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New results on P-odd asymmetry of γ-quanta emission in $^{10}\mathrm{B}(n,\alpha)^7\mathrm{Li}^* \to \gamma + {}^7\mathrm{Li(g.s.)}$ nuclear reaction

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Abstract. A series of ultra-sensitive experiments has been carried out in 2001–2009 at the ILL measuring P-odd asymmetry in γ-quanta emission in the nuclear reaction $^{10}\mathrm{B}(n,\alpha)^7\mathrm{Li}^* \to \gamma + {}^7\mathrm{Li(g.s.)}$ with polarized cold neutrons. The resulting value of the asymmetry coefficient is $\alpha_{P\text{-odd}} = +(0.0 \pm 2.6_{\mathrm{stat}} \pm 1.1_{\mathrm{syst}}) \times 10^{-8}$. These experiments profited from high-intensity PF1B neutron facility and a new version of the integral measuring method: for decreasing experimental uncertainties, the frequency of neutron spin-flip was higher than a typical reactor power noise frequency. Using the new value, we constrain the weak neutral current constant in the cluster model framework to $f_\pi^{^{10}\mathrm{B}} \le 0.6 \times 10^{-7}$ (at 90% c.l.). This constraint agrees with that following from the nuclear reaction $^6\mathrm{Li}(n,\alpha)^3\mathrm{H}$: $f_\pi^{^6\mathrm{Li}} \le 1.1 \times 10^{-7}$ (at 90% c.l.). However, they both contradict the "best" value in the quark model by Desplanques, Donoughe, and Holstein $f_\pi^{\mathrm{DDH}} = 4.6 \cdot 10^{-7}$. We invite experts in the field to contribute to the theoretical analysis of the problem.

Introduction

The existence of the weak neutral current is the principal prediction of the electroweak standard model; thus the parity violation in the nucleon-nucleon interaction in various processes in nuclei has to include both charged and neutral currents. However, the last one has not yet been observed in such interactions. We suppose that nuclear reactions of light nuclei ($A = 6$–10) with polarized slow neutrons are the most promising candidate to study the weak neutral current properties in nucleon-nucleon (NN) processes.

Such nuclei could be described, for instance, in the framework of cluster and multi-cluster models [1,2] if the excitation energy is < 25–$30\,\mathrm{MeV}$; P-odd effects could be estimated at least for the nuclear reactions with $^{10}\mathrm{B}$ and $^6\mathrm{Li}$. Using this method, the authors of refs. [3,4] calculated the P-odd asymmetry of γ-quanta emission in the reaction

$$^7\mathrm{Li}^* \to {}^7\mathrm{Li} + \gamma(M1), \qquad E_\gamma = 0.478\,\mathrm{MeV} \tag{1}$$

following the reaction

$$^{10}\mathrm{B}(n,\alpha)^7\mathrm{Li}^* \tag{2}$$

induced by polarized cold neutrons (see fig. 1). P-odd asymmetry can be presented in terms of meson exchange constants [4]:

$$\alpha_{P\text{-odd}}^{^{10}\mathrm{B}} = 0.16 f_\pi - 0.028 h_\rho^0 - 0.009 h_\rho^1 - 0.014 h_\omega^0 - 0.014 h_\omega^1. \tag{3}$$

Here f_π corresponds to the π-meson exchange, *i.e.* the weak neutral current. Using the "best values" for the exchange constants according to the quark model by

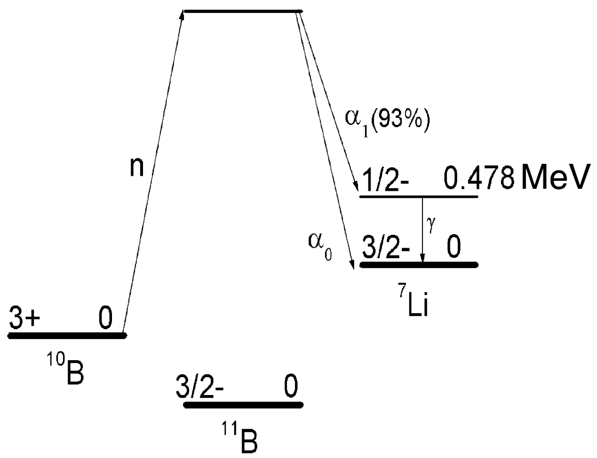

Fig. 1. A scheme of the $^7\mathrm{Li}$ nucleus formation following from the capture of a cold neutron in the $^{10}\mathrm{B}$ nucleus.

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Desplanques, Donoughe and Holstein (DDH) [5], eq. (3) yields the value

$$ {}^{\rm DDH}\alpha_{P\text{-odd}}^{^{10}\text{B, theory}} = 1.1 \times 10^{-7}. \quad (4)$$

Note that if the weak neutral current constant were equal to zero, the cluster models (3) would suggest the asymmetry value ${}^{0}\alpha_{P\text{-odd}}^{^{10}\text{B, theory}} = 0.3 \times 10^{-7}$.

Two experiments (with a total measuring time of 47 days [6,7]) provided a P-odd asymmetry value in the nuclear reaction (2) equal to

$$ {}^{\rm raw}\alpha_{P\text{-odd}}^{^{10}\text{B, exp.}} = (2.7 \pm 3.8) \times 10^{-8}; \quad (5)$$

the "0-test" resulted in

$$ \alpha_{0\text{-test}}^{^{10}\text{B, exp.}} = -(0.9 \pm 4.8) \times 10^{-8}. \quad (6)$$

The P-odd effect in the nuclear reaction

$$ ^{6}\text{Li}(n,\alpha)^{3}\text{H} \quad (7)$$

was also calculated [8] in terms of meson exchange constants:

$$ \alpha_{P\text{-odd}}^{^{6}\text{Li, theory}} \approx (-0.45 f_\pi + 0.06 h_\rho^0) = -2.8 \times 10^{-7} \quad (8)$$

and measured in ref. [9]:

$$ \alpha_{P\text{-odd}}^{^{6}\text{Li, exp.}} = (-8.8 \pm 2.1) \times 10^{-8}. \quad (9)$$

If the charged weak constant h_ρ^0 were equal to "the best DDH value" the weak neutral constant f_π would be equal to

$$ f_\pi^{^{6}\text{Li}} \approx (0.4 \pm 0.4) \times 10^{-7}, \quad (10)$$

or, at 90% confidence level, it would be constrained as follows:

$$ f_\pi^{^{6}\text{Li}} \le 1.1 \times 10^{-7}. \quad (11)$$

However, this value is by far smaller than "the best DDH value" [5]

$$ f_\pi = 4.6 \times 10^{-7}. \quad (12)$$

In order to clarify this contradiction we had to measure the asymmetry $\alpha_{P\text{-odd}}^{^{10}\text{B}}$ more precisely.

