

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

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Abstract

We present measurements of P-odd asymmetry of emission of α -particles in the $^{10}\text{B}(n,\alpha)^7\text{Li}$ nuclear reaction, which are carried out using beams of polarized cold neutrons at Petersburg Nuclear Physics Institute (PNPI, Gatchina, Russia) and Institut Max von Laue – Paul Langevin (ILL, Grenoble, France) nuclear reactors. The α -particle detector is an ionization chamber with insensitive gaseous layer.

We measured the P-odd asymmetry coefficient to be equal $\alpha_{p\text{-odd}}^\alpha = -(11.2 \pm 3.4) \cdot 10^{-8}$.

Introduction

Experimental investigations of spatial parity in reactions of polarized neutrons with light nuclei is an important topic in the framework of exploring the fundamental problem of manifestations of weak interaction in nuclear processes as well as evaluating constants of weak nucleon-nucleon (NN) potential. To describe the contribution of weak interaction, the problem is often parameterised in terms of single (π , ρ , ω) and multiple ($\pi\pi$) meson exchange with one weak and one or more strong vertices (see [1, 2] for reviews). Within this parameterisation, neutral and charged weak currents are described with dimensionless coupling constants f_π and h_ρ^0 , respectively. Several models attempt to relate these couplings to more fundamental theory. The quark model by Desplanques, Donoghue and Holstein (DDH) predicts “best values” $f_\pi = 4.6 \cdot 10^{-7}$ and $h_\rho^0 = -11.4 \cdot 10^{-7}$ within “allowed ranges” [3]. The soliton model of nucleon by Kaiser and Meissner (KM) [4, 5] predicts lower values for these couplings. During last years, the weak NN interaction effects have been analyzed actively in the framework of the effective field theory [6–8]. This approach is more general and systematic compared to the one-meson-exchange model. Anyway, one needs new precise relevant experimental data in order to verify theories.

While the observation of parity violation in proton-proton scattering is a manifestation of charged weak currents in accordance with theory [9, 10], no nonzero observation has yet been claimed for neutral weak current contributions in NN-interaction in nuclei. A popular system for the theoretical and experimental investigation of P-odd effects is the radiative neutron capture by protons, $(n,p) \rightarrow (d,\gamma)$. As shown in ref. [2], the coefficient A_γ of the P-odd asymmetry for γ emission depends on the weak neutral current alone, $A_\gamma = -0.11f_\pi$. The “best value” of the DDH model for f_π corresponds to P-odd asymmetry of the order of $5 \cdot 10^{-8}$. The model of KM predicts an even smaller value. Such a tiny observable and the fact that the

cross section for neutron absorption is much smaller than that for scattering, present considerable difficulties to perform a statistically significant measurement.

Until recently, effects of parity violation in reactions with neutron absorption had been observed only in reactions with medium and heavy nuclei, where peculiar enhancement effects may occur [11]. Measurements of P-odd asymmetry coefficients for such nuclei have not provided information on constants of weak interaction in view of the complexity of calculations and corresponding uncertainties [2]. On the other hand, considerable progress has been made in the theoretical description of light nuclear systems involving up to 10 nucleons, starting from phenomenological potential models for NN interactions and including three-body forces. In the absence of parameter-free description of light nuclear systems, we analyse in the following our data using the cluster model.

