SOVIET PHYSICS USPEKHI VOLUME 7, NUMBER 4 JANUARY-FEBRUARY 1965
539.1.03

New Instruments and Measurement Methods

SOURCES OF POLARIZED FAST NEUTRONS

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Usp. Fiz. Nauk 83, 741-752 (August, 1964)

1. INTRODUCTION

THE feasibility of nucleon polarization became evident as soon as the study of the hyperfine structure of optical lines had established that the nucleon spin is not equal to zero. The first polarized protons were obtained in Stern's measurements of the magnetic moment, while polarized neutrons were obtained by passing a beam through magnetized iron samples. In these first experiments, the polarized nucleons were obtained by using the spin dependence of the electromagnetic forces acting on the nucleons, because the magnetic moment is related to the spin. The measurement of the magnetic moment proper was the purpose of these first experiments with polarized nucleons.

As early as 1934, Wigner established by analysis of n-p scattering that the nuclear forces acting between the proton and the neutron depend on the spin. The investigation of the nuclear forces is a fundamental problem of nuclear physics. To solve this problem, it is very important to be able to use polarized nucleons. In experiments with unpolarized nucleons the different spin states are indistinguishable, and such effects as spin exchange during the course of interaction cannot be observed at all. If polarized nucleons are present in the beams and in the targets, the scattering can be observed separately in either the singlet or triplet states, and the probability of spin exchange can be determined by observing the state of polarization after the scattering. A large number of investigations have been devoted in recent years to nucleon-nucleon scattering with polarized beams. Methods for obtaining targets with polarized protons are now being vigorously developed.

The nuclear forces depend on the spin direction not only in nucleon-nucleon collisions, but also in nucleon-nucleus collisions. If the target spin differs from zero, the forces depend primarily on the relative orientations of the spins of the nucleus and the nucleon. However, even in collisions between nucleons and zero-spin nuclei, the interaction depends on the orientation of the nucleon spin relative to the orbital angular momentum. This dependence is due to the spin-orbit nuclear interaction, which is similar to the electromagnetic spin-orbit interaction that causes the fine splitting of the atomic terms. It is known that the energy levels of the nuclei experience spin-orbit splitting which is much stronger than atomic splitting. The assumption of a strong spin-orbit nuclear interaction has made it possible to explain the magic numbers and to construct a nuclear-shell scheme. Therefore spin-orbit forces are more important for the structure of the nucleus than for the structure of the atom. The spin-orbit splitting of nuclear levels gives an idea of the large value of the spin-orbit nuclear forces. A detailed investigation of these forces calls for experiments on the polarization of nucleons upon scattering.

The dependence of the interaction between the nucleon and the nucleus on the total spin can be observed in experiments with polarized slow neutrons, obtained, for example, by reflection from magnetized mirrors. To observe spin-orbit interaction it is necessary to use fast nucleons that have experienced collisions in states with orbital angular momentum l different from zero.

In nucleon-nucleon collisions, states with $l > 0$ become noticeable only at high energy, and therefore most experiments on nucleon-nucleon scattering with polarized beams were carried out at energy $E > 100$ MeV. At lower energy, the polarization effects are small and can be observed only in experiments that yield very accurate results. Observation of polarization in nucleon-nucleon scattering at low energy (< 100 MeV) is quite important for phase-shift analysis[1]. The number of phase shifts that make a noticeable contribution is in this case relatively small, so that the analysis is simpler and more reliable.

In nucleon-nucleon collisions, the states with $l > 0$ are manifest even at an nucleon energy ~ 1 MeV, so that the investigation of the spin-orbit nucleon interaction can be carried out in nucleon-nucleus collisions. Nucleons with energy sufficient for this purpose can be obtained from the most readily available conventional accelerators.

