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The polarisation observables for *dp* elastic scattering

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Abstract. Within the one-nucleon exchange approximation, collinear kinematics and invariant-amplitude method with the one-nucleon-exchange assumption, the elastic deuteron–proton scattering is considered. Calculations of polarisation characteristics of T_{20}, κ_0, $T_{20}+2\sqrt{2}\kappa_0$ vs. k, C_{yy}, K_y^y, K_{xz}^y for the deuteron wave function in coordinate representation for the Argonne v18 potential, are demonstrated. Experimental data are better described by theoretical predictions using the invariant-amplitude method than by the impulse approximation and in collinear kinematics. The obtained theoretical values of the tensor analysing power T_{20} and the polarisation transfer coefficient κ_0 in the choice of the deuteron wave function for the fss2 baryon–baryon model, Bonn one-boson-exchange potential, Argonne v18 and Paris potentials, are in good agreement with the experimental data of leading collaborations and reviews.

Keywords. Deuteron; wave function; deuteron–proton scattering, tensor analysing power, polarisation transfer coefficient; invariant-amplitude method.

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1. Introduction

In recent decades, systems consisting of three or more nucleons have been studied [1–4]. As indicated in [5], the relativistic polarised beams of deuterons, polarisation experiments to measure the analysing powers and the vector and tensor polarisation transfer coefficients are of great interest.

As deuteron is a simple two-component nucleus, the elastic deuteron–proton scattering can be an example of the process of hadron nucleus collision with a nucleon [6]. At low and high energies, the theoretical calculations of the polarisation characteristics in multinucleon systems are based on the phenomenological nucleon–nucleon potential.

Deuteron wave function (DWF) describes a quantum-mechanically coupled system of proton and neutron. If we know the behaviour of DWF in coordinate and momentum representations, we can obtain maximum information about deuteron and theoretically predict characteristics of processes involving deuteron.

Polarisation observables in inelastic scattering of deuterons on light nuclei ($A(d,d')X$ reaction) [7], in elastic deuteron–proton scattering [8] and in elastic electron–deuteron scattering [9] are theoretically described by DWF in coordinate or momentum representations. The behaviour of polarisation characteristics is determined by the form and behavior of DWF. The dependence of the high-momentum component of the polarisation observables on the DWF form (type of nucleon–nucleon interaction) is important [10].

By using theoretical calculations, it is possible to predict the behaviour of polarisation observables in the regions of momentums, which have been studied in the experiment a little. If we compare the results of theoretical calculations with experimental data, we can find out which theoretical model is in better agreement with the experiment. In the future, such a model using the potential of the nucleon–nucleon interaction can be applied to describe other polarisation characteristics of the corresponding type of process (in our case, it is *dp* elastic scattering).

The process of deuteron–proton scattering is of interest to researchers. In particular, Temerbayev and Uzikov [11] studied spin observables in *dp* scattering and tested T-invariance using the modified Glauber theory. New experimental results for the vector A_y and tensor A_{yy} and A_{xx} analysing powers in *dp* elastic scattering were obtained at Nuclotron in the energy range 400–1800 MeV and they were compared with theoretical

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results in the framework of the relativistic multiple scattering model [12]. The cross-sections, vector and tensor analysing powers, induced polarisations and vector and tensor spin-transfer coefficients have been calculated with high precision in experiments for *dp* elastic scattering at 90 MeV/nucleon [13]. Three-nucleon force effects are taken into account in the theoretical estimates of these values.

Analysing powers and spin correlation coefficients for *pd* elastic scattering at 135 and 200 MeV [14] and complete set of deuteron analysing powers from *dp* elastic scattering at 190 MeV/nucleon [15] were investigated depending on the scattering angle.

The tensor analysing power T_{20} and the polarisation transfer coefficient from deuteron to proton κ_0 are well studied in the experiment. The tensor analysing power T_{20} was measured by the following collaborations (with appropriate laboratories or experimental set ups): Dubna (ALPHA) [16], Dubna (ALPHA-96) [17], Saclay (SATURNE-95) [18], Dubna (Synchrophasotron) [19], Dubna (ANOMALON-93) [20], Dubna (ALPHA-90/88) [21,22], Saclay (SATURNE-89) [23], Saclay (SATURNE-87) [24]. The polarisation transfer coefficient κ_0 is less studied, but the following experimental data are available: Saclay (SATURNE-95) [18], Dubna (ANOMALON-93) [20], Dubna (ALPHA) [25], Saclay (SATURNE-92) [26], Dubna (ANOMALON-91) [27].