In the light of the above, we have carried out two new experiments on the highly intense PF1B beam of polarized cold neutrons [10] at the Institut Laue-Langevin (ILL), Grenoble, France. The average neutron wavelength at PF1B was $\langle\lambda_n\rangle = 4.7$ Å. The neutron beam cross-section at the sample position was equal to 80 mm by 80 mm, the total neutron flux at the sample was $\sim 3 \times 10^{10}\,\text{s}^{-1}$, and the neutron polarization was $P = (92 \pm 2)\%$.

Principle of measurement and the experimental setup

The neutron spin $\vec{\sigma}_n$, the γ-quantum momentum $\vec{p}_\gamma$ and the neutron momentum $\vec{p}_n$ were set as follows:

$$ \vec{\sigma}_n || \vec{p}_\gamma \perp \vec{p}_n. \quad (13)$$

The P-odd effect could be observed in the asymmetry of the γ-quanta emission angular distribution:

$$ \frac{\mathrm{d}N_\gamma}{\mathrm{d}\Omega} \sim 1 + \alpha_{P\text{-odd}} \cos\theta, \quad (14)$$

where θ is the angle between $\vec{\sigma}_n$ and $\vec{p}_\gamma$. The magnetic field guiding the neutron spin, and the γ-quantum momentum, were set parallel to each other with an accuracy of $\varphi = 10^{-2}$ sr.

The guiding magnetic field is produced by Helmholtz coils; it is reversed periodically during measurements. The strength of guiding magnetic field was equal to several Oersteds; no magnetic materials were used to build the experimental setup. The neutron polarization is reversed via switching the high-frequency flipper, placed at a distance ~ 1 m from the detector; the flipper frequency is ~ 20 kHz.

The sample is the amorphous powder ^{10}B with isotopic enrichment of 85% and total weight of 50 g, enclosed in an aluminium case measuring $160 \times 180 \times 5\,\text{mm}^3$. The sample was covered with an aluminium foil with a thickness of 14 μm on the neutron entrance side and installed in the neutron beam; an angle between the beam axis and the sample surface was equal to 45°. Mostly a neutron was absorbed in the sample emitting an α-particle and a γ-quantum. The distance between the sample centre and the centre of each detector is 75 mm. Each γ-quanta detector consists of an NaI(Tl) crystal with a diameter of 200 mm and a thickness of 100 mm. "Hamamatsu" S3204-03 photodiodes with a size of $18\times18\,\text{mm}^2$ were used to detect scintillation photons. The photodiodes are connected to the NaI(Tl) crystals via Plexiglas light-guides. The detectors were inserted into aluminium-alloy cases placed symmetrically on two opposite sides of the sample. The electric-current preamplifiers used in our experiment convert the detector current $I_{\rm det}$ into the output voltage $U_{\rm out}$ so that it is equal $U_{\rm out} = I_{\rm det} R_{\rm fb}$, where $R_{\rm fb}$ is the resistance feedback. The output voltages (their constant terms) were equal to $U_{\rm out} \sim 1$–2 V and the resistance feedback were $R_{\rm fb} \sim 70\,\text{M}\Omega$, *i.e.* the detector currents were $I_{\rm det} \sim 200\,\mu$A. The variable term of the detector output signal (voltage) was enhanced by a factor of about 30.

The setup (fig. 2) was surrounded with lead protection with a thickness of 15 cm. The internal surface of the lead shielding was covered with borated rubber or a borated polyethylene cover. The polarizer and spin-flippers were protected with boron collimators. The detectors were protected with boron rubber. We used boron for the protection, but avoided ^{6}Li, as the asymmetry of ^{8}Li β-decay (the energy of 12–14 MeV, resulting from a 10% admixture of ^{7}Li) is as high as $\alpha_{P\text{-odd}}^{^{8}\text{Li}} \sim 3\%$ [11]. This asymmetry could compromise the results with false P-odd effect. Background scattering (with no sample) was found to be as low as 5% compared to scattering in the sample.

The measuring procedure and data treatment

We used two detectors in the electric-current mode and a method to compensate for eventual false effects described

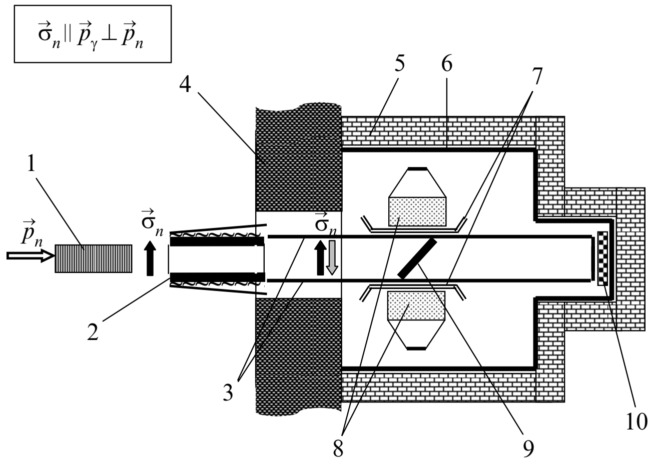

Fig. 2. A scheme of the experimental setup: 1) polarizer; 2) adiabatic "spin-flipper"; 3) tube made of boron rubber filled in with flowing-through ^{4}He; 4) concrete wall; 5) lead shielding; 6) boron rubber; 7) Helmholtz coils; 8) detectors; 9) the sample; 10) lithium absorber. $\vec{p}_n$, $\vec{\sigma}_n$ are the neutron momentum and the neutron spin, respectively; black arrows indicate the neutron spin when the flipper is switched off, grey arrows show the neutron spin when the flipper is switched on.

earlier in refs. [9,12]. To achieve an accuracy of $\sim 10^{-8}$ in the asymmetry measurement, any fluctuations in the electronics or reactor neutron flux, as well as any interference with external electric signals or other false effects, have to be minimized.