In the present review we consider primarily sources of medium-energy polarized neutrons. In spite of the fact that the first experiments with polarized fast neutrons started in 1952, the research difficulties make the results obtained so far still scanty and inconclusive. However, the interest that is attached to work with polarized nucleons is quite large; many nuclear-physics laboratories are diligently at work on the development of sources and analysis methods for polarized nucleons. In 1960, the first international conference on polarization phenomena was held in Basel[2]. The number of recent publications has been increasing rapidly and a review of the results obtained is fully justified.

Investigations with polarized protons are methodologically simpler and are therefore now more numerous and more productive. We can point, for example, to a series of papers by Rosen et al[3], dealing with left-right asymmetry of elastic scattering of polarized protons with energies up to 17 MeV by many nuclei.

Polarized protons were obtained recently with some linear accelerators in western Europe[4] and in the United States[5]. Work is in progress also on cyclotron acceleration of polarized protons and deuterons[6]. However, the greater ease of obtaining polarized protons does not obviate the need for research with polarized neutrons. In elementary nucleon-nucleon collisions, the neutrons are essential for the study of interactions that cannot be investigated with proton beams. For example, neutron beams are indispensable for n-p scattering studies, since there are no free-neutron targets. In collisions with complex nuclei, the proton interaction is complicated by the Coulomb forces, and neutrons are also preferable. Therefore, in spite of the successful development of methods for the acceleration of polarized protons, research with polarized neutrons retains its importance and is being successfully developed in many laboratories.

The first sources of polarized fast neutrons (PFN) were discussed a long time ago. These were the reactions $D(d,n)He^3$ and $Li^7(p,n)Be^7$. These yielded PFN with energies from 0.3 to 2.5 MeV, which were used for the well known experiments of Barschall et al[7,8], who studied the asymmetry of scattering by numerous nuclei. An analysis of these results, aimed at determining the spin-orbit nuclear potential, is made difficult by the presence of elastic scattering via the compound nucleus. In this connection, it would be natural to investigate the possibility of working with higher-energy neutrons. An increase in the PFN neutron energy is particularly essential for the analysis of np scattering. Therefore the search for PFN in a wide range of medium energies is an important problem in contemporary experimental nuclear physics and attracts the attention of many laboratories.

Recently the range of investigated PFN energies was greatly broadened. Reviews of the status of PFN research were reported in February 1963 by Haeberli[9] and Barschall[10] at a conference in Houston. Additional data received later[11,12] increased the investigated range of energies.

2. MEASUREMENT METHODS

Methods for the investigation of fast neutron polarization are well known and need no detailed discussion. The PFN neutron analyzer is based on either elastic scattering or a nuclear reaction whose products have a right-left asymmetry that depends on the degree of polarization in the direction perpendicular to the scattering or reaction plane. The neutron polarization P_1 is determined from the asymmetry ϵ by means of the equation

$$\varepsilon = \frac{R-L}{R+L} = P_1P_2.$$

Here R —intensity of the products observed at a certain angle on the right, L —the same on the left, and P_2 —the neutron polarization which would be obtained in the corresponding direction were the inverse process, caused by unpolarized particles, to occur in the analyzer. The equality of P_2 to the asymmetry of the products of the inverse reaction was demonstrated in several papers[13]. To determine P_1 in the general case it is necessary to know the value of P_2 characteristic of the particular analyzer. Barschall indicated[14] that if the inverse reaction is used as the analyzer, then at certain angles we get $P_1 = P_2$, and then the absolute value of the polarization is determined directly in one experiment without additional data. The practical application of the method of inverse reactions is limited both by the choice of the reactions amenable to observation and by the intensity conditions; this method was therefore used so far in only one investigation[15]. In most cases the quantity measured is the asymmetry of elastic scattering. Scattering by He^4 is most widely used. The advantage of the helium scatterer-analyzer is the large asymmetry at two values of the angle, which has a weak energy dependence, as do the maximum-asymmetry angles themselves. The properties of helium as an analyzer were investigated in greater detail than the properties of other nuclei (such as C^{12}, O^{16}, etc.). Another advantage is the relatively low mass of He^4. The recoil nuclei produced in n-He^4 scattering have sufficiently high energy and can be registered. Levintov[16] used this property to separate the scattering direction. In other modern experiments it is used to exclude the background by using coincidence circuits which register simultaneously both the scattered neutron and the recoil α particle.