In this paper, analytical forms of DWFs in coordinate representation are used for theoretical calculations of a set of polarisation observables in *dp* elastic scattering. Realistic phenomenological potentials and nucleon–nucleon interaction models are used for numerical calculations.

Theoretical estimates of polarisation characteristics were done within the one-nucleon exchange approximation, collinear kinematics and the invariant-amplitude method with the one-nucleon exchange assumption.

2. One-nucleon exchange approximation

In [5] the polarisation observables in elastic deuteron–proton scattering in the one-nucleon exchange approximation are described. The tensor analysing power T_{20}, the polarisation transfer coefficient κ_0, the spin correlation coefficient C_{yy} and the vector coefficient of the recoil proton polarisation K_y^y are determined by radial DWF in the momentum representation $u(k)$, $w(k)$:

$$T_{20} = \frac{1}{\sqrt{2}} \frac{2\sqrt{2}uw - w^2}{u^2 + w^2}, \tag{1}$$

$$\kappa_0 = \frac{u^2 - w^2 - uw/\sqrt{2}}{u^2 + w^2}, \tag{2}$$

$$C_{yy} = \frac{2}{9} \frac{u^4 - 2w^4 + 3u^2w^2 - uw(5u^2 - 2w^2)/\sqrt{2}}{u^2 + w^2}, \tag{3}$$

$$K_y^y = \frac{1}{9} \left[\frac{(u - \sqrt{2}w)^2}{u^2 + w^2} \right]^2. \tag{4}$$

In [5] it is stated that the values of T_{20} and κ_0 are identical in *dp* elastic scattering reaction at the angle $\theta = 180^\circ$ (calculations in the one-nucleon exchange approximation) and the deuteron breakup reaction (d, p) with proton detection at 0° (in the impulse approximation). T_{20} and κ_0 in the one-nucleon exchange approximation or in the impulse approximation are related through the identity:

$$\left(T_{20} + \frac{1}{2\sqrt{2}} \right)^2 + \kappa_0^2 = \frac{9}{8}. \tag{5}$$

3. Polarisation observables of *dp* elastic scattering in the collinear kinematics

The definition of the general polarisation observable $C_{\alpha,\lambda,\beta,\gamma}$ and the results of the theoretical description for the number of polarisation observables of *dp* elastic scattering in collinear kinematics, is given in [28]. Polarisation observables are written in the form according to the original designations of values

$$T_{20} = -\sqrt{2} C_{0,NN,0,0}, \tag{6}$$

$$\kappa_0 = \frac{3}{2} C_{0,N,N,0}, \tag{7}$$

$$C_{yy} = C_{N,N,0,0}, \tag{8}$$

$$K_y^y = C_{N,0,N,0}, \tag{9}$$

where

$$C_{0,NN,0,0} = 2N(2ReAB^* + B^2 - 2ReCD^* - D^2),$$
$$C_{0,N,N,0} = 4N(Re(2A^* + B^* + D^*)C + C^2),$$
$$C_{N,N,0,0} = 4N(2ReAC^* + ReBC^* - ReCD^* - C^2),$$
$$C_{N,0,N,0} = 2N(3A^2 + 2ReAB^* + B^2 - 2C^2 - 4ReCD^* - 2D^2),$$
$$N = 1/Tr(FF^+),$$
$$Tr(FF^+) = 2(3A^2 + 2ReAB^* + B^2 + 6C^2 + 4ReCD^* + 2D^2).$$

Here the expressions for A–D were calculated in the framework of the pole mechanism and they are expressed through DWF in the momentum representation $u(k)$, $w(k)$

$$A = \left(u + \frac{w}{\sqrt{2}}\right)^2,$$
$$B = -\frac{3}{2}w(2\sqrt{2}u - w),$$
$$C = \left(u + \frac{w}{\sqrt{2}}\right)(u - \sqrt{2}w),$$
$$D = \frac{3}{\sqrt{2}}w\left(u + \frac{w}{\sqrt{2}}\right).$$

4. The invariant-amplitude method with the one-nucleon exchange assumption

The spin observables in *dp* backward elastic scattering at intermediate and high energies were investigated in [29] using the invariant-amplitude method with the one-nucleon exchange assumption. Discrepancies between the theoretical calculations and the experimental data for the value of κ_0–T_{20} correlation were reduced by including effects for imaginary parts of absorption in invariant amplitudes. Calculations of T_{20} and κ_0 with different nucleon–nucleon potentials (except T_{20} at high energies) explain the dependence of these magnitudes on the relative momentum of the proton–neutron system.

