Search and Measurement of P -Odd Asymmetry in the Emission of Secondary Particles Produced in Reactions of Polarized Thermal and Cold Neutrons with Light Nuclei

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Abstract—Investigation of spatial parity in reactions of polarized neutrons with light nuclei is an important topic in the framework of exploring the fundamental problem of understanding the manifestation of the weak interaction in nuclear reactions and for estimating the parameters of the weak nucleon–nucleon interaction. In this paper, the ongoing experimental program of highly sensitive and high-precision measurements of P -odd asymmetries in the reactions of polarized thermal and cold neutrons with lithium and boron nuclei is reviewed. Within this program, the coefficients of P -odd asymmetry of reaction products in the reactions induced by cold- and thermal-neutrons on the isotopes of light nuclei ${}^6\text{Li}$ and ${}^{10}\text{B}$ were measured with record-high sensitivity $\sim 10^{-8}$ as $\alpha_{P\text{-odd}}^{{}^6\text{Li},\text{exp}} = -(8.8 \pm 2.1) \times 10^{-8}$, $\alpha_{P\text{-odd}}^{{}^{10}\text{B},\gamma,\text{exp}} = (0.0 \pm 2.6_{\text{stat.}} \pm 1.1_{\text{syst.}}) \times 10^{-8}$, and $\alpha_{P\text{-odd}}^{\alpha_0+\alpha_1,{}^{10}\text{B},\text{exp}} = -(11.2 \pm 3.4) \times 10^{-8}$. For the first time ever, nonzero values were obtained for two of these asymmetries. Our data for tritium emission in the ${}^6\text{Li}(n,a){}^3\text{H}$ reaction and γ emission in the ${}^{10}\text{B}(n,a){}^7\text{Li}^* \rightarrow \gamma \rightarrow {}^7\text{Li}(\text{gr.st.})$ reaction agree with those of other experiments when interpreted within the cluster model, but rule out the so-called “best DDH values” of weak-interaction coupling constants. Interpreting the data on these reactions relying on “first principles” only would be highly desirable.

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INTRODUCTION

Studies of spatial-parity violation in reactions induced by polarized neutrons on light nuclei are important for understanding the role of weak interactions in nuclear processes and for estimating the coupling constants of the weak nucleon–nucleon (NN) interaction.

The existence of weak neutral currents was predicted by the unified theory of electromagnetic and weak interactions formulated in 1973 [1]. Soon thereafter, these were experimentally detected in muonless neutrino reactions [2]. In 1978, weak neutral currents were found to induce a P -odd rotation of the polarization plane for a laser beam passing through the atomic-bismuth vapor [3]. The discovery of weak neutral currents was a heyday for the electroweak theory. Neutral-current observations in the leptonic sector

provide a strong motivation for experimental searches for neutral current contributions to the NN interaction as a mechanism of nuclear reactions.

The weak-interaction contribution to the NN interaction is often described in terms of one-meson-exchange (π , ρ , ω) or multimeson-exchange ($\pi\pi$) Feynman diagrams featuring one weak and one or more strong vertices (see reviews [4] and [5]). In this parametrization, the neutral and charged weak currents are characterized by the f_π and h_p^0 coupling constants, respectively. In some schemes, attempts are made to associate the values of the latter constants within more fundamental theories. In the Desplanques–Donoghue–Holstein (DDH) quark model in particular, f_π and h_p^0 are predicted to lie in definite allowed regions with the “best values” of $f_\pi \times 10^{-7}$ and $h_p^0 = -11.4 \times 10^{-7}$ [6]. Smaller values of these coupling constants are predicted by the Kaiser–Meissner (KM)

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soliton model [7, 8]. Recently, weak contributions to the NN interaction were actively analyzed within the framework of effective field theory [9–11]. This approach is more general and systematic than the one-meson-exchange scheme. Yet another theoretical approach consists in expanding the parity-violating NN interaction in powers of the small parameter $1/N_c$ where N_c denotes the number of quark colors [12, 13]. In this approach, the neutral current coupling constant f_π is predicted to be significantly smaller than the charged-current coupling constant h_p^0 as indeed observed experimentally [14–18]. For this reason, it is particularly interesting from the viewpoint of our measurements reported in this paper. Anyway, new precise and reliable measurements of P -odd effects in NN collisions are required for critically testing the aforementioned theoretical predictions.

P -odd contributions to the NN interaction observed in different reactions involving few-nucleon systems and nuclei are induced by both the charged and neutral weak currents. In order to reliably estimate the neutral current contribution, at least three conditions must be satisfied. First, the investigated system should have a simple structure amenable to a reliable theoretical description. Second, any spurious systematic effects mimicking observed P -odd asymmetries should be ruled out. Finally, the sought-after effect should be sufficiently large to be detected experimentally. Selecting a physical system that would answer these criteria is a formidable task. The measurements reported in this paper involve nuclear reactions that have been selected taking the following factors into consideration.

Measuring a small P -odd asymmetry requires large event statistics that can be collected only with a very intense particle source. Thus, at least $\sim 10^{16}$ particles should be detected in order to measure an asymmetry on the order of $\sim 10^{-8}$ so as to reduce the statistical uncertainty to an acceptable level. The actually required statistics should be greater than that by a further one or two orders of magnitude as soon as one considers the test runs, measurements of systematic effects, sensitivity losses due to a particular experimental scheme, etc. The event statistics as large as this can only be collected with one of the most intense neutron sources over a long period of data taking.

However, intrinsic P -odd effects in the NN system can be significantly enhanced within a multinucleon system, consistently estimating the degree of such enhancement is impossible today and will hardly be possible in the near future. Compared with those for heavy nuclei, P -odd effects in few-nucleon systems and light nuclei are enhanced to a lesser degree: within any of the aforementioned theoretical schemes, they are expected to be on the order of the weak-interaction

coupling constant, that is, about 10^{-7} . Given adequately optimized experimental conditions and an intense neutron source, measuring such an asymmetry is realistic albeit marginally possible. Unlike multinucleon ones, few-nucleon systems are amenable to theoretical descriptions owing to their relatively simple structure. Over the past decades, ample experience was gained with measuring small asymmetries in neutron-induced reactions and with tackling spurious systematic effects arising in such measurements. Relying on this experience, appropriate experimental conditions for systematics-free measurements of P -odd asymmetries in neutron-induced reactions can be conceptually formulated. This renders the measurements of P -odd effects in light nuclei interesting and realistic.

Theoretically, P -odd effects in proton–proton scattering [19, 20] are largely induced by charged rather than neutral weak currents. Neutral-current contributions to NN interactions in nuclei have so far escaped experimental detection.

Both theoretically and experimentally, much interest is shown in P -odd effects in the reaction of neutron radiative capture by the proton: $(n, p) \rightarrow (d, \gamma)$. As demonstrated in [5], the γ -emission asymmetry in this reaction is fully determined by the weak neutron current, and its coefficient is expressed as $A_\gamma = -0.11f_\pi$. The f_π “best value” in the DDH scheme corresponds to a P -odd asymmetry of 5×10^{-8} while the KM model predicts a still smaller asymmetry. Measuring the P -odd asymmetry in this reaction is complicated by its smallness and by that the neutron-capture cross section is much smaller than the elastic-scattering cross section.

To date, P -odd effects in neutron-capture processes have been detected in the areas of nuclear fission and neutron optics and in the neutron-induced (n, γ) and (n, p) reactions on medium and heavy nuclei in which parity violation can be enhanced by specific effects [21]. Until now, extracting the NN weak-interaction constants from the measurements of P -odd asymmetries in reactions with heavy nuclei proved to be impossible due to large uncertainties and complexity of the data analysis [5]. On the other hand, significant advances were made in theoretically describing light nuclear systems of up to ten nuclei in terms of phenomenological NN -interaction potentials and three-body forces. Since no parameter-free description of light nuclear systems is currently available, the data analysis reported in this paper relies on the cluster model. The results of such data analysis should be viewed as accurate and reliable since this model adequately reproduces the properties of light nuclei.

At excitation energies below some 20–25 MeV, a number of light nuclei can be visualized as consisting of several nucleon clusters [22]:

$${}^6\text{Li} \rightarrow \alpha + n + p \rightarrow \alpha + d',$$

$${}^6\text{Li} \rightarrow \alpha + 2n + p \rightarrow \alpha + t,$$

$${}^9\text{Be} \rightarrow 2\alpha + n,$$

$${}^{10}\text{Be} \rightarrow 2\alpha + n,$$

$${}^{11}\text{Be} \rightarrow 2\alpha + 3n,$$

so that neutron reaction with a light nucleus can be viewed as that with a few-nucleon system in the field of one or more α particles. In this case, the problem can be solved in terms of meson-nucleon couplings. Thus, within the cluster formalism which adequately reproduces nearly all experimental data, the ${}^6\text{Li}$ nucleus with a 70% probability clusterizes into an α particle and a deuteron deformed in the α field. Therefore, the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ transition can be viewed as a three-particle pickup reaction: $n + \{\alpha d'\} \rightarrow \{nd\} + \alpha \rightarrow t + \alpha$.