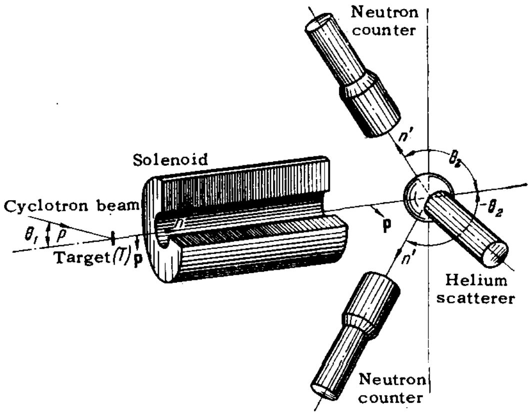

FIG. 1. Diagram of installation for the measurement of the polarization of fast neutrons.

Figure 1 shows the set-up used in the Kurchatov Atomic Energy Institute to measure polarization. Helium at a pressure of approximately 100 atm, mixed with 3–5% of xenon, fills a scintillator chamber, the window of which is in contact with a photomultiplier that registers the recoil α particle. The neutrons scattered at an angle $\theta_2 = 123°$ are registered by two plastic-scintillator counters. The use of two counters in place of one eliminates instabilities and makes it possible, generally speaking, to operate without a monitor. An essential part of the set-up is a Hillman solenoid[17], which turns the neutron spin 90° in the magnetic field. Its use reduces the change of observation direction from right to left (and vice versa) to a reversal of the current direction, and eliminates the false-asymmetry errors which are always appreciable in experiments of this type. When the spin is turned 90°, the counters are mounted not in the reaction plane but in a plane perpendicular to it.

Figure 2 shows one of the results of the measurements. The points represent the spectra of the recoil α-particle momenta, coinciding with the readings of the two neutron counters. The spectral line corresponds to monoenergetic neutrons of the reaction $D(d,n)He^3$, and the remainder to the background from the disintegration neutrons, target parts, and random coincidences. When the current in the solenoid reverses direction, the intensity of the line decreases in one direction and increases in the other, since the former right-hand counter becomes the left-hand one and vice-versa. Analogous installations are used in other laboratories.

Installations of this type can measure simultaneously the polarization of neutrons over a sufficiently broad range of the spectrum. A limitation is imposed by the spectrometric properties of the helium scintillator. The energy resolution of the helium scintillator under the measurement conditions is not sufficiently high. To improve the resolution, the installation can be connected in a time-of-flight spectrometer circuit. The use of the spectrometer eliminates also a considerable fraction of the background.

A practically absolute method of polarization analysis is based on the use of electromagnetic (Schwinger) neutron scattering. To calculate the scattering asymmetry it is necessary to know, in addition to the well known interaction between the magnetic moment of the neutron and the Coulomb field of the nucleus, only the cross section of the nuclear scattering, which can be measured relatively simply with sufficient accuracy. The practical difficulty in the use of this method is the need for observing the scattering at very small angles, near 1°, where the asymmetry is appreciable. Strict collimation of the beams leads to a loss in intensity and in the measurement accuracy. In spite of this, the method is used for the analysis of neutron polarization over a wide range of energies[18,19]. Double scattering, which is widely used for the analysis of proton polarization, necessitates the use of very intense beams, so that it is very rarely used in work with neutrons.