To compensate for fluctuations in the reactor power, we used special measuring procedures involving a pair of detectors for every target. Both detectors measure simultaneously the same process but provide opposite signs for the asymmetry effect (see fig. 2); fluctuations in the reactor power will have an identical impact in both detectors and will carry the same sign. In the integral method, electrical signals can be presented as the sum of their constant and variable components. The "number of events" in a time interval is proportional to the sum of the variable U/K and constant $U_{\rm C}$ components of the signal, integrated over this interval; therefore the asymmetry coefficient $a_{P\text{-odd}}$ is

$$a_{P\text{-odd}} = \frac{(U_{\rm C}^+ + U^+/K) - (U_{\rm C}^- + U^-/K)}{(U_{\rm C}^+ + U^+/K) + (U_{\rm C}^- + U^-/K)}, \qquad (15)$$

where $U_{\rm C}^+$, $U_{\rm C}^-$, U^+, U^- are the constant and variable components of the signal for two opposite neutron polarisations, relative to the detected gamma momentum in the respective detector. The coefficient K describes the amplification of the variable component of the signal. As $U_{\rm C} \gg U$ and $U_{\rm C}^+ \cong U_{\rm C}^- = U_{\rm C}$, the normalised asymmetry coefficient is given by

$$a_{P\text{-odd}} = (U^+ - U^-)/(2KU_{\rm C}). \qquad (16)$$

For every detection channel, four consecutive voltages U_1^+, U_2^-, U_3^-, U_4^+ are combined in a "single measurement" and added as follows: $U^+ = U_1^+ + U_4^+$, $U^- = U_2^- + U_3^-$. Each value U_1^+, U_2^-, U_3^-, U_4^+ is the voltage at the preamplifier output averaged over the main interval T of the experiment; the interval T defines the duration of a "single measurement" $4T$ and the frequency of switching the neutron spin. These combinations allow us to suppress linear drifts. The asymmetry was calculated for each single measurement in every detector. Formulas for the effects in each measuring channel are given in ref. [9]. In both channels the results of N subsequent measurements in a series were summed; the constant component of a signal was measured ones per each interval T.

The calculated effects $\alpha_i^{(1)} = (U_i^{+,(1)} - U_i^{-,(1)})/2$ and $\alpha_i^{(2)} = (U_i^{+,(2)} - U_i^{-,(2)})/2$ for the two detectors are of opposite sign; these values are measured synchronously. Therefore, taking advantage of the double detectors, by calculating $\bar{\alpha}_{\rm comp}$ the asymmetry value is doubled, and the effect of fluctuations in the reactor power is subtracted due to subtraction of one value from the other:

$$\left.\begin{aligned} \bar{\alpha}_{\rm comp} &= \frac{1}{N}\left(\sum_{i=1}^{N}\alpha_i^{(1)} - L\sum_{i=1}^{N}\alpha_i^{(2)}\right), \\ D(\bar{\alpha}_{\rm comp}) &= \frac{1}{N(N-1)}\sum_{i=1}^{N}\left(\left(\alpha_i^{(1)} - L\alpha_i^{(2)}\right) - \bar{\alpha}_{\rm comp}\right)^2, \\ \sigma(\bar{\alpha}_{\rm comp}) &= \sqrt{D(\bar{\alpha}_{\rm comp})}. \end{aligned}\right\} \qquad (17)$$

The compensation coefficient L is calculated for every series of single measurements with the condition that the variation $D(\bar{\alpha}_{\rm comp})$ of the average value of the absolute effect $\bar{\alpha}_{\rm comp}$ is minimal. The final result is averaged over all series; the weight is taken into account.

To further compensate false asymmetries we changed the direction of the guiding magnetic field and measured an equal number of series for both directions. For the averaged values we took into account the direction reverse of the actual P-odd effect due to the reverse of the guiding magnetic field. The field direction was reversed every 4 minutes.

We emphasise that the three stages of signal evaluation work with differences:

1) between variable parts of the signals (absolute effect of P-odd asymmetry) $\alpha = U^+ - U^-$ for opposite neutron spin polarisations; these differences are calculated for every pair of measurements for both detectors;
2) between the absolute effects for the two detectors $\alpha_i = \alpha_i^{(1)} - L\cdot\alpha_i^{(2)}$, $i = 1 \div N$. Since P-odd asymmetries in the detectors have opposite signs, the effect is doubled. These differences are calculated for each direction of the guiding magnetic field (referred to as "$\rightarrow$" and "$\leftarrow$");
3) between the effects for each direction of the guiding magnetic field: $\alpha_i(\rightarrow) - \alpha_i(\leftarrow)$, $i = 1 \div M$. P-odd effects are added in this case, because they have opposite signs.

At each of the 3 stages of the calculation described above, we subtract values measured for two opposite conditions. Effects of equal sign and equal size thus cancel, and the asymmetry persists. Taking the third difference, for instance, any influence of the guiding magnetic field on the currents in the detector or changes in the neutron absorption as a function of the field direction would cancel unless the effect is due to P-odd effects from impurity nuclei.

This conclusion is valid as well for electromagnetically induced false effects. Such influences were checked many times [6,7,12]. For instance, an additional measurement without neutron beam but with a fully working apparatus gave a value of asymmetry of $(1.1 \pm 0.7) \cdot 10^{-8}$ (normalized) [6]. Measurements of false apparatus effects were carried out from time to time with the neutron beam off. They were aimed at additional verification of the absence of parasitic electrical signals in the experiment electronics originating from the surrounding equipment in the experimental hall. The duration of such a measurement was several hours. The corresponding resulting false effect was estimated as $\alpha_{\text{noise}} = (-5.1 \pm 7.1) * 10^{-9}$ (normalized), which is considerably smaller than the experimental uncertainty.

The identical treatment of the results for two detectors and for the two directions of the guiding magnetic field thus allows us to avoid completely any noticeable influence of parasitic electromagnetic effects.

Other possible sources of systematic uncertainties

a) *The left-right asymmetry in the γ-quantum emission*

As shown in ref. [13], the left-right asymmetry in the second stage of decay of a polarized nucleus differs in the reaction ${}^7\text{Li}^*(1/2^-) \to {}^7\text{Li}(3/2^-) + \gamma$ from zero only if parity is not conserved in ^{7}Li, and transitions $E1$ and $M2$ contribute to the main transitions $M1$ and $E2$. P-odd effects in the ^{7}Li nucleus do not exceed 10^{-7}–10^{-8}. In the reference system with the center coinciding with the center of mass of a target nucleus, with the z-axis along the vector $\vec{p}_n$, and with the x-axis along the vector $\vec{\sigma}_n$, let the angle between emitted γ-quantum ($\vec{p}_\gamma$) and $\vec{p}_n$ denote Θ, and the angle between the plane of vectors $\vec{p}_\gamma$, $\vec{p}_n$ and the plane of vectors $\vec{\sigma}_n$, $\vec{p}_n$ denote Φ. In our experiment $\Phi \sim 10^{-2}$, and $\Theta \sim \pi/2$. Thus, the eventual contribution of the left-right asymmetry $(\vec{\sigma}_n \cdot [\vec{p}_n \times \vec{p}_\gamma])$ to the P-odd asymmetry is proportional to $\sin\Theta \sin\Phi$, thus it does not exceed 10^{-9}–10^{-10}.

b) *The effect of Stern-Gerlach steering of polarized neutrons upon neutron spin-flip*