A set of light nuclei can be described up to the excitation energy of 20–25 MeV as combination of a limited number of clusters; a neutron reaction with such a light nucleus can be considered as reaction in the field of one or a few α -particles. Then the problem can be solved in terms of constants of meson-nucleon interaction. The coefficient of P-odd asymmetry in triton emission in the ${}^6\text{Li}(n,\alpha){}^3\text{H}$ reaction is calculated in ref. [12] in terms of weak couplings; it is equal to $\alpha'_{p\text{-odd}} \approx -0.45f_\pi + 0.06h^0_\rho = -2.8 \cdot 10^{-7}$, where weak constants are "best values" of the DDH model. The measured coefficient is $\alpha'_{p\text{-odd}}({}^6\text{Li}) = -(8.8 \pm 2.1) \cdot 10^{-8}$ [13]. This result constrained the neutral current constant as $0 \leq f_\pi \leq 1.1 \cdot 10^{-7}$ at the 90% confidence level. This value is smaller than the "best value" in the DDH model. Calculation [14] of P-odd asymmetry coefficient of γ -quantum emission in the reaction ${}^{10}\text{B}(n,\alpha_1){}^7\text{Li}^* \rightarrow {}^7\text{Li}(\text{g.s.}) + \gamma$, ($E_\gamma = 0.478$ MeV) provided the following expression: $\alpha'_{p\text{-odd}} \approx 0.16f_\pi - 0.028h^0_\rho = 1.1 \cdot 10^{-7}$ with the DDH "best values". Measured value of this P-odd asymmetry coefficient equals $\alpha'_{p\text{-odd}}({}^{10}\text{B}) = (0.0 \pm 2.6_{\text{stat}} \pm 1.1_{\text{sys}}) \cdot 10^{-8}$ [15]. Performed experiments would not contradict to calculations if the value of neutral current constant is smaller than the theoretical "best value" and close to zero. That is why a measurement of P-odd asymmetry in the emission of α -particle in the reaction ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$, with the predicted effect as high as 10^{-7} – 10^{-6} in the α_0 -transition [16], is of interest. Observation of a non-zero effect in another nuclear reaction accompanied with theoretical calculations would allow one better evaluating neutral and charged current constants.

Reaction ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$

Energy released in this reaction equals 2.79 MeV; it is distributed over reaction products as follows: $E_{\alpha 0} = 1.78$ MeV, $E_{\text{Li}0} = 1.01$ MeV and, $E_{\alpha 1} = 1.47$ MeV, $E_{\text{Li}1} = 0.84$ MeV (see Fig. 1).

Unfortunately, in view of complexity of ${}^{10}\text{B}$ nucleus, theoretical calculations in terms of meson constants have not yet been performed. In accordance with the two level approach [17], S- and P- states with equal spin and opposite parity have to be mixed in order to provide P-odd asymmetry. Here, a single pair of resonances is present in the input channel: P-resonance ($E_P = 0.53$ MeV, $J^\pi = 5/2^-$) and S-resonance ($E_S = 0.17$ MeV, $J^\pi = 5/2^+$) [18]. The width of α_1 transition for S-resonance equals zero; thus, P-odd asymmetry for this transition associated with the input channel is absent. A P-odd effect can be associated only with α_0 -transition (for the given method of introduction of parity violation). A P-odd effect in the exit reaction channel was evaluated in ref. [19]; it is an order of magnitude smaller than its expectation for the α_0 -transition in the input channel. Besides, if P-odd asymmetry exists in α_1 -transition, a P-odd effect should exist also in 0.478 MeV γ -transition from 1st excited to

ground state in ${}^7\text{Li}$. Performed experiments [15] constrained the P-odd asymmetry coefficient of γ -quanta emission $|\alpha_{p\text{-odd}}^\gamma({}^{10}\text{B})| < 4.3 \cdot 10^{-8}$ at the 90% confidence level. Thus P-odd effect in α_1 -transition in the exit channel is absent in first approximation, and one could consider experiments with mixture of α -transitions, where α_1 is a background transition not contributing to the effect.

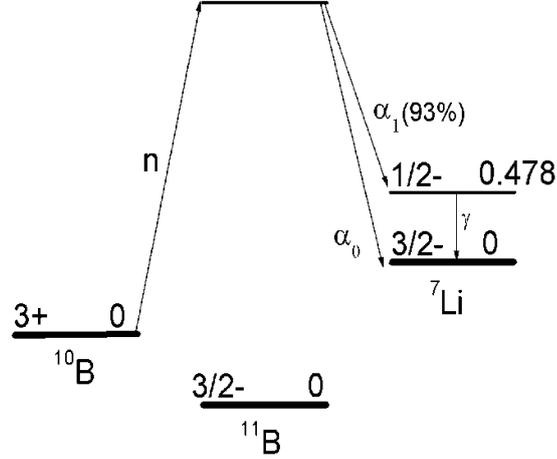


Fig. 1. A scheme of the ${}^7\text{Li}$ nucleus formation following the capture of cold neutron in ${}^{10}\text{B}$ nucleus.

