THE POLARIZATION OF FAST NEUTRONS

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ABSTRACT

It is insufficient to know coordinates and momentum to describe a state of a neutron. It is necessary to define a spin orientation. As far as it is known from quantum mechanics, a half spin has a projection in the positive direction or in the negative direction. The probability of both projections in an unpolarized beam is equal. If a direction exists, in which the projection is more probably then beam is called polarized in this direction. It is essential to know polarization of neutrons for characteristics of a neutron source, which is emitting it. The question of polarization of fast neutrons came up in 50's.

The present work is the review of polarization of fast neutrons and methods of polarization analysis. This also includes information about polarization of fast neutrons from first papers, which described polarization in the $D(d,n)^3He$, $^7Li\ (p,n)^7Be$, $T(p,n)^3He$ reactions.

INTRODUCTION

The question of polarization of fast neutrons came up in 50's. It is essential to know polarization of neutrons for characteristics of a neutron source, which is emitting it. The polarization defines of equation

$$P = \frac{N_+ - N_-}{N_+ + N_-}, \quad (1)$$

here N_+- the number of neutrons with spin projection to the direction, N_- against the direction. It is obvious that $-1<P<1$.

The reason of polarization may be any dependence of forces acting on the neutron from it spin orientation. For example, electromagnetic forces. The dependence is used for receipt polarized neutron beams by pass their through magnetic materials or by reflection at magnetic body surface. Spin dependence of electromagnetic forces is used for polarization of fast neutrons by scattering through small angles (so called Shvigner scattering). Nuclear forces also depend on neutron spin orientation. The reason of this dependence is called spin – orbit interaction. Simplest example of the dependence is interaction neutron with proton.

In 1961 F. L. Shapiro was suggested to use proton target polarized by dynamic method. Polarized proton target was created in cource few years and experiments began in Dubna on the beam of impulse reactor IBR [1-3]. The target was improved in next years, and it is used in POLYANA [4] for researches with polarized neutrons and nuclei in Dubna at present. Monocrystal of lanthanum – mangaene nitrate $La_2Mg_3(NO_3)_{12}x24H_2O$ is used in the capacity of polarized proton target in POLYANA. Detailed descriptions of experiments with monocrystal are given in review [5].

METHODS

The present work considers methods of fast neutron polarization and methods of polarization analysis.

Methods of fast neutron polarization

The reaction $D(d,n)^3He$

Polarization of neutron in $D(d,n)^3He$ was studied in big number of experiments:

- At small deuteron energies to 2MeV [6,7].
- Dubbeldam and Walter obtained more complete data at deuteron energies to 11MeV [8].
- Baicker and Jones [9] in the energy region $E_d<5$ MeV.
- Trostin and Smotryaev [10] at deuteron energies 9 and 12 MeV.
- Alekseev et al. at $E_d=12 – 20$ MeV [11].

The reaction $^7Li\ (p,n)^7Be$

$^7Li\ (p,n)^7Be$ reaction was used as polarized neutron source in researches of scattering asymmetry.

The reaction $T(p,n)^3He$

The reaction $T(p,n)^3He$ is monoenergetic neutron source and it is more comfortable than reaction $^7Li\ (p,n)^7Be$ as it have smaller threshold and higher cross section. Therefore, the reaction allows received higher neutron yeld and gives monoenergetic neutrons in more wide energy region.

The reaction $C^{12}(d,n)^{13}N$

The polarization was calculated from right-left asymmetry: $P_1=\varepsilon/P_2$, where right-left asymmetry

$$\varepsilon = \frac{N_{left} - N_{right}}{N_{left} + N_{right}},$$

P_1 – measured neutron polarization from reaction and P_2 – polarization arising at unpolarized neutron scattering on helium. The value P_2 was took from paper of Levintov et al. [12].

The reaction $B^{11}(d,n)^{12}C$

The neutron polarization of the reaction was determined from azimuth asymmetry of scattering on He^4. The polarization at scattering on He^4 is α – particle recoil angle averaging $\varphi_\alpha(\pm\Delta\varphi_\alpha=4-6^\circ)$.

