

ENERGY DEPENDENCE OF THE TENSOR ANALYZING POWER T_{20} IN THE $dd \rightarrow {}^3\text{He}$ AND $dd \rightarrow {}^3\text{He}$ REACTIONS

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Abstract

The final data on the energy dependence of the tensor analyzing power T_{20} in the $dd \rightarrow {}^3\text{He}$ and $dd \rightarrow {}^3\text{He}$ reactions in collinear geometry are presented. The data demonstrate the sensitivity to the spin structure of the deuteron and three-nucleon bound states, however, disagree with the one-nucleon exchange calculations using standard light nuclei wave functions.

During last several years a new generation of NN potentials are built (Nijmegen, CD-Bonn, AV-18 etc.). These potentials reproduced the NN scattering data up to 350 MeV with very good accuracy. However, these potentials cannot reproduce the triton binding energy (underbinding is 0.8 MeV for CD-Bonn), deuteron-proton elastic scattering and breakup data [1].

Incorporation of the 3 nucleon forces (3NF), when interaction depends on the quantum numbers of the all 3 nucleons, allows to obtain the correct value of the triton binding energy and to describe the unpolarized deuteron-proton scattering and breakup data. However, the 3NF cannot reproduce polarization data intensively accumulated during last decades [2]-[11]. This may indicate that the spin dependences of 3NF are not understood sufficiently. On the other hand, the nucleon-nucleon interaction (2NF) has also serious problems to take into account relativistic and off-shell effects, non-locality etc.

Therefore, the investigations of the polarization observables sensitive to 2NF and 3NF in different kinematical conditions for different reactions is of great importance.

The $dd \rightarrow {}^3\text{He}({}^3\text{He})$ process is devoted to the one nucleon exchange (ONE) reactions. The theoretical analysis of the polarization phenomena for this reaction in the collinear geometry has been performed [12, 13]. It has been shown that the tensor analyzing power T_{20} due to polarization of the incident deuteron is expressed in terms of the D/S -waves ratio in the ${}^3\text{H}({}^3\text{He})$ and deuteron, when three-nucleon bound state is emitted in

the forward and backward directions in the center-of-mass system, respectively. A new experiment has been proposed [14] to measure the energy and angular dependence of the tensor analyzing powers in the $dd \rightarrow {}^3\text{He}({}^3\text{He})$ process at RIKEN.

The experiment has been performed at RIKEN Accelerator Research Facility (RARF). A polarized deuteron beam was produced by the high-intensity polarized ion source (PIS) [15] and accelerated by AVF and Main Ring cyclotrons up to required energy. The direction of the beam polarization axis was controlled with a Wien filter located at the exit of the PIS. The polarization of the beam has been measured with the beam-line polarimeters based on the asymmetry measurements in dp- elastic scattering reaction, which has large values of tensor and vector analyzing powers [4, 5]. New values of the analyzing powers for dp- elastic scattering at 140 and 270 MeV obtained through absolute calibration of the deuteron beam polarization via ${}^{12}\text{C}(d, \alpha){}^{10}\text{B}^*[2^+]$ reaction [16] have been used.

The measurements have been performed using the SMART (Swinger and Magnetic Analyzer with a Rotator and a Twister) spectrograph described elsewhere [17]. In this system, the incident beam can be swung by rotating the swinger magnet, while the magnetic analyzer is fixed. The measurement of the momentum and separation from the primary beam was achieved by the analyzer part of SMART spectrograph consisting of two dipole and three quadrupole magnets ($Q - Q - D - Q - D$).

The beam intensity during the experiment was about 1-2 nA, the solid angle was 10^{-2} sr. The live time of DAQ system [18] was more than 80% at the trigger rate of few thousands per second. A CD_2 thin sheet [19] has been used as a deuterium target. The measurements on CD_2 and carbon targets were made for each setup setting to obtain the contribution from deuterium via the $CD_2 - C$ subtraction. The thicknesses of the CD_2 and carbon targets used were ~ 54 mg/cm² and ~ 34 mg/cm², respectively.

Three plastic scintillators viewed by photomultipliers from the both sides were used in coincidence for the trigger and to provide the information about time-of-flight and energy losses of the particles. The distance between the target and detection point is about 17 m, which is enough to separate tritons, deuterons and protons with the same momentum. The information about the charge of the particles was used at the trigger level. Protons and deuterons were partly suppressed in the cases of ${}^3\text{He}$ and ${}^3\text{H}$ detection by the raising threshold levels of the discriminators.

The set of multiwire drift chambers has been used to obtain the information on the hit position in the focal plane and, therefore, on the momentum of the particle and emission angle from the target. The energy resolution was ~ 300 keV. The typical track efficiency reconstruction was better than 99%.

The event was accepted in the following analysis if the energy losses in all the three scintillation counters was correlated. The timing information on the radio-frequency signal of cyclotron was also used to select the events coming from the cyclotron bunches.