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In first measurements of P-odd asymmetry, rather significant P-even left-right effect was observed in nearly all neutron reactions with light nuclei accompanied with emission of charged particles. The coefficient of left-right asymmetry for the 1.78 MeV transition in the reaction ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$ was measured to be equal $\alpha_{lr}^{\alpha 0} = (0.77 \pm 0.06) \cdot 10^{-4}$; the coefficient of left-right asymmetry for α_1 -transition was estimated as $\alpha_{lr}^{\alpha 1} = -(0.28 \pm 0.14) \cdot 10^{-5}$ [20]. As left-right asymmetry has to accompany P-odd asymmetry, the later estimation also indicates that P-odd asymmetry is expected to be present only in α_1 -transition.

Ionization chamber

The experimental geometry and the experimental setup were the same as in ref. [13] studying the reaction ${}^6\text{Li}(n,\alpha){}^3\text{H}$ (see Fig. 2).

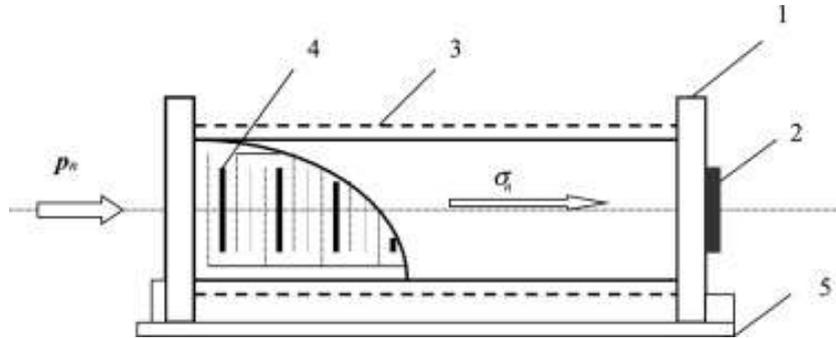


Fig. 2. A sketch of the ionization chamber in the neutron beam: 1 – ionization chamber; 2 – ${}^6\text{LiF}$ beam-stop for absorption of neutrons at the chamber exit; 3 – solenoid for guiding the magnetic field; 4 – grids and ${}^{10}\text{B}$ targets; 5 – base plate of the ionization chamber.

Due to large partial ionization losses, passes of α -particles are small, thus solid film absorbers cannot be used for absorbing the heavy component and defining certain mean cosine of α -particle emission. Instead, we created insensitive gas volume with the thickness of 9 mm installed an additional grid between target and signal electrode. Working gas was argon at the pressure of 0.3 bar. Operation of the ionization chamber was simulated using Monte-Carlo method for these parameters and for the actual detector geometry; the target thickness was assumed to be distributed non-uniformly in accordance with the normal statistical law; the mean target thickness was $180 \mu\text{g}/\text{cm}^2$. The mean cosine of α_0 -particle emission angle is calculated to be equal $\langle \cos(\sigma_n \mathbf{p}_\alpha) \rangle = 0.77$ (σ_n and \mathbf{p}_α are unit vectors of neutron spin and emitted α -particle momentum). Calculated contributions of the reaction products (energies taken into account) into the current measured in the detector are equal: $\alpha_0(E = 1.78 \text{ MeV}) - 11.4\%$, $\text{Li}_0(E = 1.01 \text{ MeV}) - 0.8\%$, $\alpha_1(E = 1.47 \text{ MeV}) - 82.0 \%$, $\text{Li}_1(E = 0.84 \text{ MeV}) - 5.8\%$. To shape the neutron beam, we installed three collimators made of ${}^6\text{LiF}$ ceramics inserted in Al foil envelopes inside the chamber along its total length. The beam is smaller than the target size at both the entrance to and the exit from the chamber. The deviation of the neutron beam along the vertical axis is smaller than 5 mm. The chamber is installed on concrete blocks so that the horizontal misalignment between the neutron beam and the chamber axis is smaller than 5 mm/m. A solenoid wired around the ionization chamber produced the longitudinal magnetic field, which guided the neutron spin. The direction of magnetic field in the chamber is aligned along the chamber axis with the accuracy better than 1° . For this geometry, a contribution of left-right asymmetry into P-odd effect is suppressed by 4-5 orders of magnitude compared to its maximum value.