The strength of the guiding magnetic field from the adiabatic spin-flipper is equal to $\sim$ 10 Oe at the edge; the strength of guiding fields from Helmholtz coils is $\sim$ 5–10 Oe in the target. We provided adiabatic spin-flip conditions by cross linking these magnetic fields. The asymmetry due the Stern-Gerlach effect is measured in ref. [14] in a setup with about the same adiabatic spin-flipper; it does not exceed 10^{-10}, thus providing an estimate for our experiment.

c) *β-decay of ^{8}Li*

A systematic contribution of bremsstrahlung from the parity-odd β-decay of ^{8}Li in the beam stop to P-odd asymmetry in the γ-channel could be estimated taking into account 10% content of ^{7}Li, the cross-sections $\sigma_{n\alpha}^{{}^6\text{Li}} = 945\,\text{b}$, $\sigma_{\text{act}}^{{}^7\text{Li}} = 0.036\,\text{b}$, the distance from the detectors to the beam stop of $\sim 1\,\text{m}$, and the fact that about 1% of incoming polarized neutrons reach the beam stop avoiding the target. If all β-particles would convert into γ-quanta, the count rate of the γ-quanta in the detector originating from the β-decay of ^{8}Li would be equal to $\sim 2\,\text{s}^{-1}$. If the asymmetry is 100% then, taking into account the count rate of γ-quanta in the detector equal to $3.5 \cdot 10^9$ one could constrain the asymmetry: $\alpha'_{\beta\text{-decay}} = \frac{2}{7\times 10^9} \approx 3 \times 10^{-10}$. In fact, as follows from ref. [11], the residual γ-asymmetry is 3% of the β-decay asymmetry, as it is suppressed due to the interaction of the magnetic moment of ^{7}Li with external non-nuclear fields, *i.e.* $\alpha_{\beta\text{-decay}} = 9 \times 10^{-12}$.

d) *The false P-odd effect caused by eventual impurities in the ^{10}B sample*

P-odd asymmetry has been observed for the following nuclei: Cl, ${}^{\text{nat}}$Br, ${}^{\text{nat}}$Cd, ^{117}Sn, ^{139}La and Fe; therefore we have to provide that their admixtures do not contribute to our measurements of the boron asymmetry. The admixture of each mentioned nuclear is smaller than 0.1% compared to the ^{10}B isotope. The maximum P-odd asymmetry coefficient was measured in the integral spectrum of γ-quanta in the reaction with Cl; it is equal to $-(2.8 \pm 0.5) \times 10^{-5}$. Taking into account that the admixture of Cl in the boron target does not exceed $\sim 10^{-3}$, also keeping in mind the cross-sections of neutron reactions with B and Cl, we constrain the admixture of the P-odd effect in Cl as follows: $\alpha_{\text{impurity}}^{\text{calc.}} < \alpha_{P\text{-odd}}^{\text{Cl}} \times \frac{n_{\text{Cl}}}{n_{\text{totB}}} \times \frac{\sigma_{n\gamma\text{Cl}}}{\sigma_{\text{totB}}} \cong 8 \times 10^{-10}$.

Analogous calculation for another nucleus, ^{139}La, with its asymmetry coefficient of $-(1.8 \pm 0.2) \times 10^{-5}$, provides the following constraint: $\sim 5 \cdot 10^{-11}$. Other mentioned nuclei result to even smaller eventual contributions to P-odd effects.

We have been searching systematically for P-odd effects in (n,γ)-reactions with other nuclei larger than those mentioned above, but have not discovered them. Therefore their contribution to the B effect, if any, does not exceed the values given above.

The uncertainty of our experiments with boron is $\sim 10^{-8}$ that is at least an order of magnitude larger than eventual admixtures of P-odd effects in impurity nuclei.

e) *Eventual false effects from α-particles*

Secondary reactions involving α-particles emitted from the studied reaction ($E_{\alpha 0} = 1.78\,\text{MeV}$, $E_{\alpha 1} = 1.47\,\text{MeV}$) take place in the target and in aluminum:

$$\begin{aligned}
&{}^{10}\text{B}(\alpha,n)^{13}\text{N}, \quad Q_{\alpha n} = 1.06\,\text{MeV}; \quad \sigma < 10^{-2}\,\text{b},\\
&{}^{10}\text{B}(\alpha,\gamma)^{14}\text{N}, \quad Q_{\alpha\gamma} = 11.61\,\text{MeV}; \quad \sigma < 10^{-7}\,\text{b},\\
&{}^{11}\text{B}(\alpha,n)^{14}\text{N}, \quad Q_{\alpha n} = 0.16\,\text{MeV}; \quad \sigma < 10^{-1}\,\text{b},\\
&{}^{11}\text{B}(\alpha,\gamma)^{15}\text{N}, \quad Q_{\alpha\gamma} = 10.99\,\text{MeV}; \quad \sigma < 10^{-5}\,\text{b},\\
&{}^{27}\text{Al}(\alpha,\gamma)^{31}\text{P}, \quad Q_{\alpha\gamma} = 9.67\,\text{MeV}; \quad \sigma < 10^{-8}\,\text{b}.
\end{aligned} \tag{18}$$

The upper bounds for the values of these cross-sections for α-particle energies 0–1.78 MeV could be found in the library ENDF. Taking into account isotopic content in the target and paths of α-particles, we constrain the contributions of events originating from these reactions: $N_n/N_{\gamma B} < 4 \times 10^{-7}$, $N_\gamma/N_{\gamma B} < 10^{-10}$, where N_n, N_γ is the number of fast neutrons and γ-quanta from secondary reactions, $N_{\gamma B}$ is the number of γ-quanta from the studied reaction. The angular and energy distribution of products of secondary reactions is asymmetric relative to the α-particle momentum because of the kinematics and the orbital momentum; however, it is isotropic in the laboratory reference system if the distribution of α-particles is isotropic. P-odd effects in the reaction $^{10}B(n,\alpha)^7Li$ have been studied in [15]; P-odd asymmetry coefficients are equal:

$$\begin{aligned} \alpha_{PNC}(\Sigma) &= -(1.9 \pm 1.2) \times 10^{-7} \\ &\quad \text{—for the sum of the lines } \alpha_0 \text{ and } \alpha_1; \\ \alpha^0_{PNC} &= (3.4 \pm 6.7) \times 10^{-7} \text{ —for the line } \alpha_0; \\ \alpha^1_{PNC} &= -(2.5 \pm 1.6) \times 10^{-7} \text{ —for the line } \alpha_1. \end{aligned} \tag{19}$$

