V. For this reason we did not exclude muon events when we calculate the N^+/N^--ratio to extract T_{20} according to (3).

The pion momentum p_π varied from 3.5 to 5.3 GeV/c at a fixed deuteron beam momentum of p_d=9.0 GeV/c to range x_c from 1.08 to 1.76. The measurements at p_π=3.5, 4.0, 4.5 and 5.0 GeV/c were carried out with the hydrogen target (7 g/cm^2). To study the target dependence, the measurement at p_π=5.0 GeV/c was performed also with the beryllium target (36 g/cm^2), and the highest x_c point , x_c=1.76, was taken with the carbon target (55 g/cm^2). Such relatively thick targets do not affect on the T_{20}. According to (3) the T_{20} depends on the N^+/N^--ratio only at fixed $p^\pm_{zz}$. It means that the results of T_{20}-measurements are not affected by the distortion of the cumulative pion spectra due to secondary interactions in a target and beamline materials as the distortion factor is the same for both polarization states of the primary deuteron beam. Monte Carlo simulation shows that pion rescattering in the carbon target (55 g/cm^2) increases the angular acceptance by 10% with respect to a thin target; an effective value of x_c increases by $\simeq 2\%$ due to energy losses and πA-interactions in the target. Experience in studying T_{20} in deuteron breakup confirmed its independence of target thickness [9] [10]. The background pions not from the target, were measured to be about 3% for a 36 g/cm^2 target and 8% for a 7 g/cm^2 target. They cannot change radically the N^+/N^--ratio. To estimate an effect of pions originated not from the reaction (2) which can affect on N^+/N^-, we estimated a contribution from the two step process where high momentum nucleons from a deuteron breakup produce high momentum pions in secondary collisions in a target: $dA \to NX$, $NA \to \pi X$. Our numerical estimations for a thick target (55 g/cm^2), based on the known approximation of the cross sections near the kinematic limit for $NA \to \pi X$ [29] , showed that the contamination of pions from this process is no more than 1%.

Table 1 presents values on T_{20} obtained in this experiment for π^- production as a function of x_c and k_{min}. At Fig.3 the new T_{20} data are plotted together with the $\pi^{\pm}$ data obtained in the previous experiment on carbon [23].

Table 1

T_{20} as a function of x_c and k_{min} ; δx_c is the width of x_c-bin (1σ) due to the beam momentum resolution and energy losses in the target with the indicated thickness Δ_T (g/cm^2). All the momenta (p_π, k_{min}) are in GeV/c. The invariant cross section $\sigma_{inv} = E_\pi d\sigma/d^3p_\pi$ is in $\mu b \cdot GeV^{-2} \cdot c^3 \cdot sr^{-1}$/nucleus, the uncertainty of σ_{inv} is estimated to be equal to 20%. The systematic error of T_{20} is caused by the uncertainty of beam polarization.

p_π	Target	Δ_T	x_c	δx_c	k_{min}	$\sigma_{inv}(x_c)$	$T_{20} \pm stat. \pm sys.$
3.5	H	7.1	1.08	±0.03	0.051	23.5	$0.064 \pm 0.059 \pm 0.004$
4.0	H	7.1	1.25	±0.03	0.155	19.6	$0.048 \pm 0.047 \pm 0.003$
4.5	H	7.1	1.43	±0.04	0.270	3.53	$0.120 \pm 0.058 \pm 0.008$
5.0	H	7.1	1.61	±0.04	0.392	0.75	$0.158 \pm 0.098 \pm 0.010$
5.0	Be	36	1.63	±0.04	0.396	6.59	$0.128 \pm 0.056 \pm 0.008$
5.3	C	55	1.76	±0.05	0.520	1.81	$0.162 \pm 0.118 \pm 0.010$

Comparing the values of T_{20} obtained on hydrogen, beryllium and carbon targets, T_{20} in pion production was found to be independent of the mass number of the target. Although a weak target dependence was seen in the inclusive cross sections for cumulative hadron production [30] [31], it is evident that T_{20} is predominantly ruled by the internal structure of the fragmenting nucleus, in this case the deuteron.

In the framework of the direct mechanism, the increasing x_c corresponds to the increasing k_{min}, thus decreasing internucleonic distances r_{NN}. Using the momentum-space transformation, r_{NN} is evaluated to be $r_{NN} \simeq 0.4$ fm at x_c=1.7. This internucleonic distance corresponds to a large D-wave contribution to the DWF, and therefore a large value of the tensor analyzing power could be expected. The results of the calculations [23] performed in the framework of the direct mechanism using the Paris DWF [3] are shown in Fig.3. It is notable that the measured values of T_{20} have a positive sign opposite to the sign predicted by the calculations. The value of T_{20} is nearly zero at x_c=1.0 and increases up to $\simeq 0.15$ at $x_c = 1.7$ not showing an extremum at $k \simeq 0.3$ GeV/c peculiar to IA predictions (Fig.1). Taking account of relativistic effects