The polarisation characteristics of this method are written as [29]

$$T_{20} = \{2\sqrt{2}R\cos\Theta - R^2 - 32R'^2 + 12RR'\cos(\Theta' - \Theta)\}/N_R, \quad (10)$$
$$\kappa_0 = \left\{\sqrt{2} - R\cos\Theta - 4R'\cos\Theta' - 3\sqrt{2}RR'\cos(\Theta' - \Theta) - 30\sqrt{2}R'^2\right\}/N_R, \quad (11)$$
$$C_{yy} = \frac{2\sqrt{2}}{9}\left\{1 - \frac{5}{\sqrt{2}}R\cos\Theta + 2\sqrt{2}R'\cos\Theta' + 2R^2 - 70R'^2 + 13RR'\cos(\Theta - \Theta')\right\}/N_R, \quad (12)$$
$$K_y^y = \frac{\sqrt{2}}{9}\{1 - 4\sqrt{2}R\cos\Theta + 14\sqrt{2}R'\cos\Theta' + 8R^2 + 98R'^2 - 56RR'\cos(\Theta - \Theta')\}/N_R, \quad (13)$$
$$K_{xz}^y = 3\{-R\sin\Theta + 5\sqrt{2}RR'\sin(\Theta - \Theta')\}/N_R, \quad (14)$$

where

$$N_R = \sqrt{2} + 2\sqrt{2}R^2 + 34\sqrt{2}R'^2 - 4R'\cos\Theta',$$
$$R = \frac{4|\rho|}{4 + \rho^2},$$
$$R' = \frac{\rho^2}{\sqrt{2}(4 + \rho^2)},$$
$$\rho = \frac{w(k)}{u(k)}.$$

The angles (Θ, Θ') (or relative phases between the invariant amplitudes of U, T, T') characterise the contribution of open channels (as the absorption effect) [29]:

$$\Theta = \theta_T - \theta_U, \quad \Theta' = \theta_{T'} - \theta_U.$$

The imaginary parts of the invariant amplitudes are parametrised by the relative phases (Θ, Θ') between the scalar amplitude U and the second-rank tensor ones T, T', which include effects of the D-component of the internal wave function of the deuteron [29]:

$$U = \frac{9}{\sqrt{2}}\left\{u^2(k) + \frac{1}{4}w^2(k)\right\}t(k),$$
$$T = \frac{9}{\sqrt{2}}u(k)w(k)t(k),$$
$$T' = \frac{9}{8}w^2(k)t(k),$$

where $t(k)$ is the scattering amplitude of a proton by a neutron at momentum k.

The magnitude K_{xz}^y in formula (14) is the tensor-to-vector polarisation transfer coefficient.

The effect of Θ' on the momentum-dependence of T_{20} and κ_0 was investigated by the combination of T_{20} and κ_0 at a fixed value of Θ [29]:

$$T_{20} + 2\sqrt{2}\kappa_0 = \frac{4}{N_R}\left\{1 - \frac{1}{4}R^2 - 38R'^2 - 2\sqrt{2}R'\cos\Theta'\right\}. \quad (15)$$

Thus, the polarisation characteristics in the invariant-amplitude method with the one-nucleon exchange assumption are determined using DWF in the momentum representation $u(k)$, $w(k)$ and a pair of angles (Θ, Θ').

5. Calculations and conclusions

DWF in momentum representation is written according to the Hankel transformation:

$$u(k) = \int_0^\infty U(r)j_0(kr)\mathrm{d}r,$$
$$w(k) = \int_0^\infty W(r)j_2(kr)\mathrm{d}r, \quad (16)$$

where $j_0(kr)$ and $j_2(kr)$ are the spherical Bessel functions of the zero and second order; $U(r)$ and $W(r)$ are the radial DWFs for S- and D-states for orbital moment a $l = 0$ and $l = 2$.

Calculated DWF in coordinate representation for the potential of Argonne v18 [30] can be approximated and represented in the form of Gaussian expansions with the corresponding coefficients [31]

$$\begin{cases} U(r) = r \sum_{i=1}^{N} A_i \mathrm{e}^{-a_i r^2}, \\ W(r) = r^3 \sum_{i=1}^{N} B_i \mathrm{e}^{-b_i r^2}. \end{cases} \tag{17}$$

We use the obtained DWF in coordinate representation for the Argonne v18 potential for numerical calculations of the polarisation observables in dp elastic scattering (figures 1–4).