With these data, we constrain eventual contributions to the studied effect coming from secondary reactions: $|\alpha_n^{sec}| < 1.6 \times 10^{-13}$ —for fast neutrons, $|\alpha_\gamma^{sec}| < 4 \times 10^{-17}$ —for γ-quanta.

f) *Doppler shift value of the γ-line*

The Doppler shift of the γ-line 0.478 MeV could reach $\Delta E_\gamma^{Dop}/E_{\gamma 0} = 1.5 \times 10^{-2}$, depending on the value and direction of the momentum of decelerating the ^7Li nucleus in the moment of γ-quantum emission. As the lifetime of the excited ^7Li state is compatible to the deceleration time, the energy distribution of γ-quanta is non-isotropic within ΔE_γ^{Dop}. However, the angular distribution of ^7Li recoil nuclei and the energy distribution of γ-quanta is equal for any direction of the neutron spin if there is no correlation with the neutron spin in the reaction $^{10}B(n,\alpha)^7Li$. Using the data on P-odd asymmetry for the line α_1 from [15] we constrain eventual asymmetry caused by the difference in energy of emitted γ-quanta: $|\alpha^{Dop}| \leq 8 \times 10^{-9}$.

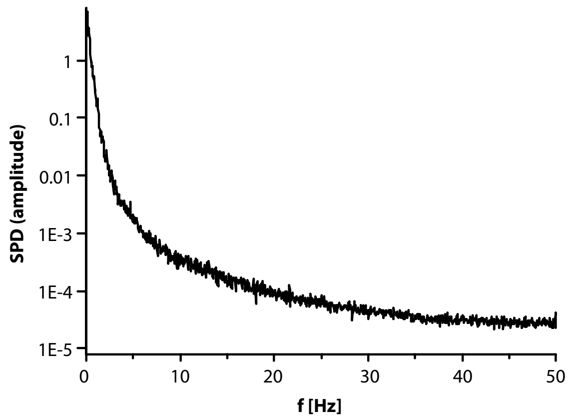

Fig. 3. Spectral density (SPD) of the ILL reactor power fluctuations (in arbitrary units), as a function of frequency, measured during the experiment.

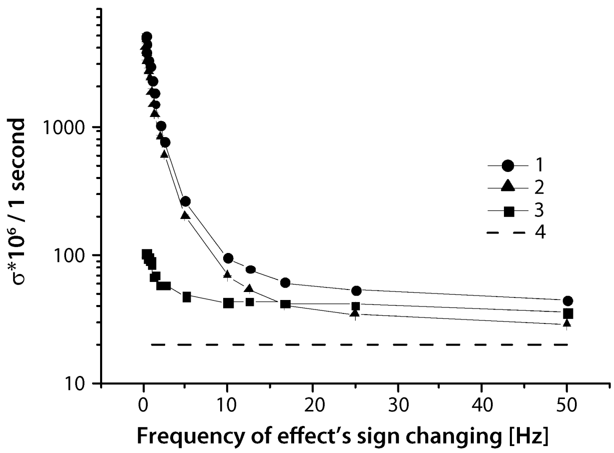

Fig. 4. The uncertainties σ in measuring the P-odd effect in the reaction $^{10}B(n,\alpha)^7Li^* \rightarrow \gamma \rightarrow {}^7Li(g.s.)$ are shown as a function of the neutron spin-flip frequency. 1, 2) Uncertainties of the asymmetry measurement for the detectors 1 and 2; 3) uncertainty of the subtracted signal (the reactor power fluctuations are compensated) multiplied by $\sqrt{2}$ (for comparison with single channels); 4) the statistical uncertainty estimated from the value of the neutron flux.

New version of the integral measuring method

A new version of the integral measuring method was first used to measure the P-odd asymmetry in ref. [16]: the frequency of the neutron spin-flip was higher than the typical frequency of the reactor power noise. Figure 3 shows the spectral density of the reactor power noise as a function of the frequency f measured during our experiment at PF1B. Analogous distributions were measured earlier at other reactors [17]. It has been shown in ref. [17] that the asymmetry measurement uncertainty is only due to frequencies higher than the spin-flip frequency. The spectral noise density decreases sharply at high frequency; so the corresponding systematics could generally be suppressed.

A significant fraction of light is lost in the γ-detectors, as a photodiode sensitive area is much smaller than the diameter of a NaI(Tl) crystal; we therefore had to amplify the electronic signals significantly. This amplification caused a "microphone effect" in the electronic channels induced by the mechanical vibration of the preamplifiers. As the effect depends on the electronic channel, it is not subtracted by the measuring procedure described in ref. [12]. Spin-flipping with high-frequency "cuts" low-frequency non-correlated components of the two signals and therefore reduces the corresponding uncertainty. In order to suppress the microphone effect, we built a new electronic system measuring the current. It is adapted to neutron spin-flip frequencies of 0.01–50 Hz [18].

The uncertainty of the P-odd effect measurement in the nuclear reaction (1) is shown in fig. 4 as a function of the neutron spin-flip frequency. One can see that increasing the spin-flip frequency reduces uncertainties in single and subtracted channels. The decrease in uncertainty of the subtracted signal is due to the suppression of the "microphone effect". One can see in fig. 4 also the uncertainty calculated for the neutron beam intensity $N_n \sim 3 \cdot 10^{10}\,\mathrm{s}^{-1}$. Taking into account the solid angles to the detectors $\Omega \sim 0.15$ and the efficiencies of the γ-quantum detectors $\varepsilon \sim 0.78$, we get the γ-quanta flux in the detectors $N_\gamma = N_n \cdot \varepsilon \cdot \Omega \sim 3.5 \cdot 10^9\,\mathrm{s}^{-1}$. Thus the statistical uncertainty is $\sim 2 \cdot 10^{-5}$.

Experimental results

In 2007 and 2009, we carried out in the ILL two measurements of P-odd asymmetry in the reaction $^{10}\mathrm{B}(n,\alpha)^7\mathrm{Li}^* \to \gamma \to {}^7\mathrm{Li(g.s.)}$ using a new system of experiment control and read-out. All measurements were carried out in series of ~ 4 min. The frequency of the neutron spin-flip was equal to 5 Hz. In order to reduce effects of apparatus asymmetry and radio noise, we reversed the direction of the guiding magnetic field at the sample ("→" or "←") in every series using Helmholtz coils. We measured an equal number of series for two field directions in analogy to ref. [9]. This procedure reversed the neutron spin and the measured asymmetry sign, respectively. Thus, the subtracted signal contains double asymmetry; in contrast, apparatus-related false asymmetries are subtracted. As the spin-flip frequency was not high enough to minimize the measurement uncertainty, we used also the scheme of compensation for reactor power fluctuations. This procedure minimized uncertainties.