We believe that when probing parity violation in nuclear reactions, priority should be given to measuring *P*-odd asymmetries in the reactions induced by polarized cold and thermal neutrons on light nuclei in which charged particles and γ rays are emitted. In particular, the following reaction channels should be studied:

(i) Triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction. (1)

(ii) 0.480 MeV photon emission
in the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}^* \rightarrow {}^7\text{Li} + \gamma$ reaction. (2)

(iii) α -particle emission
in the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reaction. (3)

Compared to the radiative-capture process $(n, p) \rightarrow (d, \gamma)$, the obvious advantages of these reactions are that they show significantly-larger *P*-odd asymmetries and have much larger cross sections (~ 1000 b) so that the available neutron flux can be almost fully utilized. With modern high-intensity neutron sources, sufficient event statistics can be collected for revealing *P*-odd effects even in neutron collisions with light nuclei. Within the cluster model framework, *P*-odd asymmetry coefficients for triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction, $\alpha_{\text{P-odd}}^{{}^6\text{Li}}$, and for photon emission in the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}^* \rightarrow {}^7\text{Li} + \gamma$ reaction, $\alpha_{\text{P-odd}}^\gamma$, have been expressed through the weak-interaction coupling constants in [22] and [23], respectively. Therefore, the values of these constants can be refined by comparing the theoretically predicted and measured values of the latter asymmetry coefficients.

This review reports the results of a series of precision measurements of *P*-odd asymmetry coefficients

in collisions of polarized cold and thermal neutrons with lithium and boron nuclei. *P*-odd asymmetries (i) and (ii) were measured at the Petersburg Nuclear Physics Institute (PNPI) and Institute Laue–Languevin (ILL) over different time periods, and the γ -emission asymmetry (iii) at ILL. The measurements carried out at PNPI relied on a vertically oriented neutron beam from a liquid-hydrogen source deployed in the active zone of the BBP-M nuclear reactor. The beam had an integrated intensity of $\sim (1-3) \times 10^{10} \text{ s}^{-1}$ and was polarized with a four-slit polarizing neutron guide. The neutron polarization averaged over the beam cross section was $P = 0.8$. The measurements performed at ILL employed the horizontally oriented intense PF1B beam of cold polarized neutrons with a mean wavelength of $\bar{\lambda} = 4.7 \text{ \AA}$ [24]. This was emitted by a liquid-deuterium neutron source placed in the active zone of the ILL nuclear reactor and had an integrated flux of $N \sim (4-5) \times 10^{10} \text{ s}^{-1}$. Neutrons were polarized with the help of a super-mirror polarizer having cross section of $80 \times 80 \text{ mm}^2$. The degree of neutron polarization was $P = 0.92 \pm 0.02$. In both laboratories, the sign of neutron polarization with respect to the guiding magnetic field was flipped with an adiabatic RF spin flipper, and the asymmetry of charged-particle emission was measured using an ionization chamber.

IONIZATION CHAMBER

In all investigated reactions induced by polarized cold and thermal neutrons on light ${}^{10}\text{B}$, ${}^6\text{Li}$, ${}^{14}\text{N}$, and ${}^{35}\text{Cl}$ nuclei, significant left–right asymmetries of the $W(\theta) \sim (\hat{\sigma}_n \cdot [\hat{\mathbf{p}}_n \times \hat{\mathbf{p}}_p])$ form were found. Here, $\hat{\sigma}_n$, $\hat{\mathbf{p}}_n$ and $\hat{\mathbf{p}}_p$ are unit vectors parallel to those of the neutron spin σ_n , neutron momentum $\mathbf{p}_n$, and charged-secondary particle momentum $\mathbf{p}_p$, respectively. Thus, the coefficient of left–right asymmetry of triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction is measured as $\alpha_{\text{lr}} \approx 1.0 \times 10^{-4}$ [25] which exceeds the sought-for *P*-odd effect by several orders of magnitude. Towards excluding any systematic effect of the dominant left–right asymmetry on the actually measured *P*-odd one, the experimental geometry should be chosen so that the σ_n , $\mathbf{p}_n$, and $\mathbf{p}_p$ vectors were parallel to each other: $\sigma_n \parallel \mathbf{p}_n \parallel \mathbf{p}_p$. The discussed ionization chamber is designed so as to satisfy this collinearity condition. The “left–right” contribution to the *P*-odd asymmetry is proportional to ε^2 where ε is the angular uncertainty of collinear alignment of the above three vectors. As soon as these vectors are aligned to $\varepsilon \sim 5 \times 10^{-3}$, the left–right contribution to the *P*-odd asymmetry of triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction does not exceed $\sim 2.5 \times 10^{-9}$. Aligning the σ_n , $\mathbf{p}_n$, and $\mathbf{p}_p$ vectors with such precision can be easily obtained experimentally.

Fig. 1. Schematic layout of the ionization chamber installed in the neutron beam for detecting P -odd asymmetries of charged secondaries, showing the chamber housing (1), the ${}^6\text{LiF}$ beam stop for absorbing uninteracted neutrons (2), the solenoid generating longitudinal magnetic field guiding the neutron spin (3), the target and grid electrodes of a chamber module (4), and the chamber table (5). $\mathbf{p}_n$ and $\boldsymbol{\sigma}_n$ are the neutron 3-momentum and spin vector, respectively. Solid and shaded arrows depict the neutron-spin directions for the flipper-off and flipper-on regimes.

The ionization chamber aimed at detecting small P -odd asymmetries [26] is schematically shown in Fig. 1. The neutron beam enters the target at an angle of 90° which results in a much smaller neutron-capture rate than could be obtained with a target placed at a small angle to the beam axis. To increase the neutron-capture rate, the detector features as many as 24 normally oriented targets with their up- and downstream detection chambers successively deployed along the beam axis. Apart from increasing the event statistics, multiple targets help reduce the gas specific ionization whereby the system's linearity is improved and the useful fraction of the neutron flux is increased. This assembly of ionization gas chambers is enclosed in a cylindrical duralumin box. With the $70 \times 150 \text{ mm}^2$ entrance and exit windows in the edge walls covered with 0.5-mm-thick zirconium foil, a wide neutron beam can be employed with a negligibly small loss of

beam intensity. One of the double-ionization-chamber modules is schematically shown in Fig. 2 where T is the target, H_1 and H_2 are high-voltage electrodes, and C_b and C_f are the up- and downstream charge-collection electrodes. The external H_1 high-voltage electrode is shared by two neighboring modules. The chamber is filled with argon gas. By choosing appropriate gas pressure and interelectrode distances, total ranges of reaction products can be tuned to be less than the width of the H_1H_2 sensitive gap. The TH_2 absorption gap is used for removing the heavy secondary and for restricting the emission angle of the detected light secondary with respect to the target plane. In the experiment with the lithium target, aluminum foil of a definite thickness was employed for these purposes instead of the gas-filled absorption gap. The chosen modular structure of the detector allows one to repeat a given unit of ionization-chamber modules many times depending on the particular reaction to be investigated. As indicated above, in the measurements reported in this paper the detector consisted of 24 double ionization chambers. Figure 3 shows the dependence of the preamplifier output voltage on the high-voltage at the electrodes of the detector modules [15].

Fig. 2. Scheme of the double ionization chamber forming a detector module for performing measurements in the $\boldsymbol{\sigma}_n \parallel \mathbf{p}_n \parallel \mathbf{p}_p$ geometry, showing the target T , high-voltage electrodes H_1 and H_2 , and charge-collecting signal grids C_b and C_f .

The longitudinal magnetic field guiding the neutron spin is generated by the solenoid wound on the ionization-chamber case, and its direction is tuned so as to coincide with the beam axis within 0.01 rad . With this experimental geometry, the contribution of the left–right asymmetry to the studied P -odd one is reduced by 4–5 orders of magnitude from its maximum value.

Within a detector module, charged secondaries traveling in the forward and backward hemispheres with respect to the neutron-beam direction are detected with the “forward” and “backward” charge-collecting electrodes C_f and C_b , respectively. Since the

P-odd asymmetry is detected in the form $W(\theta) \sim 1 + \alpha(\hat{\mathbf{g}}_n \cdot \hat{\mathbf{p}}_p)$, the effects arising from forward and backward charged secondaries have opposite signs. All C_b and all C_f electrodes throughout the ionization-chamber assembly are electrically connected to the same backward- and forward-signal preamplifiers, respectively.

ELECTRONICS

The data are collected using current-integration techniques. Electrical signals from the forward and backward buses are routed to corresponding preamplifiers whereby ionization-chamber currents are transformed to a voltage proportional to the flux of detected charged secondaries. Note that apart from ionization chambers, the discussed data-acquisition system can be implemented at any radiation detector with output resistance in a wide range between 10 k Ω and 1 G Ω . In the preamplifier, the signal is divided to the variable and constant components. The variable component is amplified and sent to the acquisition system. The channel amplification coefficient is measured during calibration by delivering a rectangular pulse of known amplitude to the preamplifier input.

In our early measurements of *P*-odd asymmetries, data acquisition was carried with a computer using a controlled system of CAMAC-standard modules. From preamplifiers, variable signal components were routed to integrators. Signal integration was carried out with an operational amplifier with a capacitor in the feedback loop, and the output voltage was measured with a digital voltmeter connected to the CAMAC system [26]. The operation of this analog-integration scheme was slow since all integrators were based on relay switches.

At the next stage, the system of CAMAC-standard modules was replaced by software-controlled multifunctional boards embedded in the computer whereby the data acquisition was carried out and the measurements were controlled. This rendered the data-acquisition system more reliable and helped reduce the setup's volume and mass by several times. In the measurements of the *P*-odd asymmetry of triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction in particular, integrator voltages were read out and stored in the computer memory using a programmable 12-bit analog-to-digital converter (ADC) mounted on the ACL-8112pg multifunctional data-acquisition board manufactured by ADLink Technology Inc. Operator-controlled settings of such parameters as the signal-integration time and other intervals of the time diagram were implemented using programmable timer/counters of the ACL-7120 board (ADLink Technology Inc.) which also features 32 input and 32 output TTL-compatible digital channels used in the experiment's control system. The time diagram of the detector was realized

Fig. 3. Dependences of the preamplifier output voltage on those delivered to the high-voltage electrodes of ionization-chamber modules in the measurements of triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction.

using four independently-programmed reversible 12-bit counters of the same board.