The scattering neutrons

The scattered neutron polarization is defined expression

$$P=\frac{2\mathrm{Im}(FG)}{|F|^2+|G|^2}n, \qquad (2)$$

$$F(\Theta)=f_o(\Theta)+\frac{1}{2ik}\sum_{l=0}^{\infty}\{(l+1)f_l^+ + lf_l^- -(2l-1)\}\times$$
$$\times\exp(2i\delta_l)P_l(\cos\Theta)$$

$$G(\Theta)=\frac{1}{2ik}\sum_{l=0}^{\infty}(f_l^+ - f_l^-)\exp(2i\delta_l)P_l^{'}(\cos\Theta)$$

$f_l^+(\Theta)$ and $f_l^-(\Theta)$ – scattering amplitude for each value of orbital moment l (they are identical at l=0). The sign + and – at amplitudes indicate on method of neutron spin addition with orbital moment (sum l+1/2 or difference l-1/2). $f_o(\Theta)$ – central potential scattering amplitude, $P_l^{'}$ – joined Legendre polynomial. The unit vector n is normalized to scattering surface.

Methods of polarization analysis

Method of Svigner scattering

The neutrons interact with the polarization nucleus differently at different spin orientation. Spin effects of nucleus interaction is used for fast neutron polarization analysis. However, electromagnetic spin effects are sufficiently large and analyzers founding on observation of effects were elaborated in some laboratories.

Method of nuclear scattering asymmetry

Different light nuclei He^4, C^{12}, O^{16} can use as the scatterer – analyzer. One of the first series of neutron polarization observation at scattering on many nuclei was carried out by Barshall et al. They used scattering on oxygen for neutron polarization analysis.

Method of two-channels analyzer

It is present interest method of polarization analysis, which can call method of two-channel analyzer. It is assume that reaction proceeds on two channels in analyzer with different polarization dependencies of asymmetry. It is assume that He^3 is used as analyzer. The $He^3(n,p)T$, $He^3(n,d)D$ and elastic scattering induced by neutrons in He^3. It is known that polarization neutrons differ in sign in $T(p,n)^3He$ and $D(d,n)^3He$ reactions at near front angles. Therefore, asymmetry of products of reverse reactions $He^3(n,p)T$ and $He^3(n,d)D$ will differ in sign also. This means that relation first reaction proton intensity to second reaction deuteron intensity depends on direction and value of neutron polarization. The relation can use for neutron polarization definition.

RESULTS AND DISCUSSION

Methods of fast neutron polarization

The reaction $D(d,n)^3He$

The results of Dubbeldam and Walter [8] disagree with the results of Baicker and Jones [9] in the energy region E_d<5 MeV. The data were obtained by Trostin and Smotryaev [10] at deuteron energies 9 and 12 MeV also visibly differs from [8]. The data were obtained by Alekseev et al. at E_d=12 – 20 MeV [11] rough agreement with [8] at E_d=12 MeV. Thus, there are different data about polarization. The solution of contractions was received after improvement of polarization analysis method [13]. Barschall made up polarization map on materials of different works [8,11]. The curves in the map represent levels of equal polarization. Polarization sign correspond to so called Bazel condition decided on International conference in Bazel in 1960. Polarization is positive according to the condition, if polarization direction coincides with vector $k_i\times k_o$, where k_i – wave vector of incident particle, k_o – emerging particle. Polarization maximum corresponds to angle about 45 degrees at all energies, but polarization sign changes with energy increasing. Maximum position keeps at E_d=19.2MeV according to [11].

TABLE 1. Polarization of neutrons from the $D(d,n)^3He$ reaction as a function of deuteron energy

E_d, MeV	Polarization, %
Pasma P.J. [7], $\Theta_{lab}=47^\circ$	
0.2	-5.8±2.5
0.3	-9.0±2.5
0.35	-8.2±2.4
0.4	-8.6±1.1
0.45	-9.5±1.3
0.5	-9.2±0.8
Levintov I.I [6], $\Theta_{lab}=49^\circ$	
0.9	-13.10±1.25
1.2	-13.10±1.25
1.5	-15.00±1.25
1.8	-16.30±1.25
Baicker J.A., Jones K.W. [9], $\Theta_{lab}=40^\circ$	
2.0	-22.7±3.5
2.5	-20.8±3.7
3.0	-17.9±2.9
3.5	-17.6±2.2
4.0	-15.8±2.2
4.5	-16.9±1.5

Dubbeldam P.S., Walter R.L. [8], $\Theta_{c.m.}=45^\circ$	
1.9	-12.4±2.2
3.0	-8.0±1.4
3.7	-2.4±1.6
5.5	8.5±1.8
7.0	16.4±2.4
8.9	31.±8
11.0	30.±5
Alekseyev N.V. [11], $\Theta_{lab}=30^\circ$	
11.6	30.4±6.2
13.9	33.5±6.1
15.3	31.7±6.1
17.1	23.3±8.4
19.2	23.4±7.0