Experiment in 2007

The result of ~ 20 days-run in 2007 is

$$^{\mathrm{raw}}\alpha_{P\text{-odd}}^{^{10}\mathrm{B,\ exp.}} = +(3.1 \pm 3.8) \times 10^{-8}\ [19]. \tag{20}$$

It is corrected for the finite neutron beam polarization P and for the average cosine of the detection angle θ:

$$P\langle\cos\theta\rangle = 0.77. \tag{21}$$

In contrast to the experiment studying the nuclear reaction (7) with ^{6}Li [9], in which a "zero" experiment was carried out (aluminium foil covered sample for preventing charged particles to penetrate into the ionization chamber), we cannot carry out an analogous experiment in the integral current mode with the ^{10}B sample, as γ-quanta from the neutron reaction with boron cannot be separated from those from other reactions with impurity nuclei. We therefore performed two test experiments of other kind.

One test consisted in measuring without the ^{10}B sample but with the aluminium foil only that usually was covering the sample. Then the neutron beam penetrates the material behind the sample position and produces γ-quanta, in contrast to measurements with the ^{10}B sample (the neutrons are otherwise absorbed by the sample in the main experiment). Therefore, this is not a true "zero" test, but a check for false P-odd asymmetry related to the apparatus. The statistical accuracy of such measurements is not higher than in the experiment with the ^{10}B sample. The measurement with the aluminium foil provided the result (2007):

$$\alpha_{0\text{-test}}^{^{10}\mathrm{B,\ exp.}} = (4.2 \pm 7.3) \times 10^{-8}. \tag{22}$$

The second test investigated possible false effects due to (n,γ) reactions in the apparatus material with scattered neutrons. The ^{10}B sample is replaced by a target that scatters neutrons but does not emit γ-quanta in (n,γ) nuclear reactions. If the scattering by this test target is much stronger than that by the ^{10}B sample, the false effects are greatly enhanced. Graphite is such an "ideal" scatterer. Its absorption cross-section for thermal neutrons is only $\sigma_{n\gamma} = 3.8 \times 10^{-3}$ b, but its scattering cross-section is $\sigma_{\mathrm{scatt.}} = 4.8$ b. A target of natural graphite scattered $\sim 43\%$ neutrons. The scattering is not complete because the graphite scattering cross-section is not as large as the boron absorption cross-section. The result of this test is

$$\alpha_{\mathrm{test}}^{\mathrm{graphite,\ exp.}} = (1.7 \pm 1.9) \times 10^{-6}. \tag{23}$$

Using this value and taking into account the cross-sections of absorption and scattering in boron as well as the values of the constant (spin-independent) parts of the detector signals in the experiments with boron and graphite, we calculated the contribution of the false P-odd effect due to neutron scattering in boron and the consequent absorption in the apparatus materials:

$$\alpha_{\mathrm{scatt.},{}^{10}\mathrm{B}}^{\mathrm{calc.}} = (2.7 \pm 3.0) \times 10^{-9}. \tag{24}$$

Obviously, the corresponding correction is small.

Besides, ~ 0.002 of neutrons scatter in air in vicinity of the sample. Assuming 100% scattering in graphite, taking into account the cross-sections of neutron absorption in boron and the scattering of neutrons in air, correcting for the ratio of constant parts of signals in analogy to the previous calculation, we constrain the effect of neutron scattering in air:

$$\alpha_{\mathrm{scatt.,air}}^{\mathrm{calc.}} = (3.5 \pm 3.9) \times 10^{-8}. \tag{25}$$

This is the most significant eventual contribution to the measured P-odd effect. It was present in all measurements; therefore we took it into account when making "0"-tests.

The P-odd asymmetry coefficient in the reaction (1) on boron was equal to

$$\alpha_{P\text{-odd}}^{^{10}\mathrm{B,\ exp.}} = -(1.1 \pm 8.2) \times 10^{-8}, \tag{26}$$

taking into account background measurements only with the aluminum foil.

Experiment in 2009

A new measurement of P-odd asymmetry in the reaction (1) with boron was carried out in 2009.

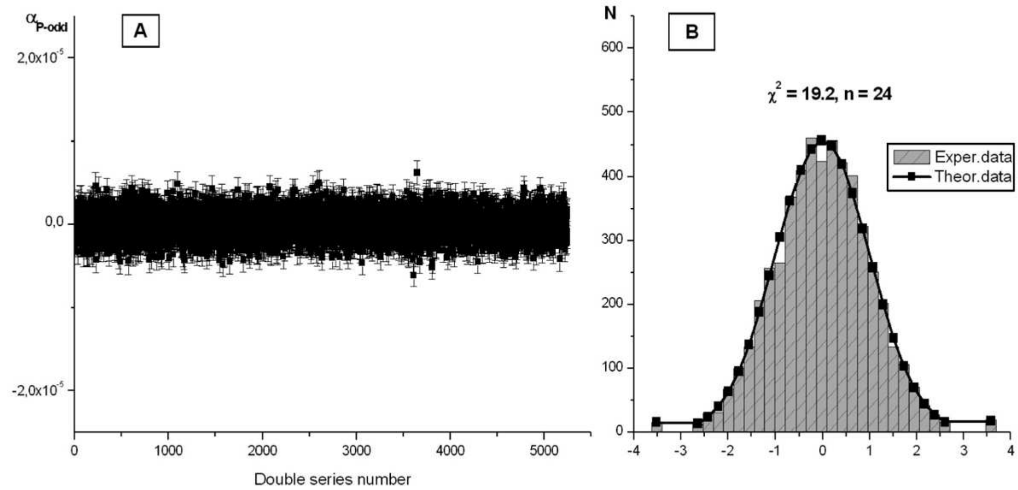

Fig. 5. (A) Results of the measurement of the P-odd asymmetry coefficient of γ-quanta emission in the reaction ${}^{10}\mathrm{B}(n,\alpha)^{7}\mathrm{Li}^{*} \rightarrow \gamma \rightarrow {}^{7}\mathrm{Li}(\mathrm{g.s.})$; the sign of the guiding magnetic field is taken into account: $\alpha_{P\text{-odd}} = \alpha(\rightarrow) - \alpha(\leftarrow)$ for each of the two consecutive series of the measurement corresponding to the opposite field directions "$\rightarrow$" and "$\leftarrow$". (B) Corresponding histogram of the statistical distribution of the measured differences compared to the normal distribution. All data are taken into account; no 3σ-cut is applied. The χ^2 values and the number of degrees of freedom are given. This experiment was carried out in 2009.