Recently, a new system for detecting and processing current waveforms was implemented [27]. This conceptually differs from the old one in that analog integration is forgone in favor of acquisition of the digitized variable component of the signal. This is carried out using the LTC1416 14-bit ADC whose operation is controlled by a digital signal processor (DSP). The latter is a specialized microprocessor for signal digitization in real time and operates in parallel with the processor of the master computer (a PC). The ADSP-2185 digital signal processor (Analog Devices Inc.) and the aforementioned ADC are mounted on the PC-embedded L780 board manufactured by L-Card, Moscow. During physical measurements, the ADC samples the analog signal with a maximum frequency of ~ 100 kHz.

The experiment's time diagram (see Fig. 4), the detector-control signals, and those synchronizing the DSP and master-computer operation are formed using a computer-embedded board of PCI-TMC12 timer/counters (ICP DAS). Its parameters and operation regimes are software-controlled. The data are exchanged between the DSP and the master computer through a direct-memory-access channel. Thereby, the master-processor software can address any cell of the DSP memory without interrupting the DSP operation. This creates favorable conditions for data acquisition in the real-time regime (the maximum data-exchange rate between the signal processor and the computer is ~ 10 Mb/s).

Since the signal is integrated in digital form, the data acquisition system allows for varying a desired parameter (in our case, the direction of neutron polar-

Fig. 4. Time diagram of the experiment. The plus and minus signs mark the flipper-off and flipper-on regimes, respectively.

ization) with frequencies over a broad range between 0.01 and 50 Hz. In the latest version of the system, switching frequencies up to 500 Hz were enabled and tested experimentally [28]. This became possible owing to a fast digital signal processor and a two-level two-processor architecture of the experiment's control system. Thereby, the restrictions imposed by the procedure of analog integration were lifted. Apart from that, compensating for synchronous external fluctuations became a redundant procedure (which however can be fully implemented if necessary).

MEASUREMENT PROCEDURE AND DATA PROCESSING

In order to measure the P -odd asymmetry with a 10^{-8} precision, one has to obtain sufficient event statistics and to suppress possible spurious effects. Acquisition of 10^{16} events within a reasonable time period requires a counting rate of $\sim 10^{10} \text{ s}^{-1}$ which can only be obtained with an intense neutron beam. Since such high counting rates render event-by-event measurements unrealistic, P -odd asymmetries are measured using the inclusive event-integration technique first proposed by Lobashov [29, 30]. To reach an experimental precision of $\sim 10^{-8}$, possible effects of equipment instabilities and neutron-flux fluctuations, noise pickups, and spurious effects must be strongly suppressed.

The reported measurements rely on different detectors but share the same procedure of data acquisition and processing. Neutron-flux fluctuations caused by variations of the reactor power are compensated by simultaneously measuring the signals arriving from two detectors. The underlying idea is that the two detector channels in which the same reaction is measured are equally affected by fluctuations but should show P -odd effects of opposite signs.

In the interaction of polarized neutrons with a nuclear target, the angular distribution of the detected secondary including the P -odd emission asymmetry is expressed as $W(\theta) \sim 1 + \alpha(\hat{\mathbf{g}}_n \cdot \hat{\mathbf{p}}_p)$ where θ is the emission angle with respect to the neutron-spin direction, and the asymmetry coefficient α can be experimentally extracted as

$$\alpha = \frac{N_+ - N_-}{N_+ + N_-},$$

where N_+ are N_- are the numbers of detector counts for parallel and antiparallel orientations of the secondary-particle momentum and neutron spin, respectively. Within the inclusive approach adopted in the reported measurements, the detector signal contains variable and constant components U and U_c , respectively. Therefore, in the above equation the number of events corresponding to a certain time interval should be substituted by the sum of these components integrated over the same time interval. As a result, for the asymmetry coefficient $\alpha_{P\text{-odd}}$ we obtain

$$\alpha_{P\text{-odd}} = \frac{((U_c^+ + U^+/K) - (U_c^- + U^-/K))}{((U_c^+ + U^+/K) + (U_c^- + U^-/K))}.$$

Here, U_c^+, U_c^-, U^+, U^- denote constant and variable components of the signal for different neutron-spin orientations with respect to the detected-secondary momentum, respectively, and (amplified) variable components are rescaled to original magnitudes by dividing them by the preamplifier amplification coefficient K . Since we have $U_c \gg U$ and $U_c^+ \cong U_c^- = U_c$, the normalized asymmetry coefficient acquires the following form:

$$\alpha_{P\text{-odd}} = \frac{(U^+ - U^-)}{2KU_c}.$$

For each detector channel, four consecutive integrator voltages U_1^+ , U_2^- , U_3^- , and U_4^+ (see Fig. 4) form a “single measurement” and are combined pairwise as $U^+ = U_1^+ + U_4^+$ and $U^- = U_2^- + U_3^-$ (where the plus and minus signs again correspond to different neutron-spin orientations). Thus combining individual voltages helps cancel out the linear drift of the system amplification. For each of thus defined single measurements, the asymmetry-coefficient value is individually extracted. A definite number (N) of consecutive single measurements carried out in both channels form a so-called measurement series. In earlier measurements,

constant components of both signals were sampled once per series. In subsequent measurements, they were sampled for each single-measurement time interval T and then averaged over the series prior to extracting the normalized asymmetry coefficient. The data are separately processed for each measurement series [26, 31].

For each measurement series, the two asymmetry-coefficient values corresponding to two detector channels are extracted using formulas (4) and (5) below where subscripts (1) and (2) refer to measurement channels 1 and 2, respectively:

$$\left. \begin{aligned} \bar{\alpha}^{(1),(2)} &= \frac{1}{N} \sum_{i=1}^N \alpha_i^{(1),(2)} \\ \alpha_i^{(1),(2)} &= (U_i^{+, (1),(2)} - U_i^{-, (1),(2)})/2 \\ U_i^{+, (1),(2)} &= U_{i,1}^{+, (1),(2)} + U_{i,4}^{+, (1),(2)}, \quad U_i^{-, (1),(2)} = U_{i,2}^{-, (1),(2)} + U_{i,3}^{-, (1),(2)}, \quad i = 1-N \\ D(\bar{\alpha}^{(1),(2)}) &= \frac{1}{N(N-1)} \sum_{i=1}^N (\alpha_i^{(1),(2)} - \bar{\alpha}^{(1),(2)})^2, \quad \sigma(\bar{\alpha}^{(1),(2)}) = \sqrt{D(\bar{\alpha}^{(1),(2)})} \end{aligned} \right\}, \quad (4)$$

$$\left. \begin{aligned} \bar{\delta}^{(1),(2)} &= \frac{\bar{\alpha}^{(1),(2)}}{K_{(1),(2)} U_{c,(1),(2)}} \\ \sigma(\bar{\delta}^{(1),(2)}) &= \frac{\sigma(\bar{\alpha}^{(1),(2)})}{K_{(1),(2)} U_{c,(1),(2)}} \end{aligned} \right\}. \quad (5)$$

For a given series, the values of the asymmetry coefficient and its uncertainty corrected by combining the data of both detector channels are obtained as follows:

$$\left. \begin{aligned} \bar{\alpha}_{\text{comp}} &= \frac{1}{N} \left(\sum_{i=1}^N \alpha_i^{(1)} - L \sum_{i=1}^N \alpha_i^{(2)} \right) \\ D(\bar{\alpha}_{\text{comp}}) &= \frac{1}{N(N-1)} \sum_{i=1}^N ((\alpha_i^{(1)} - L \alpha_i^{(2)}) - \bar{\alpha}_{\text{comp}})^2 \\ \sigma(\bar{\alpha}_{\text{comp}}) &= \sqrt{D(\bar{\alpha}_{\text{comp}})} \end{aligned} \right\}, \quad (6)$$

$$\left. \begin{aligned} \bar{\delta}_{\text{comp}} &= \frac{\bar{\alpha}_{\text{comp}}}{K (U_{C,(1)} + U_{C,(2)})} \\ \sigma(\bar{\delta}_{\text{comp}}) &= \frac{\sigma(\bar{\alpha}_{\text{comp}})}{K (U_{C,(1)} + U_{C,(2)})} \\ K &= \frac{K_{(1)} + L K_{(2)}}{2} \end{aligned} \right\}. \quad (7)$$

In Eqs. (4)–(7) above, $\bar{\alpha}^{(1),(2)}$, $\bar{\delta}^{(1),(2)}$ are the absolute (i.e., unnormalized) and relative (normalized) effects in channels 1 and 2, respectively; $U_{i,1}^{+, (1)}$, $U_{i,2}^{-, (1)}$, $U_{i,3}^{-, (1)}$, $U_{i,4}^{+, (1)}$ are the mean output voltages of the first-channel preamplifier; $U_{i,1}^{+, (2)}$, $U_{i,2}^{-, (2)}$, $U_{i,3}^{-, (2)}$, $U_{i,4}^{+, (2)}$ are those of the second-channel preamplifier; $\bar{\alpha}_{\text{comp}}$ and $\bar{\delta}_{\text{comp}}$ are the absolute and relative effects corrected by compensating for

reactor-power fluctuations with compensation factor L , and $\sigma(\bar{\alpha}_{\text{comp}})$ and $\sigma(\bar{\delta}_{\text{comp}})$ are their estimated uncertainties, respectively; $K_{(1)}$ and $K_{(2)}$ are amplification coefficients of channels 1 and 2, respectively, determined from calibration; and $U_{c,(1)}$ and $U_{c,(2)}$ are constant signal components for the first- and second-channel preamplifiers, respectively.