Trostin I.S., Smotrryaev V.A. [10]

E_d, MeV	Θ_{lab},degree	E_n, MeV	P,%
9	20	11.4	-1.6±1.0
	30	10.7	1.6±3.4
	40	9.8	10.1±3.9
12	20	14.0	2.2±1.1
	30	13.1	18.5±2.3
	40	11.9	10.8±3.3
	50	10.5	-2.2±3.7

The reaction $Li^7(p,n)^7Be$

The assumption about neutron polarization in $^7Li\ (p,n)^7Be$ reaction was made by Adair [14]. The magnitude of neutron polarization was measured at neutron scattering on liquid oxygen and it is nearly equal to 50%. The oxygen can use in the capacity of analyzer because for it have resonance at 435 keV for neutron scattering. The neutron energy changed in bounds 270 – 600 keV and observations carried out at 42° and 50° in next measurements [15,16]. All these measurements showed that magnitude of polarization equals about 40% independently of values Θ and E_n. Striebel et al. [17] continued polarization measurements to neutron energy 1.5 MeV. They found, that the polarization is approximately constant +(30±2)% at all more high energy, and at 380 keV – +(38±4.5%). Decrease angle Θ to 30° did not lead to essential changes. High degree of neutron polarization is observed in resonance at E_p=2.35 MeV. The neutrons (E_n=300 keV) emitted at 50° have polarization more 60%.

TABLE 2. Neutron polarization of reaction $Li^7(p,n)^7Be$ under angle $\Theta_{lab}=50^\circ$

E_p, MeV	Polarization, %
Striebel H.R. [17]	
2.618	-30.4±6.6
2.667	-31.4±4.5
2.739	-27.2±2.7
2.798	-25.6±1.8
2.857	-30.4±0.9
2.990	-35.5±5.2
3.127	-36.6±3.9
3.284	-24.3±3.3

Baicker J.A., Jones K.W. [9]	
2.98	40.2±7.7
3.15	29.9±3.7
3.36	35.4±6.0
3.58	35.6±7.2
3.78	39.0±3.6
3.99	41.2±3.8
4.20	34.3±4.9
4.42	35.4±3.4
4.57	27.4±4.8
4.66	28.6±6.0
4.86	17.2±3.5
5.01	9.9±3.3
5.03	5.4±2.9
5.20	-8.6±2.3
5.39	-15.2±2.5
5.58	-23.8±3.7
5.78	-32.5±4.8
5.98	-23.0±4.2

The reaction $T(p,n)^3He$

For the first time, neutron polarization of $T(p,n)^3He$ reaction was found by Samoylov et al. [18] in Institute of Atomic Energy in 1959. Detailed researches of neutron polarization of this reaction carried out in Vinskonsine at proton energy to 12 MeV [19], which confirm previous results. Alekseyev N.B. et al. obtained the data at E_P=10.5 MeV and $\Theta_{lab}=40^\circ$ [20]. The $T(p,n)^3He$ and $D(d,n)^3He$ reactions proceed with the formation of same final products He^3+n, therefore it is interesting to compare its polarization. Maximum neutron polarization in the reactions corresponds to approximately same angle $\Theta_{c.m.}=45^\circ$ in wide energy range. The reactions are widespread laboratory monoenergetic neutron source. The neutrons with any energy to 20 MeV and with degree of polarization 20-30% emitted in the reactions. The deficiency of the reactions is formation of continuous neutron spectrum at energy exceeding thresholds of three – partial reactions, that is at E_p>8.34 MeV in first reaction and at E_d>4.45 MeV – in second reaction. It is interesting that neutron polarization sign in the $T(p,n)^3He$ reaction is opposite polarization sign in the $D(d,n)^3He$ reaction Asymmetry of products in reverse reactions $He^3(n,d)D$ and $He^3(n,p)T$ will have also opposite sign under corresponding angles.