We noticed in the 2007-year experiment that the relative uncertainty of measurements in the reaction with boron and that in the "0-test" (normalized to the constant signal in the boron measurement) were approximately equal. On the other hand, the uncertainty in the "0-test" should be much smaller because currents in γ-quanta detectors in "zero" experiments were much smaller than currents in the main experiment with boron. We concluded that there have been high-energy γ-quanta in all experiments; their energy of $E_\gamma = 5$–$7\,\mathrm{MeV}$ was typical for the (n,γ)-reaction in constrictive materials and in air in detector vicinity; the intensity of such γ-quanta in the main experiment and in the "0-test" were approximately equal. In the integral detection method, the current in detectors is proportional to NE_γ, where N is the number of γ-quanta, and E_γ is the γ-quanta energy, thus even a small amount of γ-quanta of high energy could increase considerably the measurement uncertainty as the energy of γ-quanta in the reaction (1) is only $E_\gamma = 0.478\,\mathrm{MeV}$.

In order to decrease the amount of such high-energy γ-quanta we built a new system to deliver neutrons to the target. It included a tube with the length of 2 m made of boron rubber filled in with flowing-through ${}^{4}\mathrm{He}$. The substitution of air by helium allowed a decreasing of the neutron scattering; scattered neutrons were totally absorbed in the boron rubber; helium consumption was $\sim 100\,\mathrm{l/day}$. The boron target of the enriched ${}^{10}\mathrm{B}$ isotope was installed inside the tube close to the γ-quanta detectors.

This modification decreased the relative uncertainty in the main measurements by a factor of 1.2. The measurement resulted in the P-odd asymmetry value

$$ {}^{\mathrm{raw}}\alpha_{P\text{-odd}}^{{}^{10}\mathrm{B,\,exp.}} = -(2.0 \pm 2.5) \times 10^{-8}. \qquad (27) $$

measured for 31 days. The principal gain in the experimental accuracy arrived from the "0-test", in which the intensity of γ-quanta produced in the aluminum foil became small. Compared to the uncertainty of measurements without using the helium-filled tube, now the uncertainty decreased by a factor of 3 (from 1.5×10^{-7} to 0.5×10^{-7} per day). The "zero" measurements resulted in the following contribution to the P-odd asymmetry:

$$ \alpha_{0\text{-test}}^{{}^{10}\mathrm{B,\,exp.}} = -(1.3 \pm 1.6) \times 10^{-8}. \qquad (28) $$

This value is normalized to constant signals in the main measurements with the boron target; it is corrected for finite neutron polarization and the average cosine of the solid angle covered by the detectors. Taking into account the "0-test" we get the following result for the 2009-year experiment:

$$ \alpha_{P\text{-odd}}^{{}^{10}\mathrm{B,\,exp.}} = -(0.7 \pm 3.0) \times 10^{-8}. \qquad (29) $$

Figure 5 presents the results of the measurement of differences of P-odd asymmetry coefficients of γ-quanta emission in the reaction (1) for each two consecutive 4-minutes series. One of them corresponds to one of the two opposite directions of the guiding magnetic field (a pair of series provides a double value for the P-odd effect), that is $\alpha_{P\text{-odd}} = \alpha(\rightarrow) - \alpha(\leftarrow)$. The histogram of the statistical distribution of the differences is compared to the normal distribution. Figure 6 shows analogous results and the histogram for the "0-test". Calculated values of χ^2 indicate the statistic nature of the scattering of the experimental results and their normal distribution.

Table 1 presents values of the P-odd asymmetry coefficients of γ-quanta emission in the reaction ${}^{10}\mathrm{B}(n,\alpha)^{7}\mathrm{Li}^{*} \rightarrow \gamma \rightarrow {}^{7}\mathrm{Li}(\mathrm{g.s.})$ as well as results of "zero" experiments measured in all performed experiments in ILL (all data are taken into account; no 3σ-cut is applied).

Table 2 shows measured and estimated systematic effects and corrections in our measurements.

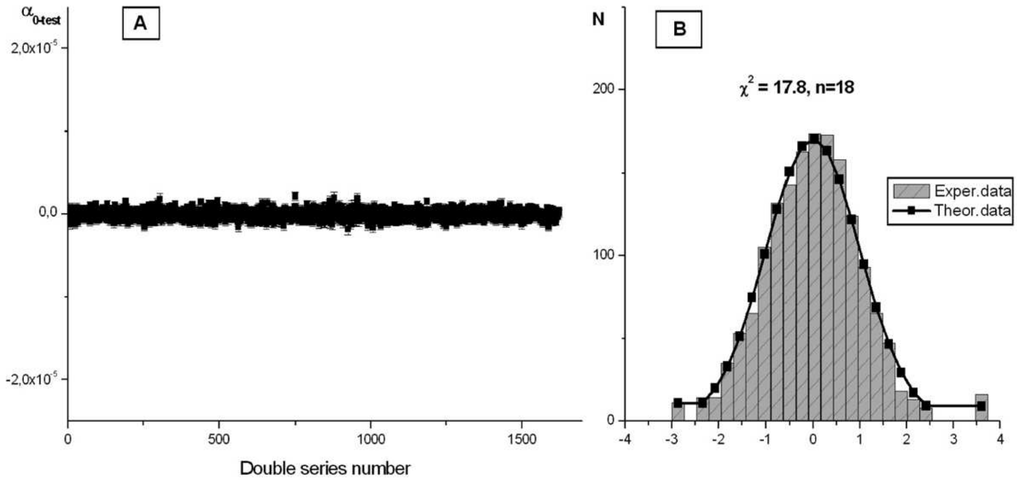

Fig. 6. (A) The results of the "0-test" measurement normalized by constant signals in the main measurements; the sign of the guiding magnetic field is taken into account $\alpha_{0\text{-test}} = \alpha_0(\rightarrow) - \alpha_0(\leftarrow)$. (B) Corresponding histogram of the values distribution compared to the Gauss distribution. All data are taken into account; no 3σ-cut is applied. The χ^2 values and the number of degrees of freedom are given. This experiment was carried out in 2009.

Table 1.

	${}^{\text{raw}}\alpha_{P\text{-odd}}^{^{10}\text{B, exp.}}$	$\alpha_{0\text{-test}}^{^{10}\text{B}}$	$\alpha_{P\text{-odd}}^{^{10}\text{B, exp.}}$	
ILL, 2001-2002	$(2.7 \pm 3.8) \times 10^{-8}$	$-(0.9 \pm 4.8) \times 10^{-8}$	$(3.6 \pm 6.1) \times 10^{-8}$	[6,7]
ILL, 2007	$(3.1 \pm 3.8) \times 10^{-8}$	$(4.2 \pm 7.3) \times 10^{-8}$	$-(1.1 \pm 8.2) \times 10^{-8}$	[19]
ILL, 2009	$-(2.0 \pm 2.5) \times 10^{-8}$	$-(1.3 \pm 1.6) \times 10^{-8}$	$-(0.7 \pm 3.0) \times 10^{-8}$	
Average measured value			$(0.0 \pm 2.6) \times 10^{-8}$	

Table 2.