Reactor-power fluctuations synchronously affecting the opposite-sign signals $\alpha_i^{(1)}$ and $\alpha_i^{(2)}$ extracted from single-measurement data of the two integrators are compensated for by taking their difference and then summing these over the measurement series (see Eq. (6)). Thereby, the effect is doubled while reactor-power fluctuation cancels out. For each single-measurement series, the compensation factor L is obtained by minimizing the dispersion of the absolute-effect value $\bar{\alpha}_{\text{comp}}$, $D(\bar{\alpha}_{\text{comp}})$ (6), and is expressed as

$$L = \frac{\sum_{i=1-N}^N \alpha_i^{(1)} \alpha_i^{(2)} - \frac{1}{N} \sum_{i=1-N}^N \alpha_i^{(1)} \sum_{i=1-N}^N \alpha_i^{(2)}}{\sum_{i=1-N}^N (\alpha_i^{(2)})^2 - \frac{1}{N} \left(\sum_{i=1-N}^N \alpha_i^{(2)} \right)^2}.$$

The final values of the asymmetry coefficient and its uncertainty are determined by taking a weighted average of the $\alpha_i \pm \sigma_i$ values obtained in large number (n) of measurement series:

$$\bar{A} = \frac{\sum_{i=1}^n p_i \alpha_i}{\sum_{i=1}^n p_i}, \quad p_i = \frac{1}{\sigma_i^2}, \quad \sigma(\bar{A}) = \frac{1}{\sqrt{\sum_{i=1}^n p_i}}.$$

Spurious asymmetries were eliminated by periodically reversing the direction of the guiding magnetic field and collecting equal numbers of measurement series for the two magnetic field directions. That reversing the field direction flips the sign of the observed P -odd effect was considered when averaging the $\alpha_i \pm \sigma_i$ measurements for individual series.

Processing of the data on P -odd asymmetries is seen to involve calculating the following differences:

(1) That between the signal variable components for opposite neutron-beam polarizations, $\alpha = U^+ - U^-$ (the absolute P -odd asymmetry effect). These differences are calculated for each pair of measurements carried out with each detector channel.

(2) That between the absolute effects obtained with two detector channels: $\alpha_i = \alpha_i^{(1)} - L \cdot \alpha_i^{(2)}$, $i = 1-N$. Thereby, the P -odd effect is doubled since those measured with two detector channels have opposite signs. These differences are calculated for each of the two directions of the guiding magnetic field (further denoted as “ $\rightarrow$ ” and “ $\leftarrow$ ”).

(3) That between the effects corresponding to opposite magnetic field directions: $\alpha_i(\rightarrow) - \alpha_i(\leftarrow)$, $i = 1-N$. Thereby, the two P -odd effects are added up rather than subtracted since they have opposite signs.

At each stage of this subtraction procedure, same-sign spurious effects are cancelled out whereas the investigated opposite-sign P -odd effect is doubled. Spurious effects completely cancel out as soon as their absolute values remain unchanged.

P -ODD ASYMMETRY OF TRITON EMISSION IN THE ${}^6\text{Li}(n, \alpha){}^3\text{H}$ REACTION

The P -odd asymmetry coefficient for triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction induced by polarized neutrons, $\alpha_{P\text{-odd}}^{{}^6\text{Li}}$, was derived in [22] as

$$\alpha_{P\text{-odd}}^{{}^6\text{Li}, \text{theor}} \approx (-0.45f_\pi + 0.06h_p^0)$$

in terms of the weak-interaction coupling constants h_p^0 and f_π corresponding to the ρ - and π -meson exchanges, respectively. Their “best values” in the DDH scheme are $h_p^0 = -11.4 \times 10^{-7}$ and $f_\pi = 4.6 \times 10^{-7}$.

Experimentally, this asymmetry coefficient was measured at PNPI [32] and ILL [15]. In the PNPI experiment, incident neutrons were polarized using a focusing polarizer with a cross section of $100 \times 50 \text{ mm}^2$, and in the followup ILL experiment, a supermirror polarizer with a cross section of $80 \times 80 \text{ mm}^2$. At both venues, the data were collected with a gas-filled ionization chamber (see above).

In the ILL measurements, the degree of polarization of neutrons passing through the setup was measured as $P = 0.88$ and 0.94 for the first and second experimental runs, respectively. The neutron-beam transverse profile within the chamber were controlled with three ${}^6\text{LiF}$ collimators, and the beam spot was fully contained in the areas of upstream and downstream targets. The neutron-beam vertical deviation from the detector axis was within 5 mm/m . The ionization chamber was mounted on concrete blocks so that its horizontal deviation from axis passing through the chamber’s center was within 5 mm/m . The total polarized neutron flux amounted to $N \sim (4-5) \times 10^{10} \text{ s}^{-1}$. The sign of neutron polarization was reversed with an adiabatic spin flipper.

The 4.78-MeV energy release of the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction is distributed between the secondaries as $E_\alpha = 2.05 \text{ MeV}$ and $E_t = 2.73 \text{ MeV}$. Since the specific energy loss to ionization is much larger for α particles than for tritons, the triton range is five times larger than that of the α particle. This allows one to select a pure triton component with no α admixture.

Since the triton angular distribution has the form $W(\theta) \sim 1 + \alpha(\hat{\mathbf{g}}_n \cdot \hat{\mathbf{p}}_t)$ where θ is the angle between the neutron spin vector and triton 3-momentum, emitted tritons should be selected within a certain solid angle when measuring the P -odd asymmetry. This task is performed by an “insensitive gap” of aluminum foil on the target surface in which α particles are absorbed fully, and tritons only at certain emission angles. Each target has the form of a ${}^6\text{LiF}$ layer with thickness of $(400-500) \mu\text{g/cm}^2$ deposited on a $14\text{-}\mu\text{m}$ -thick aluminum backing which also serves as an insensitive gap. The second insensitive gap is formed by $14\text{-}\mu\text{m}$ -thick aluminum foil glued to target’s opposite face. In the ionization chamber instrumented with such targets, nearly 60% of the incident neutron flux is absorbed. For the mean cosine of the triton emission angle from the target, the simulation yielded $\overline{\cos(\hat{\mathbf{g}}_n \cdot \hat{\mathbf{p}}_t)} = 0.75$. In one ionization chamber, two targets were installed together thus forming a $28\text{-}\mu\text{m}$ -thick backing which was fully opaque for both tritons and α particles. Thereby, the total current was reduced by a factor of ~ 2 .

In the discussed reaction, the left–right asymmetry prior to kinematic selections reaches $\alpha_{lr} \approx 1.0 \times 10^{-4}$ [25]. By rendering the magnetic field guiding the neutron spin parallel to the beam axis with an uncertainty below 0.01 rad , the “left–right” contribution to the P -odd effect was reduced to $\sim 2.5 \pm 10^{-9}$. Charged secondaries were detected by ionization of argon gas under an excess pressure of 1.4 and 0.9 atm in the PNPI and ILL experiments, respectively. Given such gas pressure, the range of tritons emitted from the target was within the 21-mm -thick sensitive gas gap between the target surface and the charge-collecting

grid. Different gas pressures were selected for the two experiments so as to carry out measurements under slightly different experimental conditions.

In either experiment, secondary tritons were inclusively detected by integrating current signals of the two detector channels. The current was sampled once per second ($T = 1$ s is the basic interval of the time diagram shown in Fig. 4) with an integration time of 0.8 s, the spin flipper was switched on and off every two seconds, and 64 consecutive single measurements were combined in a series with a 256-s duration. The compensated value of the *P*-odd effect (see Eqs. (7)) had a 40–100 times smaller dispersion than the uncompensated values obtained for each detector channels. Any spurious asymmetries were eliminated by periodically reversing the magnetic field direction in the ionization chamber and collecting equal amounts of measurement series for the two field orientations. At ILL, the magnetic field direction was automatically reversed every 30 min and ~4 min (i.e., once per series) during the first [33] and second [14] experimental runs, respectively. The data-processing procedure detailed above relies on independent measurements carried out with two detectors. Thereby, one is able to reject all conceivable spurious effects arising from possible dependences of the ionization-chamber current and the neutron-absorption cross section on the direction of the guiding field, electromagnetic pickups, etc.

Spurious *P*-odd effects induced by electromagnetic pickups were experimentally investigated for different reactions in [14, 32, 33]. In particular, the measured asymmetry of triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction was found to be affected by pickups induced by switching the flipper and turning on the flipper RF field. Upon applying the data-processing procedure as detailed above and normalizing the pickup to the sum of constant and gain-corrected variable components of the signal for ${}^6\text{Li}(n, \alpha){}^3\text{H}$, the electromagnetic-pickup contribution to the measured *P*-odd asymmetry was estimated as $-(0.4 \pm 1.5) \times 10^{-9}$ [34]. This is significantly below the experimental uncertainty on the *P*-odd asymmetry estimated as $\sigma \sim 10^{-8}$. Thus, the pickup effect is practically suppressed as soon as the independent measurements carried out with two detector channels and two magnetic field directions are processed in combination.

The measurements are also affected by the uncompensated magnetic field of the Earth and by stationary fields created by other running detectors. These fields induce a left–right asymmetry whose sign is not changed by reversing the direction of the magnetic field guiding the neutron spin [32]. Its contribution to the measured *P*-odd asymmetry cancels out as soon as equal numbers of measurement series for opposite magnetic field directions are logged and the subtraction procedure is applied.