TABLE 3. Polarization of neutrons from the $T(p,n)^3He$ reaction as a function of proton energy

E_p, MeV	Polarization, %
Walter R.L. et al.[19], $\Theta_{c.m.}=45^\circ$	
2.9	26.±3
4.0	8.1±2.0
5.0	-1.1±2.0
6.0	-11.2±2.0
9.0	-17.±4
12.0	-20.±4

Θ_{lab}=45°	
6.0	-14.3±2.0
8.0	-19.±2.5
10.0	-23.±3
Alekseyev N.V. [20]Θ_{lab}=40°	
10.5	28.6±4.1
Alekseyev N.V. [11]Θ_{lab}=45°	
12.2	-17.8±3.1
14.5	-19.4±6.1
16.5	-18.3±8.6
Samoylov et al. [18] Θ_{lab}=40°	
6.3	-14.4±4.4
7.8	-19.4±4.4
8.8	-22.5±2.5
10	-30. ±2.5

The reaction $C^{12}(d,n)^{13}N$

The study of polarization in stripping reactions is interesting for understanding of stripping reaction mechanism. The reaction $C^{12}(d,n)^{13}N$ was studied at E_d from 2 to 3 MeV and at 11.8 MeV [21,22].

Babenko et al. [22] measured neutron polarization at E_d=(6.2±0.4) MeV, for Θ_{lab}=28.7,40,46,48,57.2 and 67°.

TABLE 4. Angular distributions of polarization of neutrons from the $C^{12}(d,n)^{13}N$ reaction (the data of Babenko et al. [22])

E_d, MeV	$\Theta_{c.m.}$, degree	Polarization, %
2.8	11	-38±3
	22	-44±3
	34	-42±3
	43	-33±3
	63	-18±4
3.0	11	-31±4
	22	-42±2
	34	-38±3
	43	-29±3
	65	-10±4
6.2	31	-5±3
	43	-24±3
	49	-20±3
	52	-22±3
	62	-4±3
	72	5±3
11.8	22	-3±3
	32	0±2
	44	-12±4
	49	-22±3
	54	-37±2
	65	-33±4
	75	-11±4
	85	24±4

The reaction $B^{11}(d,n)^{12}C$

The neutron polarization in the $B^{11}(d,n)^{12}C$ reaction was measured for transition to ^{12}C ground level and transition to first excited level at E_d=12.3±0.3 MeV [23]. The neutron angular distribution anisotropy correction were took at determine of neutron polarization in the $B^{11}(d,n)^{12}C,^{12*}C$ reaction; the magnitudes of corrections did not exceed 6%.

TABLE 5. Polarization of neutrons from the $B^{11}(d,n)^{12}C,^{12*}C$ reaction (the data of Smotryaev V.A., Trostin I.S. [23])

Θ_{lab},degree	Polarization, %
$B^{11}(d,n)^{12}C$	
20	8.125±4.375
30	20. ±3.75
40	5.63±3.75
50	-6.875±6.25
60	-16.875±8.125
70	-1.25±3.75
80	5. ±3.125
90	-8.125±4.375
100	-16.875±4.375
110	-3.75±3.13
120	-3.125±5.625
130	18.125±3.125
140	18.125±3.125
150	-4.375±2.5
$B^{11}(d,n)^{12*}C$	
20	-2.5±5.0
30	0.625±3.125
40	-2.5±3.13
50	-14.375±8.125
60	-22.5±8.13
70	-21.25±1
80	-10.625±4.375
90	-12.5±1
100	0. ±3.75
110	8.125±1.875
120	11.875±1.
130	15.625±1.875
140	16.875±2.5
150	9.375±1.

The scattering neutrons

Series of experiments were devoted to study of polarized neutron scattering, most consideration was gave elements with mass number A>50 [15,24 – 26]. Neutron polarization was measured for 22 elements mainly with number A<65 in [27]. The neutrons with energy 3.5 MeV were formed in D+D reaction at elastic scattering their through angle Θ_{lab}=30°. It was measured scattering asymmetry R without calculation of multiple scattering.

$$R=[1-P_1(\Psi)P_2(\Theta)]/[1+ P_1(\Psi)P_2(\Theta)]. \quad (3)$$

$P_1(\Psi)$ – degree of primary neutron beam polarization, $P_2(\Theta)$ – degree of neutron polarization at scattering their on sample through angle Θ. Influence of multiple scattering on asymmetry value was experimental verified for carbon. Real value of asymmetry will exceed value carried out in experiment to 30 percent. Polarization calculations were carried out in formula (3). The polarization smooth changes with atomic weight and its character cannot changes essentially with introduction of corrections on multiple scattering.