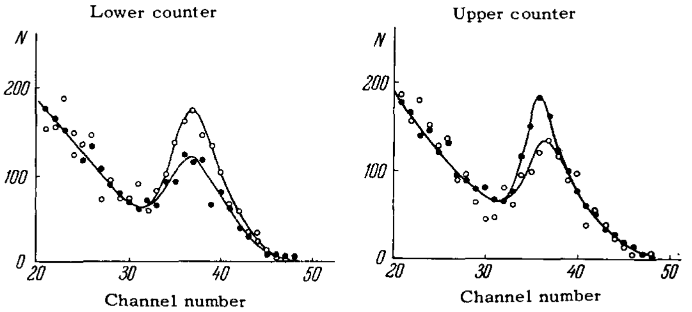

FIG. 2. Spectra of recoil α particles in coincidence with two neutron counters for opposite directions of the magnetic field of the solenoid. Reaction $D(d, n) He^3$, $E_d = 11.6$ MeV, $\theta_1 = 25°$.

3. CHARACTERISTICS OF SOURCES

The experiments performed so far indicate that the polarization of nuclear-reaction products, particularly neutrons, is a usual phenomenon even in cases when the reacting particles are unpolarized. To the contrary, zero polarization of fast neutrons is a unique case, observed only under certain special conditions. This is not surprising, since spin-orbit interaction plays an essential role in nuclear collisions.

We can expect any neutron-producing reaction to serve as a source of PFN. However, it is still impossible to predict the magnitude of the polarization, and the data are still very scanty even for the development of approximate empirical rules, since polarization has been investigated only for a small number of reactions. The main measurement results pertain to the reactions (p, n) and (d, n) on the lightest nuclei. These reactions were used earlier as sources of unpolarized fast neutrons. Indeed, the neutron polarization at $\theta_1 = 0°$ and at some other special angles is

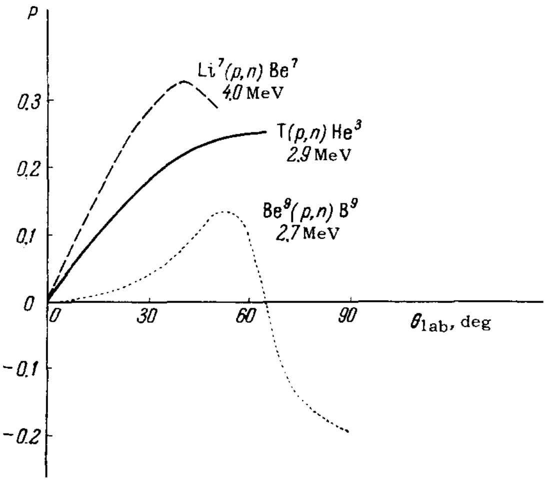

FIG. 3. Angular dependence of the polarization of the neutrons from (p, n) reactions at low energies.

equal to zero. In general, however, the neutrons from these reactions are polarized.

The character of the polarization has certain features that are common to identical reactions on different nuclei. Figure 3 shows the angular distribution of the polarization of neutrons of the reaction (p, n) on T, Li^7 and Be^9 at $E_p \approx 3-4$ MeV. The polarization is positive (in accordance with the Basel convention) in all cases and has a maximum at angles from 45 to 90°. A polarization of this type corresponds in scattering from a spinless nucleus to interference in the S and P states. The polarization turns out to be positive when the phase of $P_{3/2}$ is larger than the phase of $P_{1/2}$. In low-energy (p, n) reactions the character of the polarization is apparently determined by analogous interference conditions in states corresponding to the smallest values $l = 0$ and 1. With increasing energy, the maximum of polarization remains the same at forward angles, but its sign is reversed. Figure 4 shows the energy dependence of the polarization near the forward maximum in the reactions T, Li^7, Be^9(p, n). In all cases the polarization reverses sign at $E_p = 4-6$ MeV. At low energies, resonance effects are observed in the angular and energy dependences of the polarization (see, for example, the curve for Li^7 on Fig. 4). With increasing energy, the resonance effects become smoothed out and are averaged out.