The results from the one-nucleon exchange approximation were chosen to compare them with the results using the invariant-amplitude method. In both these methods, the polarisation characteristics of elastic deuteron–proton scattering are determined by the DWF in the momentum representation. Given the dependence of polarisation observables on the internal momentum k, the one-nucleon exchange approximation, the invariant-amplitude method and collinear kinematics are precisely those methods that ensure the finding of polarisation characteristics that interest us.

In figures 1 and 2 the comparison of the calculated values of T_{20} and κ_0 with the experimental values is shown. Calculations using the invariant-amplitude method were done depending on the angles for five cases (sets) [29]: A – (135°, −105°); B – (180°, 105°); C – (180°, 120°); D – (135°, 90°); E – (0°, 180°).

The results in impulse approximation (IA) are in good agreement with the obtained values in collinear kinematics. Theoretical predictions within the invariant-amplitude method with the one-nucleon exchange assumption are in better agreement with the experiment.

The values of T_{20} and κ_0 depend on the internal momentum k, which is related to the light cone or infinite momentum frame variables [32]:

$$k^2 = \frac{m_N^2}{4\alpha(1-\alpha)} - m_N^2.$$

Here m_N is the nucleon mass and α is the Lorentz invariant:

$$\alpha = \frac{p_p + E_p}{p_d + E_d} = \frac{q + E_q}{m_d},$$

where p_p, E_p, p_d, E_d are the momentum and energy of the detected proton and deuteron beam respectively and m_d is the mass of deuteron. The proton momentum q and its energy E_q in the deuteron c.m. frame are related by the expression

$$E_q^2 = q^2 + m_p^2.$$

In [10,29], the polarisation characteristics of T_{20} and κ_0 were calculated within the framework of the invariant-amplitude method using DWF for the Reid93 and Paris potentials, respectively. There is a visual similarity of the obtained values of T_{20} and κ_0 in this paper with the results in [10,27].

$T_{20} + 2\sqrt{2}\kappa_0$ combination vs. the internal momentum k is obtained at $\Theta = 0°$ and is shown in figure 3. The angle range at $\Theta' = 0$–$180°$ is selected for this value. Theoretical calculations are compared with the experimental data of the collaboration in Saclay (SATURNE) [18].

The polarisation characteristics of C_{yy}, K_y^y, K_{xz}^y are shown in figure 4. The spin correlation coefficient C_{yy} is characterised by a similar form of behaviour on the internal momentum k and there is a pit at $k = 0.3$–0.5

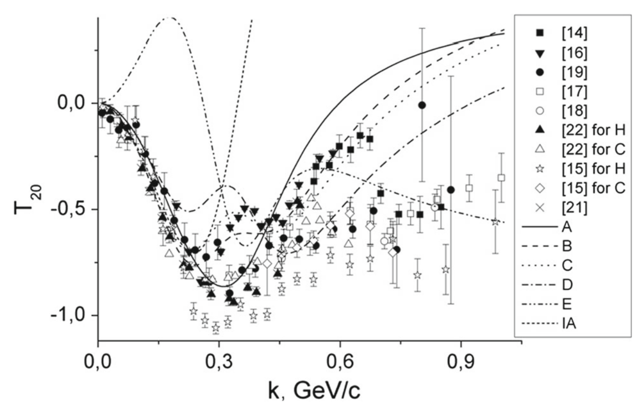

Figure 1. The comparison of calculated values of T_{20} with the experimental values.

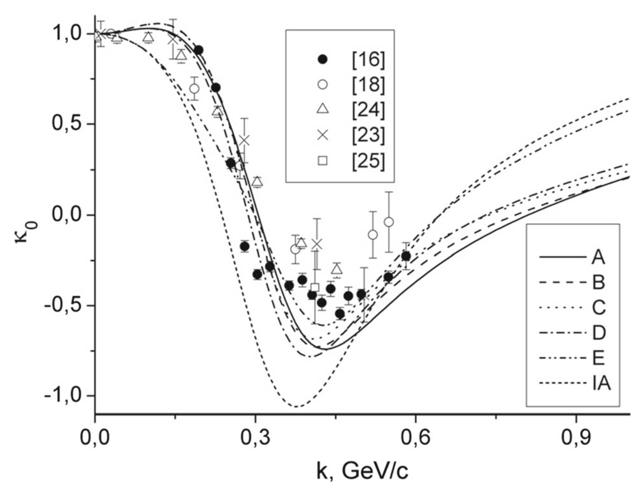

Figure 2. The comparison of calculated values of polarisation transfer coefficient κ_0 with experimental values.