24 double targets and detection chambers are installed inside the ionization chamber along the longitudinally polarized neutron beam. Targets were produced using sedimentation of amorphous B suspended in acetone to Al foils with the thickness of $20 \mu\text{m}$. Each double chamber is equipped with two targets folded back to back so that each B-coated side looks to its own chamber. Target substrates totally absorb reaction products. One half of a double chamber detects α -particles emitted along the neutron momentum ("forward"), another half detects α -particles emitted against the neutron momentum ("backward"). Due to the

correlation (σ_{np_ω}), P-odd effects in “forward” and “backward” particle emission are of opposite signs. Signal electrodes of chambers are connected to two common electronic lines: "forward" for chambers detecting α -particles emitted along the neutron momentum and "backward" for chambers detecting α -particles emitted in the opposite direction. Signals of all detector chambers "forward" ("backward") are sent to respective preamplifiers (PA), which transform ionization chamber current into voltage. The voltage at the PA exit is recorded in PC using programmable analog-to-digital converter (ADC).

PA divides signals into variable and constant parts. Variable part is amplified and then recorded. The amplification coefficient is calibrated sending a rectangular-step signal of known amplitude to the PA entrance.

Measuring procedure

To achieve maximum accuracy, we used the scheme of two detectors ("forward" and "backward") and special procedure of measurements. The principle of the scheme is based on the fact that both detector channels measure simultaneously the same process, however the signs of real effects are opposite while the effect of synchronous fluctuations is the same.

P-odd asymmetry in nuclear reactions with polarized neutrons is defined as:

$$\alpha = (N_+ - N_-)/(N_+ + N_-), \quad (1)$$

where N_+ and N_- are detector counts corresponding to the emitted particle momentum parallel and antiparallel to the neutron spin, respectively. For the integral measuring method applied, "number of events" per time interval is equivalent to the sum of variable U and constant U_C parts of the signal integrated over this interval and thus the asymmetry coefficient α_{p-odd} is written as follows:

$$\alpha_{p-odd} = \frac{(U_C^+ + U^+ / K) - (U_C^- + U^- / K)}{(U_C^+ + U^+ / K) + (U_C^- + U^- / K)}. \quad (2)$$

Here U_C^+ , U_C^- , U^+ , U^- are respectively constant and variable parts of the signal for different neutron spins relative to the detected particle momentum. K is amplification coefficient for variable part. As $U_C \gg U$ and $U_C^+ \cong U_C^- = U_C$, thus normalized asymmetry coefficient equals:

$$\alpha_{p-odd} = (U^+ - U^-)/(K \cdot 2U_C). \quad (3)$$

Time diagram of measurements is shown in Fig. 3. For each detector channel, tetrads U_1^+ , U_2^- , U_3^- , U_4^+ of variable part of signals from PA averaged over period T are combined in single measurements and calculated as follows: $U^+ = U_1^+ + U_4^+$, $U^- = U_2^- + U_3^-$. Signs "+" and "-" correspond to different neutron spin directions. This combination allows eliminating linear drifts in amplifiers. The asymmetry is calculated for single measurement for each detector. N consequent single measurements in both channels are combined in one series; constant signal part is measured ones in each interval T ; mean, over the series, values of constant signals are used in the normalized asymmetry coefficient. Results are treated after the series.

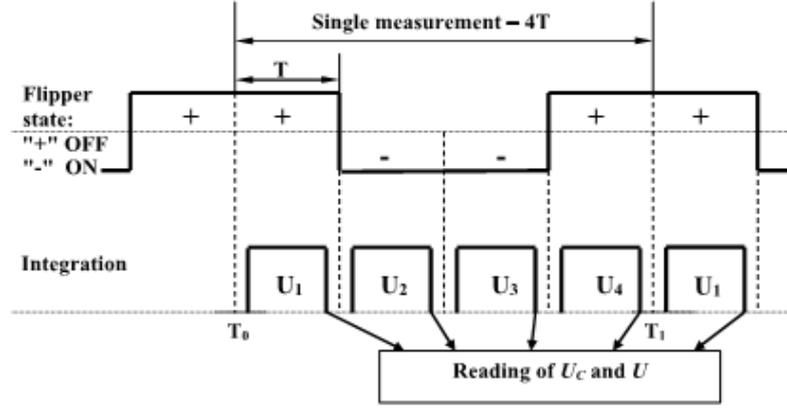


Fig. 3. Time intervals in the experiment.

