Measurement of the Tensor Analyzing Power T_{20} for $d^{\uparrow}+{}^{12}C \rightarrow p(0°)+X$ in the Region of High Internal Momenta in the Deuteron

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The tensor analyzing power T_{20} for the reaction $d^{\uparrow} + {}^{12}C \rightarrow p(0°) + X$ has been measured in the region of proton internal momenta k in light-cone dynamics up to 1 GeV/c. Measurements have been carried out at Dubna Synchrophasotron with polarized deuteron beam at deuteron momenta up to 9 GeV/c. When k increases the experimental values of T_{20} have a tendency to approach the value (-0.3) obtained by the calculation based on the reduced nuclear amplitude method in which the quark degrees of freedom are taken into account.

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The investigation of the deuteron structure at small internucleon distances (high internal momenta) is one of the most interesting subjects in nuclear physics. At small distances the wave functions of two nucleons in deuteron overlap each other strongly and the quark-gluon degrees of freedom are expected to emerge rather than the nucleon-meson degrees of freedom. The internal structure of the deuteron has been studied at short distances in the reactions $d + A \rightarrow p + X$ at 0° [1–8], $\gamma d \rightarrow pn$ [9], in inelastic [10] and elastic ed scattering at a large angle [11], and in dp elastic backward scattering [12]. The Dubna group has measured the cross section of the forward breakup reaction $d + C \rightarrow p + X$ with 8.9 GeV/c unpolarized deuteron beam at the proton momenta in the deuteron rest frame up to 0.58 GeV/c [2] (in light-cone frame [13] the corresponding internal momentum $k = 1.2$ GeV/c). The momentum spectrum obtained in the experiment was not well reproduced by the models using conventional wave functions [14,15]. On the contrary, the model with the hybrid deuteron wave function [2,16], including a small amount of six-quark admixture, described the data satisfactorily. This model also described T_{20} data obtained in the experiments at Saclay [3,4] and Dubna [5]. In accordance with the maximum deuteron beam momenta available at Saclay (3.75 GeV/c) and Dubna (9.0 GeV/c), the deuteron stripping process can be studied in $dp \rightarrow p(0°)X$ reaction up to internal momenta k of 0.57 and 1.04 GeV/c, respectively, and up to somewhat smaller momenta in $dA \rightarrow p(0°)X$ reaction [17]. The first measurements of T_{20} performed at Dubna by the Alpha group [5] contained rather large errors at k higher than 0.70 GeV/c. Recently, new measurements of T_{20} have been performed by the Anomalon group at Dubna, with the smaller errors [6]. T_{20} up to $k = 0.82$ GeV/c was found to be still negative and more similar to the QCD prediction [18] than to the calculations with conventional wave functions. A crucial test to determine which of the theoretical approaches is more adequate to describe T_{20} behavior at the highest internal momenta should be made at $k > 0.80$ GeV/c where the calculations of T_{20} with conventional wave functions give considerably different values of T_{20} against the QCD prediction.

In this paper we report the results of the tensor analyzing power T_{20} measurement for reaction $d^{\uparrow} + {}^{12}C \rightarrow p + X$ by detecting the protons emitted at forward angles $\Theta_p \leq 1.3°$. The goal of the experiment was to measure T_{20} with a good accuracy up to the highest k available with the polarized deuteron facility of JINR (Dubna) Synchrophasotron. The measurements have been carried out at 4.5, 6.5, and 7.5 GeV/c of beam line momenta for the emitted protons. To vary the internal k at fixed beam line momentum we changed the momentum of the incident tensor polarized deuterons from 6.0 to 9.0 GeV/c. The momentum k, called internal momentum in light-cone dynamics, is expressed by the following formula (see, for example, [13,16]):