The left–right contribution to the measured *P*-odd asymmetry was experimentally probed at ILL by varying the direction of the magnetic field guiding the neutron spin. In some measurements, the magnetic field was oriented normally to both the Earth's surface and the neutron-beam axis whereby the contribution of the left–right asymmetry induced by a possible horizontal misalignment of the chamber was probed. In other measurements, the field direction was normal to that of the beam and parallel to the Earth's surface so as to probe the effects due to a possible vertical misalignment of the chamber. The results of these experiments [14, 15] demonstrated that if the magnetic field is parallel to the neutron-beam axis, the left–right contribution to the measured *P*-odd asymmetry does not exceed 1×10^{-8} which is below the statistical uncertainty of the measurement.

The measured *P*-odd asymmetry may be affected by spurious asymmetries induced by charged-particle emission from reactions resulting from neutron collisions with detector's construction materials and by γ and electron emission from β -decays of radioactive nuclei. Since the sought-after *P*-odd effect is extremely small, possible contributions of such spurious asymmetries merit a dedicated measurement. This task is performed by conducting a “null experiment” with a polarized neutron beam in which no secondaries of the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction were detected. For this, the targets are additionally shielded on both sides with 20- μm -thick aluminum foil, which completely absorbs all emitted tritons and α particles. In the null experiment conducted at PNPI, the spurious-asymmetry coefficient normalized to the signal's constant components and corrected for the solid-angle acceptance and neutron polarization was measured as $\alpha_{0\text{-test}} = (2.0 \pm 1.7) \times 10^{-8}$ [32].

An additional null experiment was conducted at ILL using the PF1B polarized neutron beam. Neutron polarization was flipped using the same RF spin flipper as in physical measurements for the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction. The physical and null-test measurements were equally affected by pickups, and in both cases, the neutron polarization exceeded 94%. Since the admixture-induced signal detected in the null experiment was ~100 times smaller than in physical measurements, the ionization chamber could not be aligned using the signal's constant components. The correct alignment of the chamber with the beam axis was checked after the measurements by the beam footprint on the beam stop of ${}^6\text{Li}$ -containing rubber installed downstream of the ionization chamber. The results of null-test and physical measurements were compared upon correcting the former for the chamber misalignment, which affected the incident neutron flux. In the ILL null experiment, the following value of the spurious *P*-odd asymmetry induced by neutron interactions with impurity nuclei was obtained upon

Table 1. Measurements of the P -odd asymmetry of triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction

	$P\Omega$	$\alpha_{P\text{-odd}}$	$\alpha_{0\text{-test}}$	α_{noise}	Reference
PNPI, vertical beam	0.66	$-(5.4 \pm 6.0) \times 10^{-8}$	$(2.0 \pm 1.7) \times 10^{-8}$		[32, 33]
ILL run 1, PB1B beam	0.66	$-(8.1 \pm 3.9) \times 10^{-8}$		$(0.6 \pm 0.4) \times 10^{-8}$	[33]
ILL run 2, PF1B beam	0.70	$-(9.3 \pm 2.5) \times 10^{-8}$	$(0.0 \pm 0.5) \times 10^{-8}$	$-(0.6 \pm 0.5) \times 10^{-8}$	[14, 34]
Mean value		$-(8.6 \pm 2.0) \times 10^{-8}$	$(0.2 \pm 0.5) \times 10^{-8}$	$(0.1 \pm 0.3) \times 10^{-8}$	[15]

normalization to the signal's constant components in physical measurements: $\alpha_{0\text{-test}} = (0.0 \pm 0.5) \times 10^{-8}$ [34]. Apart from that, these measurements helped probe the pickups from the electronic equipment and spin-flipper operation. The pickup effect on the P -odd asymmetry was estimated by carrying out measurements with the neutron beam switched off. In the second run of the ILL experiment, the pickup-induced asymmetry obtained by normalizing the effect to constant components of the signal detected in physical measurements was measured as $\alpha_{\text{noise}} = -(0.6 \pm 0.5) \times 10^{-8}$ [14], which is at least ten times less than actually measured P -odd asymmetry.

A comparison between the results of physical and null-test measurements convincingly demonstrates that the P -odd asymmetry detected in physical measurements indeed arises from the investigated ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction. The results of different measurements of the P -odd asymmetry of triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction carried out by the authors at PNPI and ILL are quoted in Table 1. These have been corrected for the neutron polarization P and for the mean cosine of the triton emission angle over the selected solid-angle range, $\Omega = \overline{\cos(\hat{\mathbf{g}}_n \cdot \hat{\mathbf{p}}_t)}$.

Thus, we have carried three independent measurements of the P -odd asymmetry coefficient of triton emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction induced by polarized cold neutrons. Also folding in the additional spurious-asymmetry measurements in dedicated null experiments at PNPI and ILL, for the experimental value of this factor averaged over the complete series of measurements we finally obtain [15]

$$\alpha_{P\text{-odd}}^{\text{Li,exp}} = -(8.8 \pm 2.1) \times 10^{-8}.$$

As indicated above, in the single available theoretical derivation of the P -odd asymmetry coefficient for the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction, the latter was expressed through the weak-interaction coupling constants as [22]

$$\alpha_{P\text{-odd}}^{\text{Li,theor}} \approx (-0.45f_\pi + 0.06h_p^0).$$

Substituting the measured value of the asymmetry coefficient and $h_p^0 = -11.4 \times 10^{-7}$ for the charged-current coupling constant (its “best value” in the DDH scheme) in the above expression, for the neutral current coupling constant we obtain

$$f_\pi \approx (0.4 \pm 0.4) \times 10^{-7}$$

or, taking the positivity condition into consideration,

$$0 \leq f_\pi \leq 1.1 \times 10^{-7}$$

at the 90% confidence level. This constraint is consistent with the f_π value extracted from the measurements of γ -quanta circular polarization in the reaction with the ${}^{18}\text{F}$ nucleus [35],

$$f_\pi = (0.3_{-0.3}^{+1.0}) \times 10^{-7},$$

but is incompatible with the DDH “best value” of $f_\pi = 4.6 \times 10^{-7}$.

P -ODD ASYMMETRY OF γ EMISSION IN THE ${}^{10}\text{B}(n, \alpha){}^7\text{Li}^* \rightarrow \gamma \rightarrow {}^7\text{Li}(\text{gr.st.})$ REACTION

Theoretical predictions based on the cluster formalism for few-nucleon systems also refer to the P -odd asymmetry of γ emission from the first excited state of the ${}^7\text{Li}$ nucleus (${}^7\text{Li}^* \rightarrow {}^7\text{Li} + \gamma(\text{M1})$, $E_\gamma = 0.478$ MeV) which is populated through the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}^*$ reaction induced by polarized cold neutrons [36, 23] (see Fig. 5). In [23], the P -odd asymmetry coefficient of γ emission in this sequential reaction was expressed through the meson-exchange coupling constants as

$$\alpha_{P\text{-odd}}^{10\text{B},\gamma} = 0.16f_\pi - 0.028h_p^0 - 0.009h_p^1 - 0.014h_\omega^0 - 0.014h_\omega^1.$$

Here, f_π again denotes the π -exchange coupling constant of the weak neutral current. Substituting the DDH best values $h_p^0 = -11.4 \times 10^{-7}$ and $h_\pi = 4.6 \times 10^{-7}$ [6] for corresponding meson-exchange coupling constants, for the P -odd asymmetry coefficient we obtain the

value $^{DDH} \alpha_{P\text{-odd}}^{^{10}\text{B},\gamma,\text{theory}} = 1.1 \times 10^{-7}$ which is sufficiently large to be measurable. On the other hand, substituting a zero rather than a best value for the neutral current coupling constant yields a lower prediction of $\alpha_{P\text{-odd}}^{^{10}\text{B},\gamma,\text{theory}} = 0.3 \times 10^{-7}$.

The P -odd asymmetry of γ emission in the discussed sequential reaction was measured at ILL using the PF1B beam of polarized cold neutrons. At the target position, the neutron beam had a cross section of $80 \times 80 \text{ mm}^2$ determined by the polarimeter. Neutrons impinged on the target with a total intensity of $\sim 3 \times 10^{10} \text{ s}^{-1}$, and their polarization degree was measured as $P = 0.92 \pm 0.02$. The data on the P -odd asymmetry of γ emission in the $^{10}\text{B}(n, \alpha)^7\text{Li}^* \rightarrow \gamma \rightarrow ^7\text{Li}(\text{gr.st.})$ reaction were collected during three experimental runs in 2001–2002, 2007, and 2009.

The measurements were carried out in the $\sigma_n \parallel \mathbf{p}_\gamma \perp \mathbf{p}_n$ geometry where σ_n is the neutron spin vector and $\mathbf{p}_\gamma$ and $\mathbf{p}_n$ are the γ and neutron 3-momenta, respectively. The P -odd effect should reveal itself in the form of a forward–backward asymmetry of the γ angular distribution

$$\frac{dN_\gamma}{d\Omega} \sim 1 + \alpha_{P\text{-odd}}^\gamma \cos(\theta),$$

where θ denotes the angle between the neutron-spin vector and 3-momentum of the γ quantum. The γ 3-momentum was required to be collinear with the magnetic field direction within 10^{-2} rad. These two vectors need not be aligned more precisely since γ emission is free of the left–right asymmetry [37] which might contribute to the observed P -odd effect.

The magnetic field guiding the neutron spin was generated by Helmholtz coils which also helped periodically flip its direction during the measurements. The magnetic field strength was a few Oersteds, and the experimental setup was kept free of any magnetic materials. Neutron polarization was switched with a RF (frequency $\sim 20 \text{ kHz}$) spin flipper positioned at a distance of $\sim 1 \text{ m}$ from the detectors.