In the experiment the data for the ${}^3\text{He}$ and ${}^3\text{H}$ channels have been obtained at 140, 200 and 270 MeV. ${}^3\text{He}({}^3\text{H})$ and protons were detected in the case of 3N system emission in the forward and backward directions in the cms, respectively. ${}^3\text{He}$ and protons were registered at all the three energies, while ${}^3\text{H}$ - at 140 and 200 MeV only.

The effectiveness of the $CD_2 - C$ subtraction procedure for the $dd \rightarrow {}^3\text{He}(0^\circ)n$ and $dd \rightarrow p(0^\circ)X$ reaction at 270 MeV are demonstrated in Fig.1 and Fig.2, respectively. The

spectra are plotted versus excitation energy E_X defined as following

$$E_X = \sqrt{((E_0 - E_3)^2 - (\mathbf{P}_0 - \mathbf{P}_3)^2)} - M_3, \quad (1)$$

where $E_0 = 2M_d + T_d$ is the total initial energy; \mathbf{P}_0 is the incident deuteron momentum, E_3 , \mathbf{P}_3 and M_3 are energy, momentum and mass of the detected particle, respectively. Peaks at $E_X = 0$ MeV correspond to ${}^3\text{He}$ (proton) from the $dd \rightarrow {}^3\text{He}(pX)$ reaction, while the dashed lines show the carbon contribution.

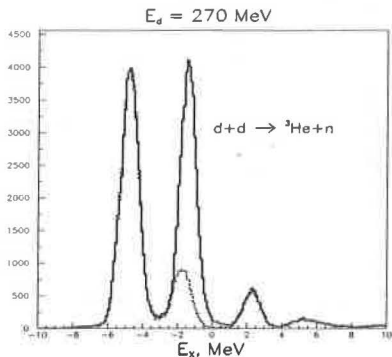


Figure 1: The CD_2-C subtraction at 270 MeV for the case of ${}^3\text{He}$ detection.

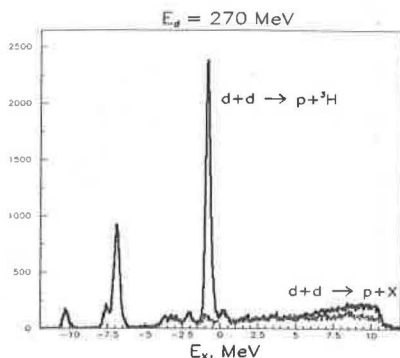


Figure 2: The CD_2-C subtraction at 270 MeV for the case of proton detection.

For the ${}^3\text{H}$ detection case the yield from carbon under peak at $E_X = 0$ MeV is negligibly small. The peak from deuterium is separated from the carbon yield by ~ 5 and ~ 10 MeV at 200 and 140 MeV, respectively.

The events considered for the analysis were selected within polar angle acceptance of $\pm 1.4^\circ$.

The measurements of the tensor analyzing powers A_{yy} and A_{xx} have been performed at 270 and 200 MeV. Only A_{xx} has been measured at 140 MeV. Only the events for unpolarized spin mode "0" and 2 spin modes with the significant values of the tensor polarization (modes "1" and "3") [15] were used for the analysis. Actual values of the beam polarization varied from $\sim 75\%$ to $\sim 15\%$ from the ideal values at 270 MeV and 140 MeV, respectively.

Tensor analyzing power A_{ii} for each polarized spin mode was calculated from the following expression

$$A_{ii} = \frac{2}{p_{ii}} \left(\frac{\sigma_{pol}}{\sigma_0} - 1 \right), \quad (2)$$

where p_{ii} is the corresponding tensor polarization of the beam, σ_{pol} and σ_0 are the numbers of useful events in polarized and unpolarized spin modes obtained via CD_2-C subtraction and corrected for dead-time, detection efficiency and beam intensity. The analyzing power A_{ii} was taken as weighted averaged for 2 polarized spin modes.

The tensor analyzing power T_{20} has been taken as $T_{20} = -\frac{1}{\sqrt{2}}(A_{xx} + A_{yy})$ at 270 and 200 MeV. Since only measurement of A_{xx} has been performed at 140 MeV, T_{20} at this energy has been obtained as $T_{20} = -\sqrt{2}A_{xx}$.

The results on the tensor analyzing T_{20} for the $dd \rightarrow {}^3\text{He}(0^\circ)n$ and $dd \rightarrow {}^3\text{H}(0^\circ)p$ reactions are shown in Fig.3. The open triangles and full circles correspond to the ${}^3\text{Hp}$ and ${}^3\text{Hen}$ channels, respectively. The T_{20} values for the both channels agree within achieved experimental accuracy.