$$k^2 = \frac{m_\perp^2}{4\alpha(1-\alpha)} - m_p^2 , \qquad (1)$$

with $m_\perp^2 = k_\perp^2 + m_p^2$ where $k_\perp$ is the proton transverse momentum. Its mean weight value is estimated as ~0.04 GeV/c for our beam line angular acceptance. The light-cone variable α is the part of the deuteron momentum carried by the proton in the infinite momentum frame [19,20] and is expressed by the formula $\alpha = (E_p + P_p)/(E_d + P_d)$. At low internal momenta the value of k is close to the proton momentum in the deuteron rest frame q. The longitudinal component of q is obtained by the Lorentz transformation of the laboratory proton momentum: $q_\parallel = \gamma(P_\parallel - \beta E_p)$ with $\gamma = E_d/m_d$

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and $\gamma\beta = P_d/m_d$, where $P_\parallel = P_p \cos\Theta_p \sim P_p$; P_p, E_p and P_d, E_d are the momenta and energies of proton and deuteron, respectively. In this paper we prefer to use the variable "k" as widely applied in analysis of the relativistic bound states [13,18,21,22].

The polarized deuterons at the Dubna Synchrophasotron are provided by the Polaris ion source [23]. The Polaris possesses the ability to operate in either the vector or tensor polarization modes and repeat pulse by pulse any combination of three polarization states "+," "0," and "−," where + and − denote positive and negative polarization states and 0 denotes the unpolarized state. A negligible depolarization at the Synchrophasotron was confirmed experimentally in the vector polarization mode [24]. For T_{20} data taking we used + and − polarization states in the tensor polarization mode. Typical beam intensity was $\sim 2 \times 10^9$ deuterons/pulse. The values of the deuteron beam polarization components were measured by detecting dp elastic scattering at 3 GeV/c with the fast two-arm-beam-line polarimeter Alpha [24]. The tensor and admixture vector polarizations of the beam were $p_{zz}^+ = +0.543 \pm 0.013(\text{stat}) \pm 0.022(\text{syst})$, $p_z^+ = 0.222 \pm 0.007(\text{stat}) \pm 0.004(\text{syst})$ for + polarization state and $p_{zz}^- = -0.709 \pm 0.013(\text{stat}) \pm 0.028(\text{syst})$, $p_z^- = 0.200 \pm 0.010(\text{stat}) \pm 0.004(\text{syst})$ for − polarization state. To estimate the systematical errors for the measured p_z and p_{zz} values we took total uncertainties for the known analyzing powers A_y and A_{yy} for dp elastic scattering [25]. T_{20} for the reaction $d^\uparrow + {}^{12}\text{C} \rightarrow p(0°) + X$ is derived from the differential cross sections defined by the formula

$$\sigma^\pm = \sigma^0(1 - \tfrac{1}{2}\rho_{20}^\pm T_{20}), \quad (2)$$

where σ^+ and σ^- are the cross sections for positive and negative aligned beams, σ^0 for unpolarized beam, and $\rho_{20} = p_{zz}/\sqrt{2}$ is the beam alignment in spherical form. Then T_{20} is reduced to

$$T_{20} = \frac{2(n^+ - n^-)}{n^+\rho_{20}^- - n^-\rho_{20}^+}, \quad (3)$$

where n^+ and n^- are counts of the detected protons normalized by the deuteron beam intensities for positive and negative alignments.