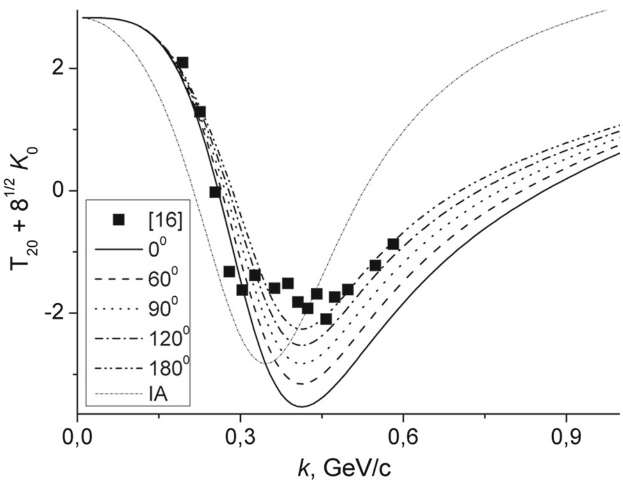

Figure 3. $T_{20} + 2\sqrt{2}\kappa_0$ vs. k.

GeV/c. The vector coefficient of the recoil proton polarisation K_y^y has only positive values. The tensor-to-vector polarisation transfer coefficient K_{xz}^y was calculated only by the invariant-amplitude method with the one-nucleon exchange assumption because no suitable formula has been found for calculations in the impulse approximation. The calculations of K_{xz}^y for set A are antisymmetric in comparison with the results for sets B and C, and zero values are obtained by selecting model E for the entire momentum range. Unfortunately, experimental data for the physical values of C_{yy}, K_y^y and K_{xz}^y, which were determined depending on the internal momentum k, are not available in open scientific sources.

Let us analyse the results of theoretical calculations for the Argonne v18 potential, the dressed dibaryon model (DDM) [8], the Paris potential [33], the Bonn one-boson-exchange potential (OBEP) [34], the fss2 model (fss2 baryon–baryon interaction is a low-energy effective model in QCD) [35], the Moscow [31] and N^{2}LO [36] potentials.

For the polarisation characteristics T_{20} and κ_0, the difference between theoretical calculations for nucleon–nucleon (NN) models (or potentials) and experimental data (for $N_{\text{data}} = 165$ and 36 respectively) is described by χ^2/N_{data} (tables 1 and 2). When the χ^2/N_{data} deviation is smaller, the theory describes the experiment better in a given region of momentum. That is, the theoretical calculations for T_{20} by DWF for the fss2 model, OBEP and Argonne v18 (Av18) potentials are consistent with the experiment. The theoretical predictions for κ_0 using the OBEP, Argonne v18 and Paris potentials and the fss2 model are in better agreement with the experimental data. The choice of sets C, D or B (for T_{20}) and E, A or C (for κ_0) in theoretical calculations by the invariant-amplitude method will be satisfactory for the experiment.

The value χ^2 per degree of freedom of the function is calculated by the formula

$$\chi^2/N_{\text{data}} = \frac{1}{N}\sum_{i=1}^{N}\left(f_i^{(\text{exp})} - f_i^{(\text{theor})}\right)^2,$$

where the number of experimental points $N = N_{\text{data}}$ for T_{20} and κ_0 are 165 and 36 respectively; $f_i^{(\text{exp})}$ –