The target consisted of 50 g of amorphous boron enriched to 85% of the ^{10}B isotope. This was pressed into an aluminum container with dimensions of $160 \times 180 \times 5 \text{ mm}^3$, and its upstream face was shielded with 14- μm -thick aluminum foil. The target was positioned at the beam axis, between two γ -detectors, and inclined by 45° with respect to the beam axis (see Fig. 6). The distance between the target and γ -detectors' centers was 75 mm. Incident neutrons were fully absorbed in the target and converted to α particles and γ quanta.

Each γ -detector was based on a NaI(Tl) crystal with a 200-mm diameter and 100-mm thickness. Scintillation photons were detected with Hamamatsu-produced S3204-03 photodiodes with sensitive areas

Fig. 5. Scheme of ^7Li production through cold- or thermal-neutron capture by the ^{10}B nucleus.

of $18 \times 18 \text{ mm}^2$ optically connected with the crystals through plexiglass light guides. The two γ -detectors enclosed in duralumin boxes were symmetrically positioned with respect to the beam axis on both sides of the target [31].

The experimental setup as a whole was shielded with 150-mm-thick lead (see Fig. 6). Interior surfaces of the shielding were coated with boron rubber or borated polyethylene whereby the setup was shielded against scattered neutrons. Boron rather than lithium was employed for this purpose since in the latter case, scattered neutrons would produce the ^8Li isotope on the 10% ^7Li admixture in ^6Li . The ^8Li isotope suffers a β -decay with electron energy $\sim 12\text{--}14 \text{ MeV}$, which shows a P -odd asymmetry of $\alpha_{P\text{-odd}} \sim 3\%$ and, therefore, may mimic the investigated P -odd effect [38]. The results of preliminary background measurements and subsequent null experiments indicate that in physical measurements with boron shielding, scattered neutrons contribute less than 5% of the total neutron intensity on the target. Neutron scattering by boron is almost incoherent, so that scattered neutron capture by construction materials would not give rise to any spurious P -odd asymmetry of γ emission.

In the first experimental run [31, 39], the control of detector operation and data acquisition relied on integrators. The signal-integration time was 0.8 s, and 64 single measurements formed a measurement series. The compensated value of the P -odd asymmetry coefficient (see Eq. (7)) had a 40-times-smaller dispersion than those obtained with each of the two detector channels. During the first half of this run, the magnetic field guiding the neutron spin was flipped one or two times per day. Thereafter, the magnetic field direction was automatically reversed at the start of each measurement series, or every 4.5 min, using a dedicated software-controlled module. This rendered

Fig. 6. Schematic layout of the detector for measuring γ emission in the $^{10}\text{B}(n, \alpha)^7\text{Li}^* \rightarrow \gamma \rightarrow ^7\text{Li}(\text{gr.st.})$ reaction, showing the beam polarizer (1), the adiabatic spin flipper (2), the borated-rubber neutron guide filled with flowing ^4He gas (3), concrete wall (4), the lead shield (5), the borated-rubber internal coating of the lead shield (6), the Helmholtz coils (7), the γ -detectors (8), the boron target (9), and the lithium absorber (10). $\mathbf{p}_n$ and $\boldsymbol{\sigma}_n$ are the neutron 3-momentum and spin vector, respectively. Solid and shaded arrows depict the neutron-spin directions for the flipper-off and flipper-on regimes.

the measurements more reliable. On the whole, the measurements carried out during the first run yielded $\alpha_{\text{P-odd}}^{^{10}\text{B}, \gamma} = (2.7 \pm 3.8) \times 10^{-8}$ for the coefficient of the P -odd asymmetry of γ emission. In the null test with aluminum foil deployed in the beam instead of the boron target, the spurious-asymmetry coefficient was measured as $-(0.9 \pm 4.8) \times 10^{-8}$. The quoted values of the P -odd asymmetry coefficient have been corrected for the neutron-polarization degree and for the mean cosine of γ -emission angle with respect to $\boldsymbol{\sigma}_n$ over the γ solid-angle acceptance.

Unlike the lithium target (see above), the boron target has to be moved off the beam when carrying a null test that refers to the $^{10}\text{B}(n, \alpha)^7\text{Li}^* \rightarrow \gamma \rightarrow ^7\text{Li}(\text{gr.st.})$ reaction. This is because γ -quanta emitted in the latter and “background” reactions cannot be discriminated as soon as current-integration techniques are employed. Therefore, null experiments of two types are possible. The first option is to run with no target at all or to leave in the beam only its upstream protective layer of 14- μm -thick aluminum foil (see above). In this case, the neutron beam irradiates the construction materials downstream of the target rather than being fully absorbed by the boron target as in physical measure-

ments. Thereby, one probes the (possible) P -odd asymmetry of γ quanta emitted in reactions on the construction materials. The second option is to run with a target in which incident neutrons are scattered but radiative (n, γ) reactions are suppressed. In this case, null-test measurements are carried out in the same geometry as physical ones provided that incident neutrons are fully scattered by the target since these again impinge on construction materials inducing γ -quanta emission. An ideal material for such neutron-scattering target is offered by graphite in which the cross sections of neutron radiative capture and neutron scattering are $\sigma_{n\gamma} = 3.8 \times 10^{-3}b$ and $\sigma_s = 4.8b$, respectively. If scattered neutrons indeed induce radiative processes with nonzero P -odd γ -emission asymmetries in construction materials, these asymmetries should be significantly enhanced when running with the null-test target since in this case the scattered-neutron flux is larger than that for the boron target. In such null test with a graphite target [16], the P -odd asymmetry of γ emission was measured as $\alpha_{\text{test}}^{\text{graphite}} = (1.7 \pm 1.9) \times 10^{-6}$ whereby the scattered-neutron contribution to the P -odd effect observed with the boron target was estimated as $\alpha_{\text{scat.}^{10}\text{B}}^{\text{calc}} = (2.7 \pm 3.0) \times 10^{-9}$. This contribution is too small for appreciably affecting the results of our measure-

ments of the *P*-odd asymmetry of γ emission from the boron target.

Note that $\sim 0.002\%$ of all incident neutrons suffer scattering in air in the vicinity of the boron target and γ detectors. Neutron scattering on air equally affects the physical and null-test measurements carried out during the first and second experimental runs. Therefore, the results of physical measurements are automatically corrected for this effect by considering the null-test measurements carried out with an aluminum foil.

By periodically reversing the magnetic field direction, all conceivable apparatus effects are automatically corrected for as demonstrated by a number of measurements [26, 31, 39]. Additional measurements in which the beam was switched off but all equipment was fully activated yielded $(1.1 \pm 0.7) \times 10^{-8}$ for the normalized value of apparatus-induced spurious *P*-odd asymmetry, which implies that apparatus effects either are absent or cancel out at a 10^{-8} level. Electronic equipment of the detector was periodically tested for parasitic signals induced by other equipment housed by the experimental hall. In such tests carried out upon switching off the neutron beam, the normalized factor of the corresponding spurious asymmetry was measured as $\alpha_{\text{noise}} = -(5.1 \pm 7.1) \times 10^{-9}$ which is significantly below the experimental uncertainty of physical measurements. The contributions of all other sources of systematic uncertainties are estimated in [40]. The net systematic uncertainty on the measured *P*-odd asymmetry of γ emission is estimated as 1.1×10^{-8} .

Light collection in γ -detectors is incomplete since the photodiode's sensitive area is significantly smaller than that of the scintillation crystal. For this reason, the γ signal should be significantly amplified prior to processing. In the high-gain regime, signal preamplifiers suffer mechanical vibrations, which give rise to "microphone effects" (different for the two channels). These cannot be compensated by taking the difference of preamplifier voltages (see above). According to the conclusions reached in [41], only those signal harmonics that lie above the frequency of flipping the neutron spin contribute to the systematic asymmetry on the measured *P*-odd effect. Since the spectral density of the ILL reactor's power steeply decreases with increasing frequency [40], the uncertainty can be reduced by flipping the neutron-beam polarization and detecting *P*-odd effects at higher frequencies. By switching the neutron-spin direction with a higher frequency, one "cuts off" the uncorrelated low-frequency components of preamplifier output voltages thus effectively reducing the uncertainty on the measured *P*-odd effect.

To suppress the "microphone effect" thus reducing the systematic uncertainty, a new current-signal detection system was developed, which is based on digital integration and operates over a broad range of the neutron-spin-flip frequency, and retains the con-

ditions for compensating the reactor-power fluctuations (see above). This new control system was implemented in the $^{10}\text{B}(n, \alpha)^7\text{Li}^* \rightarrow \gamma \rightarrow ^7\text{Li}(\text{gr.st.})$ measurements carried out during the second experimental run. These measurements followed a time diagram with the basic and signal-integration time intervals of $T = 0.1$ s and $T_{\text{int}} = 0.9$ s, respectively. The spin flipper was switched on every 0.2 s, e.g., the neutron spin was flipped with a 5-Hz frequency, which was higher than that of the microphone effect. Acquisition of one measurement series took nearly four minutes. At the start of each measurement series, the direction of the magnetic field guiding the neutron spin was reversed at the target position using Helmholtz coils, and equal amounts of measurement series were collected for the two opposite field directions as in the measurements reported in [15]. Upon reversing the magnetic field direction thus changing the sign of the true *P*-odd asymmetry, all other experimental conditions remained the same. In the difference between series-averaged measurements, the true effect was doubled whereas any apparatus-induced spurious asymmetries canceled out. Since the neutron-spin flip frequency proved to be insufficient for fully canceling out the fluctuations of reactor power, the latter were additionally compensated for when processing the data (see above) which further reduced the systematic uncertainty.