The stripping reaction $d^\uparrow + {}^{12}\text{C} \rightarrow p + X$ occurred in the carbon target located at the beam line focus $F3$ (see Fig. 1). The target was 30 cm (50 g/cm^2) along the beam and 6 cm across it, while the beam spot at $F3$ did not exceed 3 cm. The beam position at $F3$ was under control of a multiwire ionization beam profilemeter and was found stable within ± 1 mm in the data taking time. The deuteron beam intensity was measured by an ionization chamber placed in front of the carbon target. The quadrupole magnet located 4.5 m downstream from $F3$ accepted the particles emitted at angle $\Theta_p \leq 1.3°$. The beam line, consisting of bending magnets ($B1, B2, B3$) and quadrupole magnets, selected the particles with the required momentum; the momentum bite of the beam line was $\pm 2\%$. Two independent time of flight (TOF) counter systems were used for particle identification. The TOF counters were placed at $F4$, $F5$, and $F7$. The particles which passed through the beam line were detected by the magnetic spectrometer Anomalon [26] located at $F7$ (Fig. 2). A momentum resolution of the spectrometer was equal to 0.76% for 7.5 GeV/c protons. The event trigger logic of data acquisition was made according to $(N1 \times M1 \times S2 \times S3) \times (\text{TX1} \times \text{TX2})$ where $N1$, $M1$, $S2$, and $S3$ were trigger counters located at $F7$. Fourfold coincidences $N1 \times M1 \times S2 \times S3$ formed a beam particle signal. TX1 and TX2 were TOF counters; the first one was located at $F4$ and the second at $F7$. These TOF counters were used to suppress the deuteron events at the stage of fast triggering. To select the proton events the final particle identification was carried out by another TOF counter system: the start timing signal of the time-to-digital convertor (TDC) was fed from TOF counter $N1$ located at $F7$, and the stop timing signals were sent from two TOF counters $N2$ at $F4$ and $M2$ at $F5$. This system gave us two TOF timings: One is between $F4$ and $F7$ (72 m) and the other is between $F5$ and $F7$ (45 m). In the off-line analysis the correlation of these TOF timings was examined and the uncorrelated events were discarded. A typical two-dimensional plot of TOF (72 m) versus momentum is shown in Fig. 3. One can see that protons are clearly separated from deuterons.

To derive the k dependence of T_{20} we divided the events obtained with the given deuteron and beam line momenta into several k bins (typically into three to five with bites of 50 to 80 MeV/c). For some k bins we have

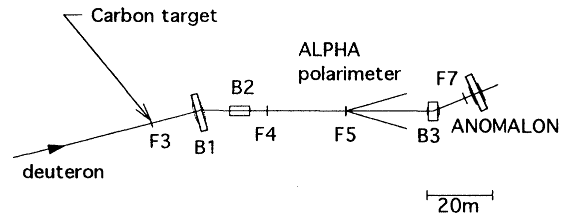

FIG. 1. Schematic layout of the beam line. B denotes the bending magnets. $F3$, $F4$, $F5$, and $F7$ are the focusing points.

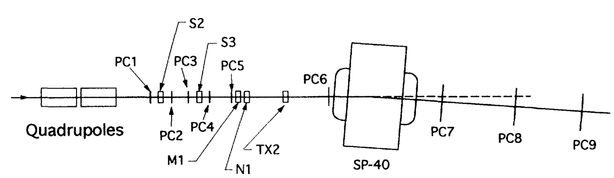

FIG. 2. Schematic layout of spectrometer Anomalon. SP40, analyzing magnet; PC1−7, three-dimensional (X, U, V) MWPCs; and PC8,9, two-dimensional (X, Y) MWPCs; $S2, S3, N1, M1$,TX2, trigger and TOF scintillation counters.

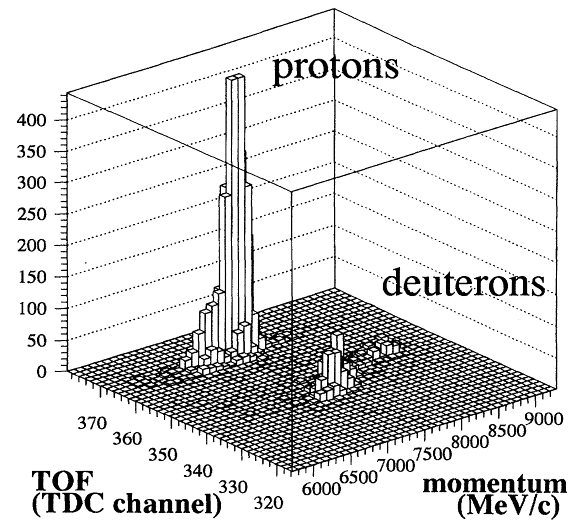

FIG. 3. The two-dimensional plot of TOF versus momentum for the detected events at the deuteron beam momentum 8.7 GeV/c and the beam line momentum 7.5 GeV/c. The TOF time scale (one digit of the TDC) was 220 ps/channel.