The energy dependence of the polarization of the neutrons from the reaction $T(p, n)He^3$ is in full accord with the analysis of the excited states of the He^4 nucleus, based on a consideration of resonance at $E_p = 3$ MeV and the angular distribution of the neutrons beyond the limits of resonance[21]. It followed from this analysis that the state at $E^* = 22$ MeV could be ascribed a momentum and parity 2^-, while for $E_p > 3$ MeV a large contribution was made by the state 1^-. If the neutron is emitted in the resonance $E_p = 3$ MeV preferably in the state $P_{3/2}$, and at higher energy predominantly in the state $P_{1/2}$, then a reversal of the sign of polarization should be observed at $E_p > 3$ MeV. Indeed, the experiments of Walter et al[22] have shown that a maximum of polarization is observed at $E_p = 3$ MeV and that its sign reverses at $E_p \approx 5$ MeV.

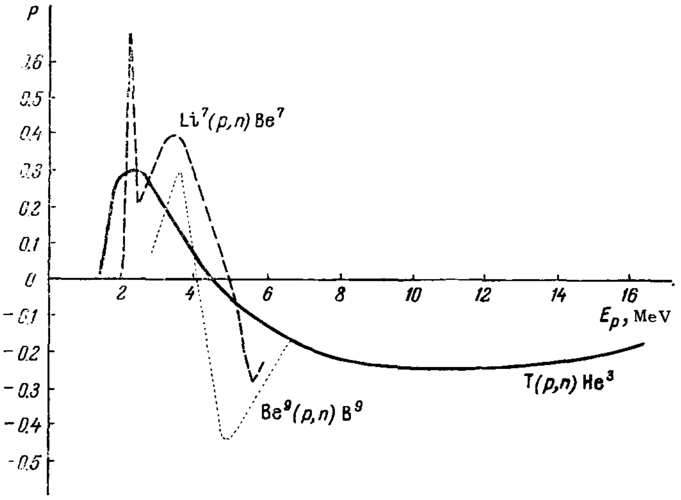

FIG. 4. Energy dependence of neutron polarization in (p, n) reactions in the region of the forward maximum.

The identical character of the energy dependence of the polarization in the reactions (p, n) on Li^7 and Be^9 indicates that the phase difference of $P_{3/2}$ and $P_{1/2}$ experiences analogous changes in these cases.

The neutron polarization in the (p, n) reactions at angles < 60° was investigated also at proton energies > 100 MeV[19]. At this energy, practically every target emits neutrons with a continuous spectrum. The neutrons have noticeable polarization over a wide range of the spectrum. The value of the polarization depends on the neutron energy, and the dependence varies with the target and also with the thickness of a target made of the same material. A polarization that varies smoothly in the range 20–40% was obtained at $E_p = 140$ MeV from an aluminum target of thickness 55 MeV at an angle of 45°. Such a target was used to obtain polarized neutrons with energy 20–100 MeV and to investigate their scattering.[23]

Consequently, the (p, n) reaction can be used at a source of PFN in a wide range of energies. However, with increasing energy, the separation of monoenergetic neutron groups becomes more difficult, and work with neutrons having a continuous spectrum is possible only if spectrometry is used, for example by the time-of-flight method. Other spectrometry methods are also possible, but usually lead to a loss in neutron registration efficiency.

The most thoroughly investigated among the (d, n) reactions are $D(d, n)He^3$ and $T(d, n)He^4$, with the reactions $B^{11}(d, n)C^{12}$ and $C^{12}(d, n)N^{13}$ investigated in lesser detail. Figure 5 shows the angular distributions of the polarization of the neutrons from the $D(d, n)He^3$ reaction in the forward hemisphere for several values of the bombarding deuteron energy. The polarization has a maximum at an angle close to 45° in the c.m.s. This position of the maximum remains in a very wide interval of energies. At maximum energy $E_d = 19.5$ MeV, the angular distribution has not been investigated, but it has been verified that the maximum does not

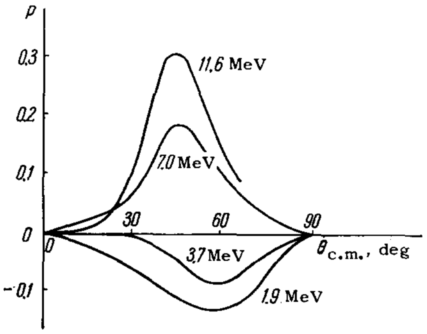

FIG. 5. Angular dependence of neutron polarization in the reaction D(d, n) He^3 at different deuteron energies.