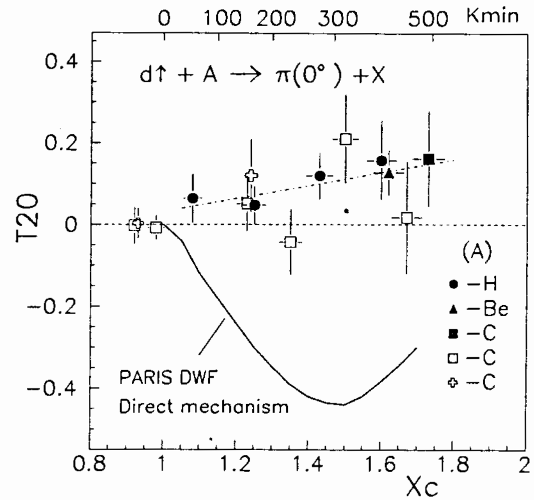

Fig.3. T_{20} vs x_c and k_{min}(MeV/c) for the reaction $\vec{d} + A \to \pi^-(0^\circ) + X$ at the fragmentation of 9 GeV deuterons on the hydrogen, beryllium and carbon targets obtained in this experiment along with the previous data [23] obtained with the carbon target for π^- (open squares) and π^+ (open cross). The dashed line is a linear fit of the data ($\chi^2/d.o.f.$=0.5). The solid curve is our calculation based on the Paris DWF [23].

[32] or processes additional to the direct mechanism like π-rescattering [33] cannot explain such a behaviour of $T_{20}(k)$.

The deuteron spin structure is also studied in the experiments with electron probes [35] [36] although the data are limited within a lower internal momentum region. Based on the hypothesis of NN-core in the deuteron, oscillating behavior of the tensor analyzing power due to variation of the D-wave contribution was predicted for *ed-* elastic scattering and also for cumulative pion production [34]. The available T_{20} data for *ed-* elastic scattering [35] [36] confirmed this prediction. Hence, we can conclude that IA calculations are successful in all previously studied reactions induced by deuterons (the deuteron breakup and dp-,ed-scattering) at low internal momenta; on the contrary, a marked deviation from IA is observed at higher k (> 0.3 GeV/c). It is different in form in different reactions as shown in Fig.1. The reasons of these deviations were discussed by many authors: in particular, final state interactions and non-nucleonic contributions (NN^*,$\Delta\Delta$ or $6q$- configurations) in the DWF were considered.

In the case of cumulative pion production, we met a more serious problem: the sign of $T_{20}(k)$ was found to be opposite to the IA calculation over the whole region of internal momenta from 0 to 0.5 GeV/c studied in the experiment. This contradiction seems not to be solved by any current models, based on the traditional picture of the deuteron as a bound state of a neutron and a proton. It may be more successfully the T_{20} pion data can be explain by introducing quark scenarios for cumulative meson production [37] [38], where the deuteron core is considered as a multiquark configuration and a quark-spectator with a high momentum is softly hadronized into a cumulative particle. To explain the behaviour of spin observables in cumulative hadron production the similar quark approaches introducing in consideration of spin degrees of freedom in nuclei should be developed.

The results of the present work are the following:

– The tensor analyzing power T_{20} of the reaction $\vec{d}+H(Be,C) \to \pi^-(0°)+X$ at a deuteron momentum of 9 GeV/c and pion momenta from 3.0 to 5.3 GeV/c has been measured . In the framework of the direct mechanism, this kinematic region corresponds to internal momenta of the nucleon in the deuteron up to $k \simeq 500$ MeV/c.

– It has been observed that the behavior of T_{20} is independent of the atomic number of the target. This fact and a weak A-dependence of the cross section shape of deuteron fragmentation into cumulative pions [30] [31] evidently confirm that T_{20} is predominantly determined by the internal structure of the deuteron.

– The sign of the measured T_{20} is positive and opposite to that obtained by the calculations using standard DWFs assuming the direct mechanism. The T_{20} data cannot be reproduced by relativistic corrections or taking pion rescattering into account either. Attention should be given to more sophisticated approaches taking account of non-nucleonic degrees of freedom in nuclei.

The authors are grateful to the LHE accelerator staff and to the cryogenic division staff supporting POLARIS and the liquid hydrogen target operation, especially to A.Kovalenko, A.Kirillov, L.Golovanov, V.Fimushkin, V.Ershov, Yu.Borzunov, A.Tsvinev. We would like to thank L.Strunov, V.Sharov, and A.Nomofilov for the primary deuteron polarization measurements by the AL-PHA polarimeter. .

This research was supported in part by Russian Foundation for Fundamental Research under grant No. 96-02-17208 and by Japan Society for the Promotion of Science(JSPS), Daikou Foundation and Toyota Foundation.

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Received by Publishing Department
on November 12, 1998.