TABLE I. T_{20} as a function of k, q, and α. δk denotes uncertainty of k due to our momentum resolution for breakup protons. The k, δk, and q are in MEV/c.

k	δk	q	α	T_{20} ± stat ± syst
47	7	47	0.500	−0.083 ± 0.027 ± 0.003
275	10	235	0.640	−0.833 ± 0.057 ± 0.033
325	11	269	0.664	−0.810 ± 0.047 ± 0.032
375	12	301	0.686	−0.790 ± 0.072 ± 0.032
425	13	330	0.706	−0.600 ± 0.056 ± 0.024
475	14	358	0.726	−0.583 ± 0.049 ± 0.023
525	15	383	0.744	−0.663 ± 0.053 ± 0.027
575	17	406	0.761	−0.572 ± 0.060 ± 0.023
625	19	427	0.777	−0.506 ± 0.062 ± 0.020
675	21	447	0.792	−0.570 ± 0.093 ± 0.023
725	23	465	0.806	−0.601 ± 0.057 ± 0.024
775	25	481	0.818	−0.520 ± 0.053 ± 0.021
840	29	500	0.833	−0.453 ± 0.048 ± 0.018
920	35	521	0.850	−0.400 ± 0.063 ± 0.016
1000	38	539	0.864	−0.351 ± 0.116 ± 0.014

obtained data at different deuteron momenta P_d. The T_{20} values corresponding to the same k bins but different P_d are displayed in Fig. 4. One can conclude that there is no indication that T_{20} depends on P_d, in accordance with the observations made in [4]. The events for the same k bins were combined and the T_{20} values were calculated. The final T_{20} values are shown in Table I as a function of k, q, and α and plotted in Fig. 5 with the data of other groups and theoretical predictions. Our data are in good agreement with the Alpha group data [5] in the region where they overlap and the Saclay data [3] below $k = 0.50$ GeV/c. We have not observed the structure in the region around $k = 0.54$ GeV/c which is seen in Saclay data [3]. We suppose that this structure is a result of the interference of two processes: deuteron stripping reaction and background dp quasielastic scattering [17]. For this reason, the Saclay points at $k \gtrsim 0.50$ GeV/c should be excluded from the comparison with our data.

Our data in the high internal momentum region, $k >$ 0.85 GeV/c, have shown a tendency to approach the QCD motivated asymptotic prediction ($T_{20} \to -0.3$) [18] based

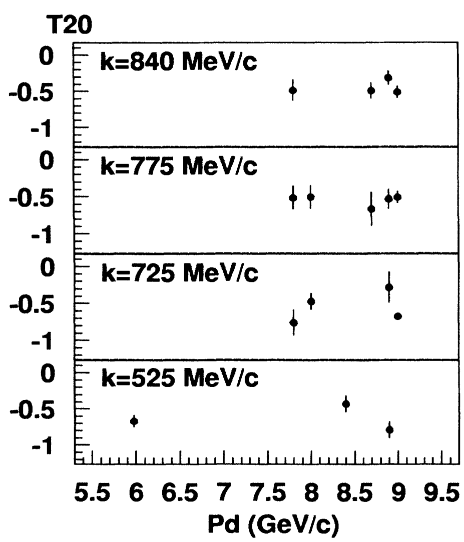

FIG. 4. T_{20} for the same k bins at different deuteron beam momenta P_d. The error bars display statistical errors.