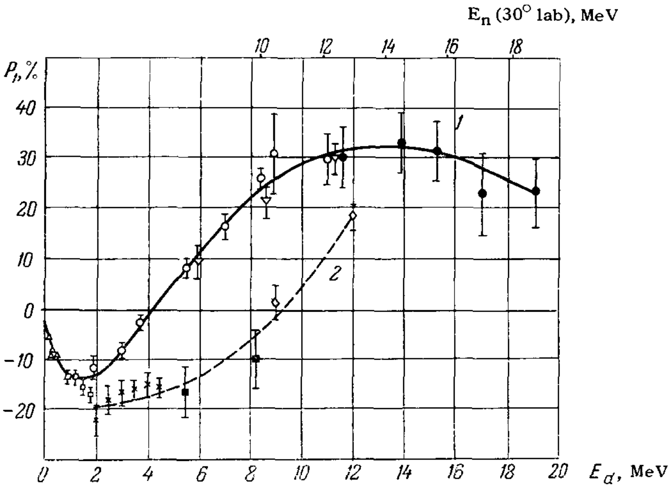

FIG. 6. Energy dependence of neutron polarization in the reaction D(d, n) He^3 in the region of the forward maximum as obtained in different measurements. Δ – Pasma (47° lab) [39]. □ – Levintov et al (49° lab) [40]; × – Baker and Jones (40° lab) [41]; ■ – Avignon et al (40° lab) [4]; ◇ – Trostin and Smotryaev (30° lab) [44]; ○ – Dubbeldam and Walter (45° c.m.s.) [24]; ▽ – Niewodniczanski et al (45° c.m.s.) [25]; ● – our data (30° lab) [11].

shift towards smaller angles[11], as expected from general considerations. However, the sign of the polarization reverses in the region of the maximum at a certain value of the energy. The existing data on the value of this energy and the magnitude of the polarization at $E_d > 2$ MeV are very contradictory. Figure 6 shows the dependence of the polarization obtained in different measurements near maximum deuteron energy. All the data cluster about two curves, which differ by much more than the experimental error. These curves were first presented in the paper by Haeberli[9]. They are supplemented by data (points) obtained at the Kurchatov Atomic Energy Institute at deuteron energies from 11.6 to 19.5 MeV. In the neighboring energy region near 12 MeV these results fit satisfactorily the curve plotted in Wisconsin[24], and continue it smoothly into the region of higher energies. We regard the upper curve as more reliable, although the reasons for the discrepancy are not obvious. The slight variations in the observation angles used by different authors apparently cannot explain so large a discrepancy, and are more likely to characterize the imperfection of the measurements. Confirmation of the upper curve was obtained by Niewodniczanski et al in Krakow[25].

The reaction T(d, n)He^4 is very interesting as a source of the fastest monoenergetic neutrons. Measurements of the polarization of these neutrons were made in Los Alamos up to E_d = 7.7 MeV[26], in Wisconsin[27] at energies 7.7 and 10 MeV, and at the Kurchatov Atomic Energy Institute[12] in the interval of energies E_d from 9 to 19 MeV. It must be noted that the determination of the polarization of neutrons with energies > 20 MeV entails difficulties because of the uncertainties in the properties of helium as an analyzer at this energy. The predictions of Gammel

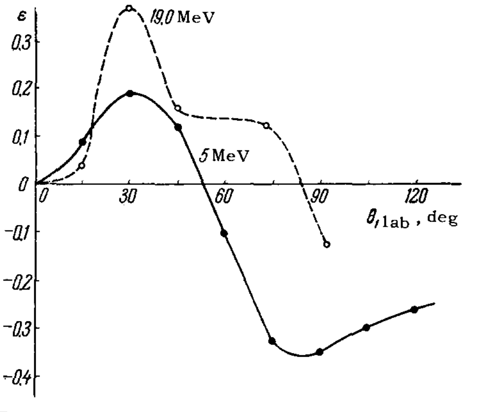

FIG. 7. Angular dependence of the asymmetry of neutron scattering in the reaction T(d, n)He^4 with E_d = 5 MeV, $\theta_2 \simeq 120°$ and E_d = 19 MeV, $\theta_2 \simeq 123°$.