Synchronous fluctuations of reactor power in measured signals are compensated due to subtraction of asymmetry coefficients for single measurements in two detectors (measuring effects of opposite sign) and summation of these differences at the end of series. Thus, the effect is doubled while reactor power fluctuations are subtracted.

The procedure of data treatment and relevant formulas are described in detail in ref. [13].

In the time diagram in Fig. 3: main time of measurement $T = 0.1$ s, integration time 0.09 s, neutron spin is flipped each 0.2 s, a series consists of $N = 250$ single measurements, i.e. continues for 100 s. Final result is obtained by weighted averaging over many series.

To avoid false asymmetries, the direction of magnetic field in the chamber (guiding the neutron spin) is reversed after each series; the numbers of series with opposite directions of the guiding field are equal. Averaging procedure takes into account that reversion of magnetic field changes the sign of P-odd effect to the opposite one. Thus, combined treatment of data for two detectors and two magnetic field directions eliminates parasitic effects as repeatedly verified in experiments [16], [21], [22]. Earth's magnetic field and external stationary magnetic fields from surrounding are not compensated for; they can increase the contribution of left-right asymmetry into P-odd asymmetry. The sign of corresponding left-right asymmetry does not change when the guiding magnetic field reverses [21]; subtraction of results for opposite directions of guiding field eliminates the contribution of this effect.

Measurements

P-odd asymmetry of α -particle emission in the reaction $^{10}\text{B}(n,\alpha)^7\text{Li}$ was measured earlier for the sum of α -lines [16]. This experiment was carried out at the vertical polarized neutron beam at the PNPI reactor (Gatchina, Russia). The integral neutron intensity was $\sim (1-3) \cdot 10^{10} \text{ s}^{-1}$; the mean neutron polarization was $P = 0.8$. Corrected for the mean cosine of α -particle emission angle and for the neutron polarization, the result was equal

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

Second experiment was carried out at the horizontal polarized neutron beam of PF1B [23] facility at the ILL (Grenoble, France). The mean neutron wavelength is $\lambda = 4.7 \text{ \AA}$; the integral flux of polarized neutrons is $(4-5) \cdot 10^{10} \text{ s}^{-1}$; the neutron polarization is $P = 92 \pm 2\%$.

Neutron polarization is flipped using an adiabatic spin-flipper with the efficiency close to 100%. Fig. 4 shows experimental results; explanations are in the caption.

The experiment at ILL provided the P-odd asymmetry value, corrected for the neutron polarization and the mean cosine of emission of α_0 -particle, equal:

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

The two results provide the value of P-odd asymmetry coefficient of α -particle emission in the reaction $^{10}\text{B}(n,\alpha)^7\text{Li}$ equal

$$\alpha_{P-odd}^{\alpha_0+\alpha_1}(^{10}\text{B}) = -(11.2 \pm 3.4) \cdot 10^{-8}.$$