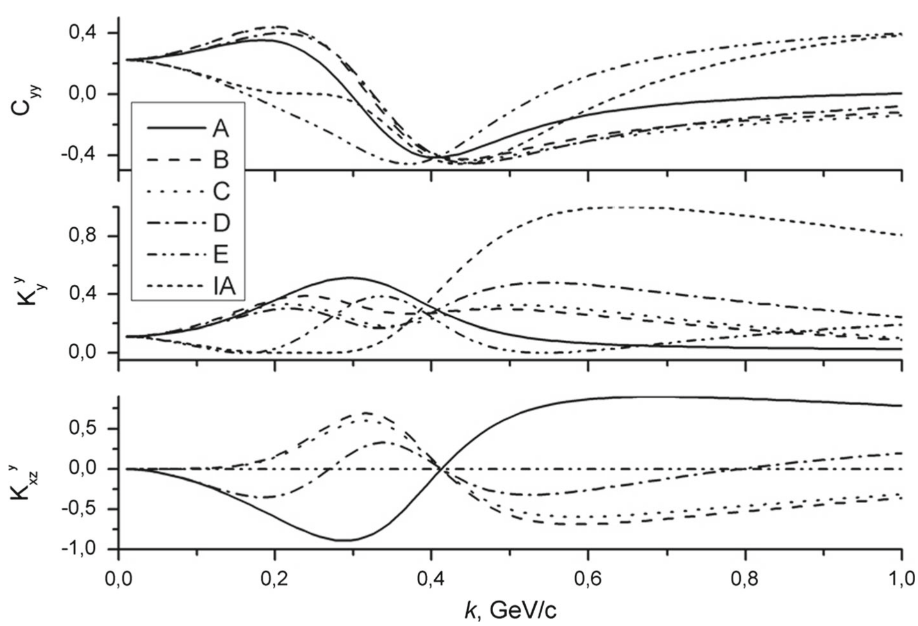

Figure 4. The polarisation characteristics C_{yy}, K_y^y, K_{xz}^yvs. k.

Table 1. The value of χ^2/N_{data} for the tensor analysing power T_{20}.

NN model or potential	A	B	C	D	E	IA
Av18	0.139750	0.095604	0.085800	0.077601	0.237152	1.71706
DDM	0.338606	0.340274	0.313388	0.221812	0.199924	1.72399
Paris	0.160636	0.121255	0.108801	0.089797	0.233073	1.72514
OBEP	0.110196	0.069974	0.065358	0.071602	0.249809	1.57194
fss2	0.097967	0.058123	0.055825	0.067894	0.246681	1.58035
Moscow	0.357193	0.349813	0.317912	0.212621	0.198749	1.84753
N^2LO	0.112936	0.092349	0.091066	0.093094	0.227543	1.44764

Table 2. The value of χ^2/N_{data} for the polarisation transfer coefficient κ_0.

NN model or potential	A	B	C	D	E	IA
Av18	0.068565	0.062829	0.050218	0.073052	0.041485	0.24662
DDM	0.093231	0.097466	0.101570	0.125373	0.208609	0.40185
Paris	0.064659	0.059506	0.047863	0.070847	0.042180	0.24726
OBEP	0.072297	0.067330	0.054654	0.075381	0.041355	0.25077
fss2	0.074667	0.069497	0.056104	0.078793	0.042811	0.25783
Moscow	0.093573	0.101820	0.108024	0.142379	0.192486	0.41651
N^2LO	0.073045	0.069252	0.055318	0.086756	0.047261	0.29614

$f_i^{(\text{theor})}$ is the difference between experimental values and theoretical calculations.

So, we can draw the following conclusions:

1. Calculations of polarisation characteristics of T_{20}, κ_0, $T_{20}+2\sqrt{2}\kappa_0$ vs. k, C_{yy}, K_y^y, K_{xz}^y are demonstrated. They characterise the *dp* elastic scattering. The results of these polarisation observables for DWF in coordinate representation for the Argonne v18 potential are demonstrated. Theoretical predictions within the invariant-amplitude method with the one-nucleon exchange assumption are in good agreement with the experiment.
2. Theoretical calculations for T_{20} by DWF for fss2 model, OBEP and Argonne v18 potentials are in better agreement with the experimental data of leading collaborations and reviews. The obtained values of κ_0 when using DWF for OBEP, Argonne v18 and Paris potentials and fss2 models are in good agreement with the experiment.
3. The obtained polarisation characteristics as the observables for reaction with the spin structure $\vec{1}+A\to\vec{\frac{1}{2}}+B$ can be applied to determine cross-sections [37]

$$\sigma(\theta,\varphi)=\sigma_0(\theta)\times\left(1+\frac{3}{2}\sum_j p_jA_j(\theta)+\frac{1}{3}\sum_{j,k}p_{jk}A_{jk}(\theta)\right),$$

$$p_{l'}\sigma(\theta,\varphi)=\sigma_0(\theta)\times\left(P_{l'}(\theta)+\frac{3}{2}\sum_j p_jK_j^{l'}(\theta)+\frac{1}{3}\sum_{j,k}p_{jk}K_{jk}^{l'}(\theta)\right),$$

where $p_{l'}$, $P_{l'}$ are the outgoing polarisations; A_j, A_{jk} are the analysing powers; $K_j^{l'}$, $K_{jk}^{l'}$ are the polarisation transfer coefficients

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