and Thaler[28], which have been regarded as the best, do not agree with recent measurements of the polarizations in n-He^4 scattering at E_n = 24 MeV[27], and p-He^4 scattering at E_p = 38 MeV[29]. There is still no reliable phase-shift analysis of $n\alpha$ scattering, and consequently no reliable data on the properties of helium as an analyzer. What is reported for the T(d, n)He^4 reaction is therefore the value of the measured asymmetry, and the polarization is determined arbitrarily by comparison with the polarization of the protons of the mirror reaction He^3(d, p)He^4 or under the assumption that the asymmetry in $n\alpha$ scattering is the same as in $p\alpha$ scattering. The asymmetry in $p\alpha$ scattering was measured for several values of the energy from 20 to 40 MeV in British experiments with polarized protons[30].

Measurements of the polarization of neutrons of the reaction T(d, n)He^4 at E_d from 9 to 19 MeV have disclosed resonant effects connected with the excited state of He^5 at $E^* \simeq 20$ MeV. In this connection, more detailed investigations at E_n > 20 MeV will be

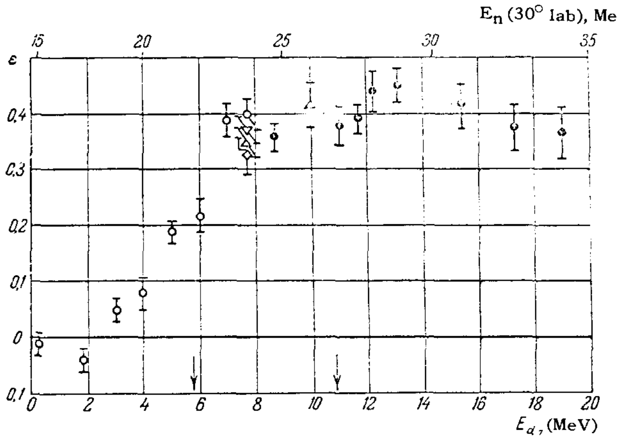

FIG. 8. Energy dependence of the asymmetry of neutron scattering in the reaction T(d, n)He^4 at θ_1 = 30°. The arrows indicate the positions of the resonances of the reaction T(d, n)He^4 and of $n\alpha$ scattering. ○ – Perkins et al [26]; ▽ – Walter et al [27]; ● – our data [12].

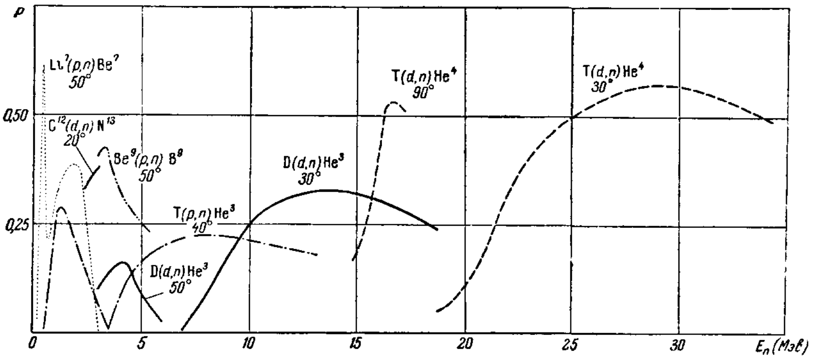

FIG. 9. Summary diagram of maximum polarization of neutrons of different investigated sources.

necessary for the phase-shift analysis of the nα scattering. The angular distribution of the observed asymmetry is shown in Fig. 7. The values of the asymmetry give the lower limit of the polarization. The polarization has a positive maximum at $\theta_1 = 30°$ for both $E_d = 5.5$ MeV and $E_d = 19$ MeV. The dependence of the polarization in the region of the maximum on the deuteron energy is shown on Fig. 8.