Physical measurements with the ^{10}B target were carried out over a time period of ~ 20 days. The *P*-odd asymmetry coefficient was extracted from the data as $\alpha_{P\text{-odd}}^{^{10}\text{B}, \gamma} = (3.1 \pm 3.8) \times 10^{-8}$ upon correcting for the neutron-polarization degree P and for the mean cosine of the γ emission angle Θ with respect to σ_n over the γ -detector acceptance in solid angle: $P \cos(\bar{\Theta}) = 0.77$. In the null test with irradiated aluminum foil, the normalized spurious-asymmetry coefficient was measured as $\alpha_{0\text{-test}}^{^{10}\text{B}, \gamma} = (4.2 \pm 7.3) \times 10^{-8}$.

An analysis of the data and measurement errors carried out in [40] indicated that all measurements performed during the first and second experimental runs were affected by hard γ -quanta ($E_\gamma = 5\text{--}7$ MeV) typically emitted in (n, γ) reactions induced by neutrons in construction materials and in the air contained in the beam volume near the γ -detectors. The intensities of such γ quanta in physical and null-test measurements were found to be nearly the same. Since we rely on current-integration techniques and the current-form signal is proportional to NE_γ where N is number of detected γ quanta and E_γ is their energy, even a small number of detected hard γ quanta with energies significantly exceeding those of signal ones ($E_\gamma = 0.478$ MeV) can noticeably increase the systematic uncertainty.

To reduce the hard- γ contribution to the signal, a new scheme of the beam transport to the target was

Table 2. ILL measurements of the P -odd asymmetry of γ emission in the $^{10}\text{B}(n, \alpha)^7\text{Li}^* \rightarrow \gamma \rightarrow ^7\text{Li}(\text{gr.st.})$ reaction and of the parasitic background-induced asymmetry

	$\alpha_{P\text{-odd}}^{10\text{B}, \gamma, \text{raw}}$	$\alpha_{0\text{-test}}^{10\text{B}, \gamma}$	$\alpha_{P\text{-odd}}^{10\text{B}, \gamma, \text{exp}}$	
ILL, 2001–2002	$(2.7 \pm 3.8) \times 10^{-8}$	$-(0.9 \pm 4.8) \times 10^{-8}$	$(3.6 \pm 6.1) \times 10^{-8}$	[31, 39]
ILL, 2007	$(3.1 \pm 3.8) \times 10^{-8}$	$(4.2 \pm 7.3) \times 10^{-8}$	$-(1.1 \pm 8.2) \times 10^{-8}$	[16]
ILL, 2009	$-(2.0 \pm 2.5) \times 10^{-8}$	$-(1.3 \pm 1.6) \times 10^{-8}$	$-(0.7 \pm 3.0) \times 10^{-8}$	[40]
Mean value			$(0.0 \pm 2.6) \times 10^{-8}$	

implemented during the third (last) experimental run. In this scheme, the beam was delivered to the target through a 2-m-long neutron guide made of borated rubber and filled with flowing ^4He (see Fig. 6). Replacing air with helium decreased scattering of neutrons in the beam; the scattered neutrons were intercepted in the borated rubber. Helium consumption was ~ 100 L/day. The boron target of separated ^{10}B isotope was deployed inside the neutron guide between the two γ -detectors. Characteristic intervals of the time diagram and the frequency of flipping the neutron polarization were the same as in the second experimental run. Using this beam-delivery scheme, the uncertainties of either the physical measurements with a boron target and the null-test measurements with a thin aluminum foil in the beam were investigated. Installing the helium-filled neutron guide was found to effectively reduce the relative uncertainty of physical measurement by a factor of 1.2. The 31-day-long physical measurements carried out within the third experimental

run yielded $\alpha_{P\text{-odd}}^{10\text{B}, \gamma} = -(2.0 \pm 2.5) \times 10^{-8}$ for the P -odd asymmetry of γ emission. The precision of the null test with aluminum foil emitting low-intensity γ quanta also benefited from implementing the new beam-delivery system: thereby, the relative uncertainty of day-long measurements was effectively reduced from 1.5×10^{-7} to 0.5×10^{-7} , or by a factor of three compared to previous null-test measurements with no helium-filled neutron guide. The parasitic contribution to the P -odd asymmetry of γ emission was extracted from the null-test data as $\alpha_{0\text{-test}}^{10\text{B}, \gamma} = -(1.3 \pm 1.6) \times 10^{-8}$ upon normalization to the constant components of the signals detected in physical measurements and correcting for the neutron polarization and for the mean cosine of the γ angle with respect to σ_n over the γ -detector acceptance in solid angle.

The values of the P -odd asymmetry of γ emission in the $^{10}\text{B}(n, \alpha)^7\text{Li}^* \rightarrow \gamma \rightarrow ^7\text{Li}(\text{gr.st.})$ reaction and of the parasitic background-induced asymmetry extracted from the data of physical and null-test measurements are shown in Table 2 for each of the three experimental runs conducted at ILL. (Note that all

data have been considered without rejecting those that lie beyond the 3σ corridor.)

Upon averaging over the three experimental runs, for the coefficient of P -odd asymmetry of γ emission one finally obtains [40]

$$\alpha_{P\text{-odd}}^{10\text{B}, \gamma, \text{exp}} = (0.0 \pm 2.5_{\text{stat}} \pm 1.1_{\text{syst}}) \times 10^{-8}.$$

Relying on the cluster-model prediction for this asymmetry coefficient and substituting the weak-charged-current coupling constants as $h_p^0 = -11.4 \times 10^{-7}$, one can estimate the value of the weak-neutral current coupling constant by constraining the predicted value of P -odd asymmetry to the measurement quoted above (compare with [15]). In the cluster-model formalism, the discussed P -odd asymmetry is expressed as [23]

$$\alpha_{P\text{-odd}} = 0.16f_\pi - 0.028h_p^0 - 0.009h_p^1 - 0.014h_w^0 - 0.014h_w^1,$$

where we substitute “DDH-best” values of all other coupling constants: $h_p^1 = -0.2 \times 10^{-7}$, $h_w^0 = -1.9 \times 10^{-7}$, and $h_w^1 = -1.1 \times 10^{-7}$. Thereby, we obtain

$$f_\pi^{10\text{B}} \approx -(2.0 \pm 1.6) \times 10^{-7},$$

which translates to a 90% upper limit of $f_\pi^{10\text{B}} \leq 0.6 \times 10^{-7}$ upon invoking the positivity condition. Thus, the value of the weak neutral current coupling constant extracted from the data on reaction (2) proves to be less than its “best value” in the DDH scheme.

On the whole, we find that the estimates of the weak neutral current coupling constant extracted from our data on triton emission in the $^6\text{Li}(n, \alpha)^3\text{H}$ reaction and on γ emission in the $^{10}\text{B}(n, \alpha)^7\text{Li}^* \rightarrow \gamma \rightarrow ^7\text{Li}(\text{gr.st.})$ reaction are consistent with each other but lie below its best DDH value of $f_\pi = 4.6 \times 10^{-7}$.

P-ODD ASYMMETRY OF α -PARTICLE EMISSION IN THE $^{10}\text{B}(n, \alpha)^7\text{Li}$ REACTION

The total energy released in this reaction is 2.79 MeV. If the transition occurs to the ^7Li ground state, this is distributed between the secondaries as $E_{\alpha_0} = 1.78$ MeV and $E_{\text{Li}_0} = 1.01$ MeV. Once the transition occurs to the ^7Li excited state, the energy budget has the form $E_{\alpha_1} = 1.47$ MeV, $E_{\text{Li}_1^*} = 0.84$ MeV, and $E_\gamma = 0.478$ MeV where the latter is the excitation energy. Theoretically, the *P*-odd asymmetry of α emission in the $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction has not yet been expressed through meson coupling constants since the ^{10}B nucleus has a relatively complex structure. This renders experimental studies of the *P*-odd asymmetry of α emission in the $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction still more interesting (see Fig. 5).

According to the model of S–P interference [42], the *P*-odd asymmetry of α emission arises from interference between S and P resonances with equal values of total angular momentum. In the entrance channel of the $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction, the only such pair is formed by the P and S resonances with $(E_p = 0.53$ MeV, $J = 5/2^-)$ and $(E_s = 0.17$ MeV, $J = 5/2^+)$, respectively [43]. Since the α -decay channel with $E_\alpha = 1.47$ MeV has a zero width for the above S resonance, in this channel no *P*-odd asymmetry can be induced by the interference between entrance-channel resonances. Still, the entrance-channel interference can induce a *P*-odd asymmetry in the emission of α particles with $E_\alpha = 1.78$ MeV (or in the α_0 channel), which is kinematically allowed for both resonances. The possible *P*-odd effect induced by the interference between exit-channel resonances estimated in [44] proved to be smaller than that for α particles with $E_\alpha = 1.78$ MeV induced by the interference between entrance-channel resonances by an order of magnitude. Apart from that, as soon as a *P*-odd asymmetry in the emission of α particles with $E_\alpha = 1.47$ MeV (or in the α_1 channel) is detected, γ quanta with $E_\gamma = 0.478$ MeV emitted in the radiative transition from the first excited to ground states of ^7Li should also show a *P*-odd asymmetry. However, our measurements reported above imposed a 90% upper limit of $|\alpha_{P\text{-odd}}^\gamma(^{10}\text{B})| < 4.3 \times 10^{-8}$ on the latter asymmetry. This implies that, in the first approximation, the *P*-odd effect in the α_1 channel ($E_\alpha = 1.47$ MeV) is small, so that the measurements can be carried out for a mixture of both α transitions in which the emission of α_1 particles with $E_\alpha = 1.47$ MeV can be viewed as a background process which does not contribute to the *P*-odd effect.