TABLE 6. Scattering asymmetry R without calculation of multiple scattering

Element	R	Element	R
Li	0.97±0.02	S	1.05±0.03
Be	0.94±0.02	Cl	1.09±0.06
C	0.86±0.02	Ca	1.01±0.02
N	0.91±0.04	Ti	0.93±0.02
O	1.02±0.03	Fe	0.98±0.02
F	1.09±0.04	Cu	1.01±0.02
Na	1.07±0.06	Nb	0.96±0.06
Mg	1.05±0.02	Sb	1.00±0.03
Al	1.04±0.02	Pb	1.02±0.02
Si	1.04±0.03	Bi	1.01±0.02
P	1.02±0.04	U	0.96±0.02

Figure 1 shows angular dependence of proton polarization with energy about 10 MeV at helium scattering. This dependence was calculated on optical model. Nuclear neutron and proton scattering is equally, the difference is visible at small angles because of Coulomb interaction. Experimental researches of fast neutron scattering and polarization is difficult because for they including recorded of small number of neutrons scattered by research sample at high background of neutrons scattered by walls and materials of constructions of plant.

The task of experiment consist in measurement of number of neutrons scattered by sample through angle Θ and define relation of scattering intensity to intensity of incident beam on sample.

Methods of polarization analysis

Method of Svigner scattering

Practical realization of fast neutron polarization analysis method founding on scattering is presented in article of Gorlov et al. [28] for measurements of neutron polarization in D (d,n)^{3}He reaction with energy about 4 MeV. Neutrons, scattered by lead target with diametrical sizes about 1 mm, were observed at angles 2-4°. Thus one of first true results of D+D neutron polarization was obtained.

Scanlon et al. [29] elaborated method of use Svigner scattering for neutron polarization analysis with energy from 20 to 120 MeV. Uranium was used as the scatterer. Scattered neutrons were observed at angle 1° on distance about 2.5 m from scatterer. Measurements of neutron polarization were carried out with this analyzer. These neutrons emitted from different targets of proton linac with energy to 120 MeV. Measurements of neutron polarization at scattering were carried out also. Analyzers founded on observation of nuclear scattering asymmetry in unpolarized sample – scatterer were received most dissemination.

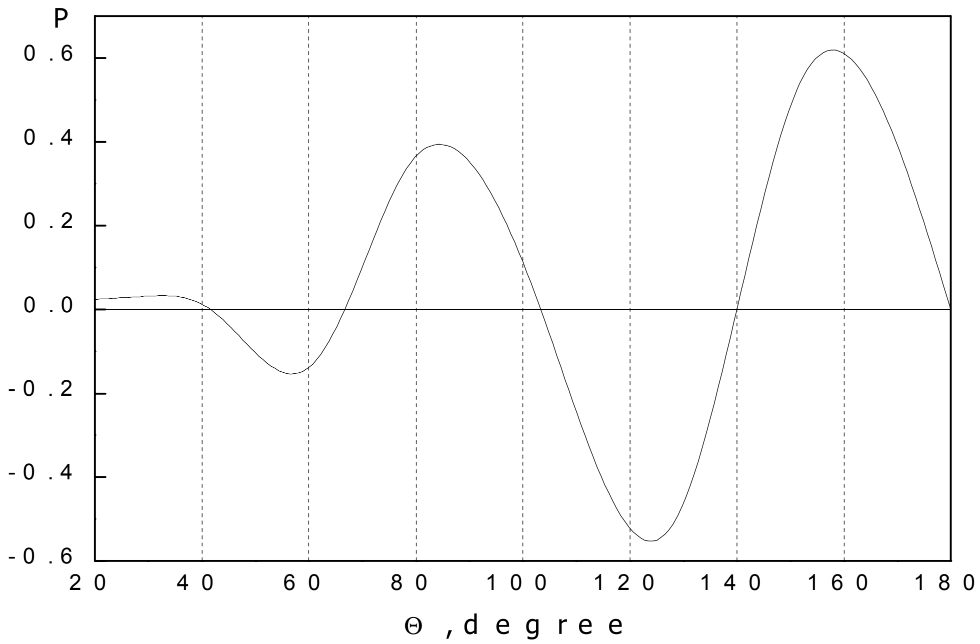

FIGURE 1. Angular dependence of proton polarization with energy about 10 MeV

Method of nuclear scattering asymmetry

Figure 2 show energy dependence of neutron polarization at scattering on oxygen through angles $\Theta_{c.m.}=60^\circ$ and $\Theta_{c.m.}=120^\circ$. It is observe complicated resonance trend of polarization with energy. Analogous polarization trend with resonance effect observes at scattering on C^{12}. This complicated dependence is very uncomfortably. Therefore, most comfortable scatterer – analyzer is helium. Polarization at neutron scattering on He^4 through two angles $\Theta_1 \approx 80^\circ$ and $\Theta_2 \approx 120^\circ$ exceeds 80%. The values of maximum polarization angles and polarization values at these angles changed very feebly with energy in very wide interval beginning from 3-4 MeV.