Data on the polarization and (d, n) reactions on other nuclei are still scanty. The reaction $C^{12}(d,n)N^{13}$ was investigated for E_d from 2 to 3 MeV and 11.8 MeV[31-34]. Neutron polarization in the reaction $B^{11}(d,n)C^{12}$ was measured for transitions both to the ground state of C^{12} and to the first excited state[35] at $E_d = 9.3$ MeV.

The summary data of the hitherto investigated sources of monoenergetic PFN are represented in Fig. 9, which shows the maximum observed polarization as a function of the neutron energy, for different source reactions. The laboratory angle at which the maximum polarization is observed is also indicated.

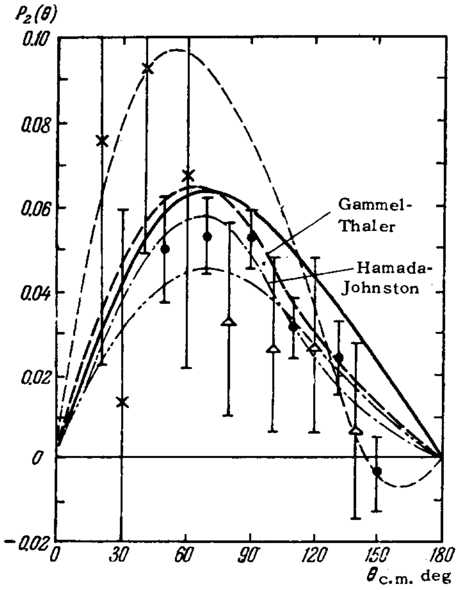

FIG. 10. Angular distribution of the polarization of neutrons in np scattering. Curves showing different variants of the theoretical analysis. x – Bowen et al, E = 20 MeV [23]; ▲ – Barschall et al, E = 24 MeV [27]; ● Perkins and Simmons, E = 24 Mev [26].

Although the number of systematically investigated reactions is still small, the data obtained for the principal laboratory sources of fast neutrons indicates that neutrons can be obtained with polarization > 20% over the wide energy interval 0.3–35 MeV. The energy dependence of the neutron polarization in the reaction $T(d,n)He^4$ gives grounds for hoping to obtain polarized neutrons with even higher energy in this reaction.

The polarized neutrons from this reaction, with energy of approximately 24 MeV, have already been used in several investigations to study the asymmetry of np scattering[23,27,36] and scattering by complex nuclei[45]. Figure 10 shows the experimental data on the polarization in np scattering, obtained in three laboratories[23,27,36] in conjunction with the predictions of different phase-shift analysis variants[1,36-38]. Neutrons with energy 20 MeV were obtained at Harwell[19] from the (p, n) reaction and were separated from the continuous spectrum by time-of-flight. The observed polarization is small, so that the results of the measurements are not sufficiently accurate for either reconciliation with one another or for unique choice of the phase shift analysis variants. Since an increase in polarization with increasing neutron energy is expected, we can hope to obtain more unambiguous results in systematic investigations at different energies, which are among the first problems to be tackled in future experiments. An essential part of future experiments is an absolute measurement of the polarizations of the neutrons in the reaction $T(d,n)He^4$, which has remained so far undetermined because of the uncertainty in the properties of the helium analyzer.

Measurements of the scattering of polarized neutrons with energy 24 MeV by different nuclei[45] have confirmed the expected sign of the spin-orbit potential, and gave in the case of heavy nuclei satisfactory agreement with optical-model calculations. The absolute value of the spin-orbit potential is 25 times larger than the Thomas potential and is approximately in agreement with the value known for protons of nearly equal energy. Of interest in this direction are also further researches with polarized neutrons of different energies.

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Translated by J. G. Adashko