The left-right asymmetries of α particles with $E_\alpha = 1.78$ and 1.47 MeV emitted in the $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction were measured as $\alpha_{lr}(\alpha_0) = (0.77 \pm 0.06) \times 10^{-4}$ and $\alpha_{lr}(\alpha_1) = -(0.28 \pm 0.14) \times 10^{-5}$, respectively [45]. This also suggests that only the α_0 transition contributes to the *P*-odd asymmetry of α emission in $^{10}\text{B}(n, \alpha)^7\text{Li}$ since the left-right asymmetry should accompany the *P*-odd asymmetry.

To reject the left–right contribution to the measured *P*-odd effect, the experimental geometry is selected so that the vectors $\sigma_n, \mathbf{p}_n, \mathbf{p}_p$ are collinear: $\sigma_n \parallel \mathbf{p}_n \parallel \mathbf{p}_p$. If the collinearity condition is satisfied with an angular precision within $\sim 5 \times 10^{-3}$ rad, which is attainable experimentally, the left–right contribution to the measured *P*-odd asymmetry of α emission in the $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction does not exceed $\sim 2 \times 10^{-9}$. The $^{10}\text{B}(n, \alpha)^7\text{Li}$ reaction was investigated in the same experimental geometry as the $^6\text{Li}(n, \alpha)^3\text{H}$ reaction (see above), and the same ionization chamber [15] was employed as a detector (see Fig. 1).

The targets were manufactured by depositing amorphous boron from suspension in acetone onto a backing of 20- μm -thick aluminum foil. Each double ionization chamber forming a detector module houses two such target placed together back-to-back, so that the chamber's up- and downstream sections service their own targets. Thus formed double backing fully absorbed all secondaries moving inward. The energy spectrum of emitted α particles was measured using a stand-alone target and a pulsed neutron beam, as well as simulated folding in the detector's geometry and assuming that random variations of target thickness follow a Gaussian distribution. The measured spectrum was adequately reproduced by the simulation for a mean boron-target thickness of 180–190 $\mu\text{g}/\text{cm}^2$ and its dispersion of ~ 120 $\mu\text{g}/\text{cm}^2$.

Owing to large specific energy losses to ionization, α -particle ranges are as small as 0.7–0.8 $\mu\text{g}/\text{cm}^2$. Therefore, the tasks of absorbing lithium ions and broad-angle α particles was performed with the insensitive gap of a 9-mm-thick gas layer rather than any solid-state absorber. The ionization chamber was filled with argon at an excess pressure of 0.3 atm. The detector performance under such experimental conditions was simulated assuming that the target thickness was 180 $\mu\text{g}/\text{cm}^2$ on average and its random variations follow a Gaussian distribution. For the mean cosine of the harder- α emission angle over the accepted solid angle, the simulation yielded $\cos(\hat{\sigma}_n \cdot \hat{\mathbf{p}}_{\alpha_0}) = 0.77$. Relative contributions of the α_0 ($E = 1.78$ MeV), α_1 ($E = 1.47$ MeV), Li_0 ($E = 1.01$ MeV), and Li_1 ($E =$

0.84 MeV) secondaries to the detected total current were simulated as 0.114, 0.820, 0.008, and 0.058, respectively.

The beam transverse profile within the chamber was controlled by three ${}^6\text{LiF}$ ceramic collimators wrapped in aluminum foil. Vertical deviation of the neutron beam was within 5 mm/m. The chamber was mounted on concrete blocks so that the beam's horizontal deviation from the axis passing through the chamber center was within 5 mm/m. Towards reducing the contribution of the left–right asymmetry to the P -odd effect, the direction of the magnetic field guiding the neutron spin was aligned with the beam axis to better than 1° .

The first measurement of the coefficient of P -odd asymmetry of α emission in the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reaction for the combination of two α -lines was carried out at PNPI [33]. Upon correcting for the mean cosine of α emission angle over the accepted solid angle and for the neutron-beam polarization, this measurement yielded

$$\alpha_{P\text{-odd}}^{\alpha_0+\alpha_1}({}^{10}\text{B}, \text{exp.}, \text{PNPI}) = -(17.4 \pm 12.2) \times 10^{-8}.$$

The second measurement was carried out at ILL. In the experimental time diagram (see Fig. 4), the basic measurement interval was selected as $T = 0.1$ s, the signal-integration time was 0.09 s, the spin flipper was activated every 0.2 s, and 250 consecutive single measurements were combined in a measurement series with a 100-s duration. Neutron-flux fluctuations were compensated for as described above. Upon correcting for the degree of neutron polarization and the mean cosine of the harder- α emission angle over the angular acceptance, $\cos(\hat{\mathbf{g}}_n \cdot \hat{\mathbf{p}}_{\alpha_0}) = 0.77$, the ILL measurement [46] yielded

$$\alpha_{P\text{-odd}}^{\alpha_0+\alpha_1}({}^{10}\text{B}, \text{exp.}, \text{PNPI}) = -(10.7 \pm 3.5) \times 10^{-8}.$$

Combining the results of these two measurements, for the coefficient of P -odd asymmetry of α emission in the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reaction we obtain

$$\alpha_{P\text{-odd}}^{\alpha_0+\alpha_1}({}^{10}\text{B}, \text{exp.}) = -(11.2 \pm 3.4) \times 10^{-8} \text{ [46]}.$$

Our measurements with a boron target were carried out using the same ionization-chamber detector as those with a lithium target discussed above and, apart from the target material, all experimental conditions were exactly the same. Therefore, the thorough analysis of background P -odd effects in various reactions induced by neutrons in construction materials carried out in [15] fully applies to our experiments with a boron target. The parasitic P -odd asymmetry arising in reactions on impurity nuclei was measured in experiments at ILL [15] and PNPI [32] in which all (lithium) targets were shielded by aluminum foil that fully absorbed the secondaries emitted from the targets. In the experi-

ments carried out within the measurements of P -odd triton-emission asymmetry in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ reaction, this parasitic P -odd asymmetry was measured as

$$\alpha_{\text{backgr}} = (0.2 \pm 0.5) \times 10^{-8}, \text{ and the spurious asymmetry induced by pickups with the beam turned off, as}$$

$$\alpha_{\text{noise}} = -(0.6 \pm 0.5) \times 10^{-8} \text{ (see Table 1). As explained above, these results fully apply to the discussed measurements carried out with a boron target. These background asymmetries are seen to be significantly smaller than the } P\text{-odd asymmetry of } \alpha \text{ emission detected in physical measurements.}$$

For the experimental geometry, the background left–right contribution to the investigated P -odd asymmetry is estimated as $\sim 2 \times 10^{-9}$. The left–right asymmetry induced by uncompensated magnetic fields created by the Earth and by physical equipment of other running experiments equally contributes to the effects measured with two detectors provided that the parasitic field direction remains the same. This contribution cancels out as soon as the data referring to opposite directions of the detector's guiding magnetic field are processed together [34]. No effects of the detector's guiding field with a strength of 5–10 Oe on the ionization-chamber operation were detected [34]. If such spurious effects are present, they should reveal themselves in the same way as those of pickups.

On the whole, the above analysis of possible background and spurious contributions convincingly demonstrates that the observed P -odd effect indeed arises from the P -odd asymmetry of α emission in the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reaction.

CONCLUSIONS

In the series of precision measurements reported in this paper, P -odd asymmetries of secondary particles emitted in the reactions induced by cold neutrons on ${}^6\text{Li}$ and ${}^{10}\text{B}$ light nuclei have for the first time been measured with sensitivity on the order of 10^{-8} : $\alpha_{P\text{-odd}}^{{}^6\text{Li}, \text{exp}} = -(8.8 \pm 2.1) \times 10^{-8}$, $\alpha_{P\text{-odd}}^{{}^{10}\text{B}, \gamma, \text{exp}} = (0.0 \pm 2.6_{\text{stat}} \pm 1.1_{\text{syst}}) \times 10^{-8}$, and $\alpha_{P\text{-odd}}^{\alpha_0+\alpha_1}({}^{10}\text{B}, \text{exp.}) = -(11.2 \pm 3.4) \times 10^{-8}$. For the first time ever, nonzero values were found for two of these asymmetries.

Relying on the cluster-model formalism, the $(\alpha_{P\text{-odd}}^{{}^6\text{Li}})$ and $\alpha_{P\text{-odd}}^{{}^{10}\text{B}, \gamma}$ asymmetry coefficients have been theoretically expressed through weak interaction coupling constants unlike that of α emission in the ${}^{10}\text{B}(n, \alpha){}^7\text{Li}$ reaction whose derivation meets with serious problems. Substituting the values of the former two asymmetries measured in different experiments into their theoretical expressions, one obtains constraints on weak-interaction coupling constants, which are illustrated in Fig. 7 (quoted from [47]). Such constraints based

Fig. 7. Experimental constraints on weak interaction coupling constants.

on our measurements of triton and γ emission in the ${}^6\text{Li}(n, \alpha){}^3\text{H}$ and ${}^{10}\text{B}(n, \alpha){}^7\text{Li}^* \rightarrow \gamma \rightarrow {}^7\text{Li}(\text{gr.st.})$ reactions, respectively, are seen to be consistent with those based on the data of other experiments but rule out the “best DDH values” of weak coupling constants. Theoretically deriving the weak interaction coupling constants from “first principles” rather than in the cluster model framework would be highly desirable. In the future, the reported measurements can be rendered more precise by carrying them out with the upgraded PF1B neutron beam at ILL.

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