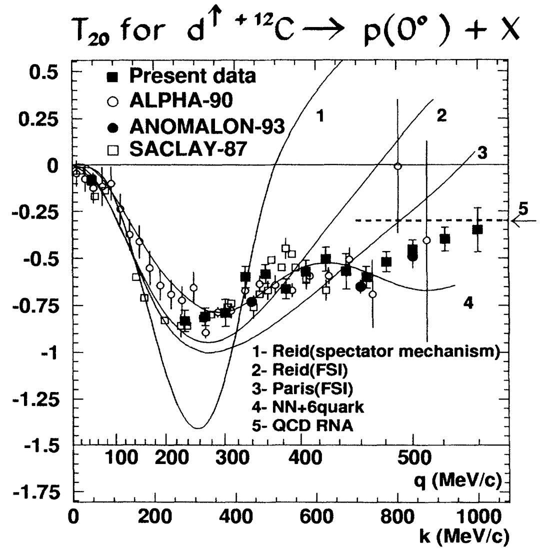

FIG. 5. T_{20} as a function of k and q. Closed squares are present results. Open and closed circles are Dubna data from [5] and [6], respectively. Open squares are data from [3]. The curves and the arrow are explained in the text.

on the reduced nuclear amplitude (RNA) method [27] (Fig. 5, arrow 5). Curves 1, 2, and 3 are the results of calculations [22] by relativistic treatment using conventional wave functions: 1, spectator mechanism with the Reid soft core wave function; 2, calculation with the Reid soft core wave function taking account of final state interaction (FSI); and 3, calculation with the Paris wave function taking account of FSI. All of them indicate the sign change of T_{20} at k below 0.95 GeV/c. On the contrary, our results show that T_{20} still remains negative even at $k = 1.00$ GeV/c. Curve 4, being in agreement with our data up to $k = 0.70$ GeV/c, is the result of the calculation with allowance for the composite six-quark component [22,28].

To conclude, for the first time the tensor analyzing power T_{20} has been measured for the reaction $d^{\uparrow} + {}^{12}C \rightarrow p(0°) + X$ in the region of proton internal momenta in light-cone dynamics up to 1 GeV/c. The results have shown a tendency of T_{20} approaching the asymptotic prediction (-0.3) obtained in the calculation based on the QCD reduced nuclear amplitude method where the quark degrees of freedom are taken into account.

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[17] The maximum proton momentum $P_{\max}^{dp}$ which can be observed at 0° corresponds to dp backward elastic scattering. The internal momentum distribution can be studied in the dp reaction up to $k_{\max}^{dp}$ defined by $P_{\max}^{dp}$ in accordance with Eq. (1). For $dA \rightarrow pX$ the $k_{\max}^{Ap}$ corresponds to exclusive reaction $d + A \rightarrow p(0^{\circ}_{\rm c.m.}) + A(180^{\circ}_{\rm c.m.}) + n(180^{\circ}_{\rm c.m.})$. One can see that $P_{\max}^{dA} > P_{\max}^{dp}$ and so $k_{\max}^{dA} > k_{\max}^{dp}$ at fixed P_d. In the case of $dA \rightarrow p(0°)X$ reaction one meets an interference of the deuteron stripping process with a proton knockout, in particular with the backward elastic scattering on quasifree protons, $dp_{\rm qf}$. Obviously, a peak of $dp_{\rm qf}$ scattering should be broadened due to Fermi motion in nucleus. We can conclude that we may study the deuteron stripping process in the $dA \rightarrow p(0°)X$ reaction without interference with $dp_{\rm qf}$ scattering only up to $k_{\max} = k_{\max}^{dp} - k_1$, where k_1 is defined by the requirement to cross sections at $k_{\max}$: $\sigma(dp_{\rm qf}) \ll \sigma(dA \rightarrow p(0°)X)$. In the range from $k_{\max}$ to $k_{\max}^{dA}$ one should take into account an interference of the stripping process with the other ones.
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