The solid, dashed and dotted curves in Fig.3 are the results of non-relativistic ONE calculations [14] using Urbana [20], Paris [21] and RSC [22] ${}^3\text{He}$ wave functions. Paris deuteron wave function [13] was used in the calculations.

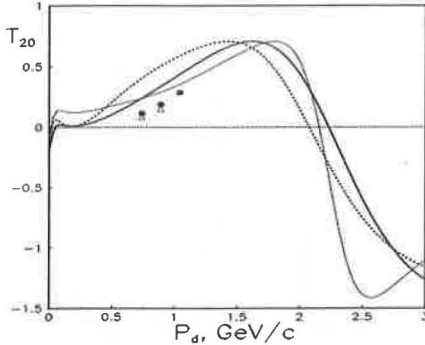


Figure 3: Tensor analyzing power T_{20} for the ${}^3\text{Hen}$ (solid circles) and ${}^3\text{Hp}$ (open triangles) channels. The curves are the ONE calculations [14] using different ${}^3\text{He}$ wave functions.

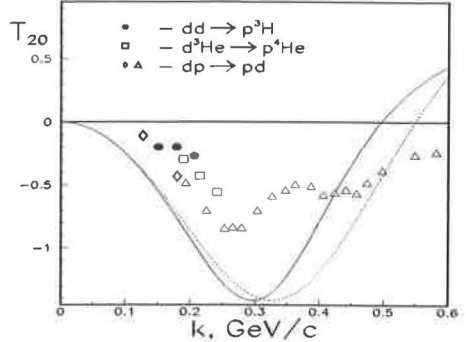


Figure 4: T_{20} data for the $dp \rightarrow pd$ (open triangles and diamonds), $d{}^3\text{He} \rightarrow p{}^4\text{He}$ (open squares) and $dd \rightarrow p{}^3\text{H}$ (closed circles) reactions.

One can see that the sign of T_{20} is positive being in the agreement with the sign of the D/S waves ratio in the ${}^3\text{He}({}^3\text{H})$. Therefore, one can conclude that our data are sensitive to the ${}^3\text{He}$ (${}^3\text{H}$) spin structure. On the other hand, the deviation on the non-relativistic ONE predictions [14] using standard ${}^3\text{He}$ wave functions is observed.

T_{20} data for the $dd \rightarrow p{}^3\text{H}$ (closed circles) reaction are plotted in Fig.4 along with the data for the $dp \rightarrow pd$ [2, 5] (open triangles and diamonds) and $d{}^3\text{He} \rightarrow p{}^4\text{He}$ [10] (open squares) reactions versus internal momentum k . The solid and dashed curves are the calculations performed within ONE for the $dp \rightarrow pd$ reaction using Paris [13] and Bonn B [24] DWFs, respectively. All these data have negative values of T_{20} at $k \leq 0.4$ GeV/c and, therefore, reflect the sign of D/S - waves ratio in the deuteron.

However, the dependence of T_{20} on the internal momentum k is different. Therefore, one can conclude that mechanisms additional to ONE give different contributions for different reactions. Such a difference in the k - behaviours may be due to the necessity to take into account the Fermi motion of the nucleon in the target and recoil particles, which are different for these processes [10, 25].

The results can be summarized as following. The final data on the tensor analyzing power T_{20} in the $dd \rightarrow {}^3\text{Hp}({}^3\text{Hen})$ reaction at intermediate energies and in the collinear geometry are presented. The sign of T_{20} is positive and negative, when ${}^3\text{H}({}^3\text{He})$ is emitted in the forward and backward directions in the c.m., respectively. This fact reflects the sensitivity of the data to the D/S - ratio in the ${}^3\text{H}({}^3\text{He})$ and deuteron. The data obtained for both channels $dd \rightarrow {}^3\text{He}(0^\circ)n$ and $dd \rightarrow {}^3\text{H}(0^\circ)p$ are in good agreement. The strong deviation of T_{20} , especially, for the $dd \rightarrow {}^3\text{H}(180^\circ)p$ channel, on the ONE predictions is

observed. The further development of the theoretical models (taking into account $3N$ scattering amplitude, additional to ONE mechanisms etc.) are desired. The continuation of the measurements of T_{20} , as well as other polarization observables at higher energies is desirable.

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Discussion

Q. (Yu.Uzikov, JINR, Dubna): You obtained a quantitative agreement between measurement T_{20} for $dd \rightarrow {}^3\text{He}n$ and one nucleon exchange. But what is order of distortions in this reaction? For initial state dd -collision it could be very important, because deuteron is weakly bound system.

A. Distortions were not taken into account.

Q. (G.Lykasov, JINR, Dubna): The experimental data about T_{20} in $dd \rightarrow {}^3\text{He}n$ reaction are very closed to ones measured in $dd \rightarrow dp$. Is it right?

A. Yes, they are very closed each to other. Moreover, within the one-nucleon exchange model, these observables are the same.