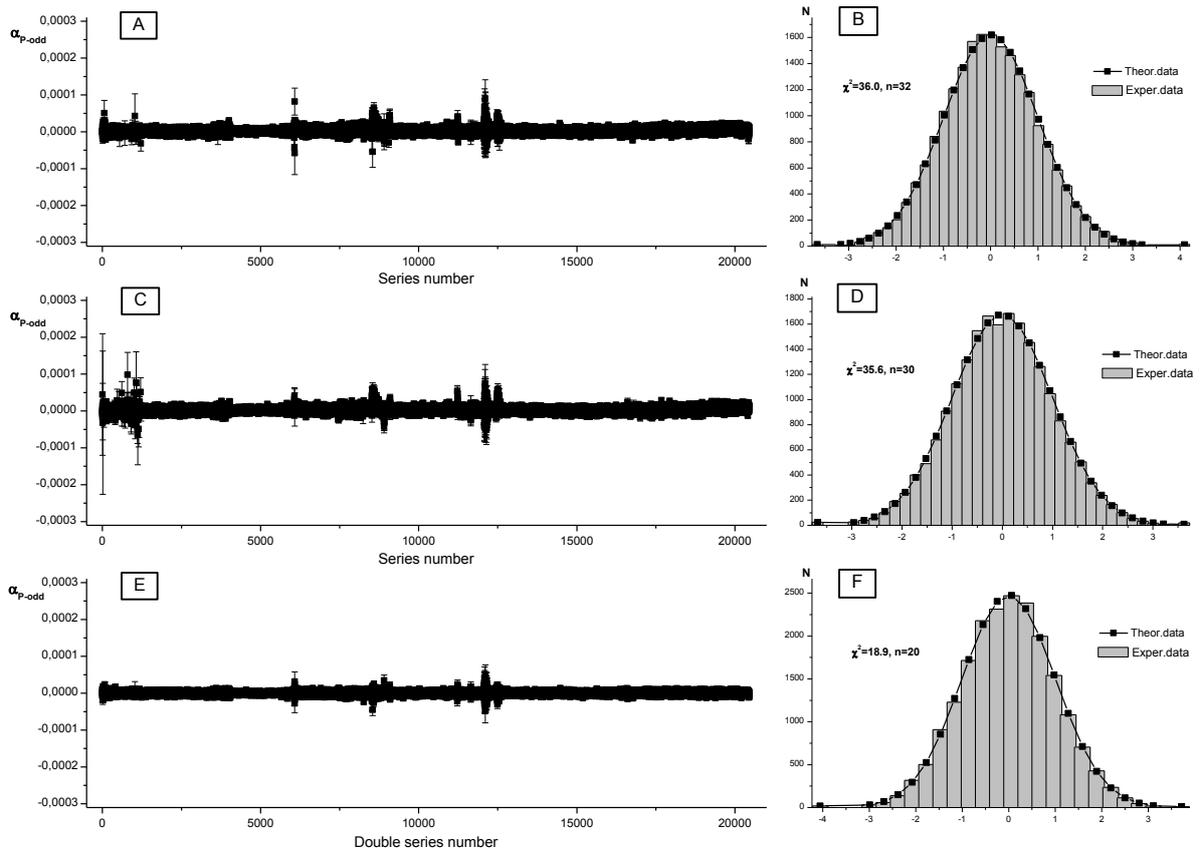


Fig. 4. All results of the presented experiment. A) P-odd asymmetry measured for one direction of the guiding magnetic field (\rightarrow), C) P-odd asymmetry measured for the opposite direction of the guiding magnetic field (\leftarrow), E) the resulting P-odd asymmetry. B), D), F) respective distributions, in comparison with Gaussian distributions.

Control experiments

Ref. [13] presents detailed analysis of possible background P-odd effects in different reactions of neutrons with the construction materials of the experimental setup. As reliable calculation of these effects is complicated, we had to verify experimentally the contribution of

possible false asymmetry caused by neutron reactions with other-than-B nuclei. Thus, we measured P-odd asymmetry with all targets covered with foils completely absorbing reaction products. We performed this experiment in studied of P-odd asymmetry of triton emission in the reaction ${}^6\text{Li}(n,\alpha){}^3\text{H}$ [13]. The chamber and all surrounding of the chamber in the two experiments are equivalent. Taking into account earlier analogous measurements at PNPI [16], the result is

$$\alpha_{backgr} = (0.2 \pm 0.5) \cdot 10^{-8}.$$

This value can be used also for experiments with B, as the detector of charged particles, the ionization chamber, is the same. Thus, we can state that the effect of P-odd asymmetry in the presented experiment is associated with the reaction ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$.

Conclusion

The precision of measurement of P-odd asymmetry in the emission of α -particles in the reaction ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$ ($\alpha_{P\text{-odd}}^{\alpha_0+\alpha_1}({}^{10}\text{B}) = -(11.2 \pm 3.4) \cdot 10^{-8}$) is comparable with the precision of measurement of P-odd effect in the reaction ${}^6\text{Li}(n,\alpha){}^3\text{H}$ [13]. The non-zero result in the reaction ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$ is obtained for the first time. ${}^{10}\text{B}$ is the second light nucleus, after ${}^6\text{Li}$, where P-odd effect has been observed.

P-odd effect in the reaction ${}^{10}\text{B}(n,\alpha){}^7\text{Li}$ can be theoretically calculated within the cluster model; it would be of high importance to describe the considered reaction also from “first principles”.

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