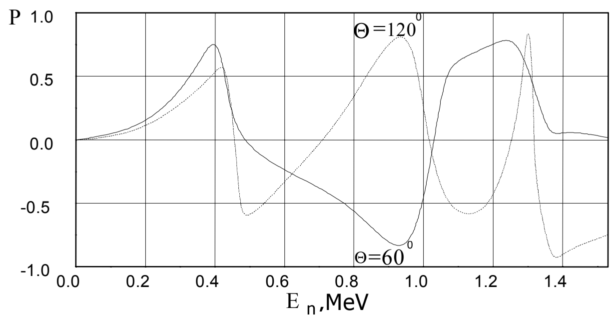

FIGURE 2. Neutron polarization at scattering on oxygen

Method of two-channels analyzer

Publication [19] is interesting as first use of reverse reaction method for study polarization. Experiment essence – proportional telescope of counters is used in the capacity of neutron analyzer. Reverse reaction proceeds in the radiator of proportional counter recorded protons at certain angles. The radiator was made in the form of gas chamber with depth 5 cm, diameter 5 cm, with thin back window. The chamber was filled with helium He^3 up to a pressure of 10 atmosphere. It was obtained rather strong (to 30%) neutron polarization of the $T(p,n)^3He$ reaction with energy 6-10 MeV. Next measurements carried out others methods confirmed this result and gave polarization sign. Practical application of the method meets with difficulties because of necessity to make use of thin analyzer (radiator), it efficiency may be insufficient. It is interesting that neutron polarization sign in the $T(p,n)^3He$ reaction is opposite polarization sign in the $D(d,n)^3He$ reaction Asymmetry of products in reverse reactions $He^3(n,d)D$ and $He^3(n,p)T$ will have also opposite sign under corresponding angles. This give possibility to use He^3 as analyzer permitting determine neutron polarization with energy > 5 MeV.

Any effect leading to neutron polarization can use for polarization analysis. Simplest polarizer – analyzer is target with polarized protons. If target contain pure hydrogen with 100%-polarized protons; small thickness is enough for strong polarization of arriving beam. It is clear that other polarization nuclei can use instead of proton.

CONCLUSION

The summary diagram of basic methods of fast neutron polarization is presented in figure 3. These data were obtained in Visconsin University, Kurchatov Institute of Atomic Energy and some other laboratories. These data confirm possibility of neutron receipt with polarization 20-60% in energy region 1-40 MeV. The diagram allows choosing polarized neutron source with necessary energy. All of these sources can use in IPPE for study polarization.

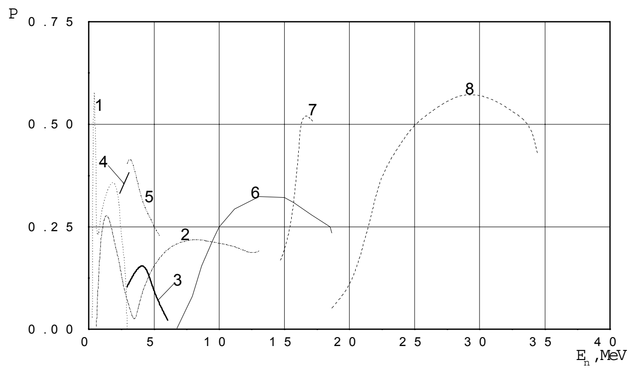

FIGURE 3. Maximum neutron polarization of different sources:

1 – $Li^7(p,n)^7Be$ 50°; 2 – $T(p,n)^3He$ 40°;
3 – $D(d,n)^3He$ 50°; 4 – $C^{12}(d,n)^{13}N$ 20°;
5 – $Be^9(p,n)^9B$ 50°; 6 – $D(d,n)^3He$ 30°;
7 – $T(d,n)^4He$ 90°; 8 – $T(d,n)^4He$ 30°.

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