1) Neutron polarization	$(92 \pm 2)\%$ (*)
2) Left-right asymmetry	$< 10^{-9}$ (**)
3) Stern-Gerlach steering asymmetry	$< 10^{-10}$ (*)
4) ^{8}Li beta decay	$< 9 * 10^{-12}$ (**)
5) False P-odd effect from impurities	$\leq 8 * 10^{-10}$ (*)/(**)
6) P-odd asymmetry in secondary reactions involving α-particles emitted from the studied reaction	$\lvert\alpha_n^{\text{sec}}\rvert < 1.6 \times 10^{-13}$ —for fast neutrons, $\lvert\alpha_\gamma^{\text{sec}}\rvert < 4 \times 10^{-17}$ —for γ-quanta. (**)
7) Asymmetry caused by the difference in energy of emitted γ-quanta	$\lvert\alpha^{\text{Dop}}\rvert \leq 8 \times 10^{-9}$ (**)
8) Electromagnetically induced false effect	$\alpha_{\text{noise}} = (-5.1 \pm 7.1) * 10^{-9}$ (*)
9) "0"-test	$\alpha_{0\text{-test}}^{^{10}\text{B, exp.}} = -(1.3 \pm 1.6) \times 10^{-8}$ (*)

(*) Measured effects.
(**) Estimated effects.

Thus, we obtain the final result

$$\alpha_{P\text{-odd}}^{^{10}\text{B, exp.}} = (0.0 \pm 2.6_{\text{stat}} \pm 1.1_{\text{syst}}) \cdot 10^{-8}. \qquad (30)$$

Discussion and estimation of the weak neutral current constant

One could estimate the weak neutral current constant value using the cluster nuclear model, the measured value (30) of the P-odd asymmetry coefficient in the γ-quanta emission in the reaction ${}^{10}\text{B}(n,\alpha){}^7\text{Li}^* \rightarrow \gamma \rightarrow {}^7\text{Li(g.s.)}$, and the value of the weak charged current constant $h_\rho^0 = -11.4 \times 10^{-7}$, as this has been done in studying the reaction ${}^6\text{Li}(n,\alpha){}^3\text{H}$ [9]. We used eq. (3) and "the best" values of constants $h_\rho^1 = -0.2 \times 10^{-7}$, $h_\omega^0 = -1.9 \times 10^{-7}$ and $h_\omega^1 = -1.1 \times 10^{-7}$ within the DDH theory.

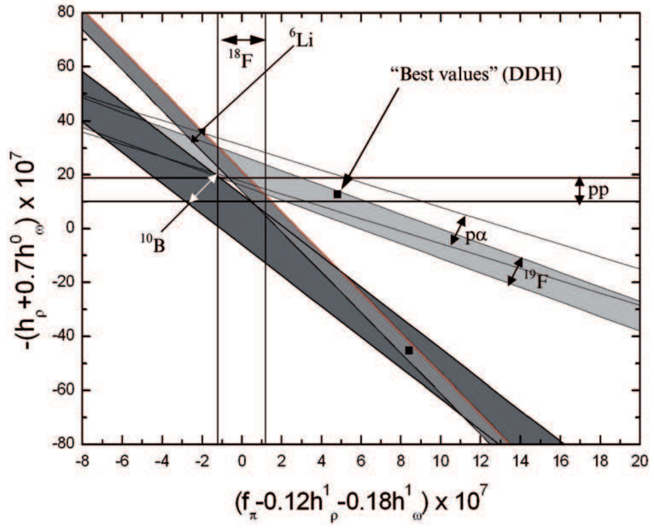

Fig. 7. Experimental constraints for the weak-interaction constants.

Thus, the weak neutral current constant and its uncertainty would be given by

$$f_\pi^{^{10}\mathrm{B}} \approx -(2.0 \pm 1.6) \times 10^{-7}, \quad (31)$$

or, at 90% confidence level

$$f_\pi^{^{10}\mathrm{B}} \le 0.6 \times 10^{-7}. \quad (32)$$

The existing data is sufficiently precise to state that the weak neutral current constant in the reaction $^{10}\mathrm{B}(n,\alpha)^7\mathrm{Li}^* \to \gamma \to {}^7\mathrm{Li}$(g.s.) is smaller than the "best DDH value". As mentioned above, the constraint for the weak neutral constant obtained in the reaction with ^{6}Li [9] in the cluster model framework [8] $f_\pi^{^6\mathrm{Li}} \le 1.1 \times 10^{-7}$ is also smaller than the "best DDH value". Finally, we conclude that the two measured constraints (with ^{10}B and ^{6}Li) for the weak neutral constant agree with each other but contradict the "best DDH value" $f_\pi = 4.6 \times 10^{-7}$.

Figure 7 shows a plot of constraints for the weak-interaction constants following from different experiments. We used a diagram from ref. [20] updated by new data measured in the reactions $^6\mathrm{Li}(n,\alpha)^3\mathrm{H}$ and $^{10}\mathrm{B}(n,\alpha)^7\mathrm{Li}^* \to \gamma \to {}^7\mathrm{Li}$(g.s.) treated in accordance with the cluster model. As it is seen in fig. 7, our data agree well with the results of other experiments; we suppose that the application of the cluster model is justified.

Conclusion

We measured the P-odd asymmetry in γ-quanta emission in the reaction $^{10}\mathrm{B}(n,\alpha)^7\mathrm{Li}^* \to \gamma \to {}^7\mathrm{Li}$(g.s.) and in "0"-tests using in the last experiment a new method based on the neutron polarization switching with a frequency higher than the frequencies of reactor power fluctuations. This method allowed reducing the asymmetry uncertainty to $\delta \sim 1.4 \times 10^{-7}$ per day, that is compatible to the uncertainty in the P-odd asymmetry in the reaction $^6\mathrm{Li}(n,\alpha)^3\mathrm{H}$, where measurements were carried out using the ionization chamber, in which external non-synchronous components of detector noise are absent [9]. Further significant increase in accuracy due to methodical improvements is not expected.

The resulting value of the P-odd asymmetry coefficient is

$$\alpha_{P\text{-odd}}^{^{10}\mathrm{B,\,exp.}} = (0.0 \pm 2.6_{\mathrm{stat}} \pm 1.1_{\mathrm{syst}}) \cdot 10^{-8}.$$

If the measuring time in new experiments will be as long as 120–150 days, the accuracy would increase twice. Such a measurement would improve the accuracy in the P-odd asymmetry measurement to $\delta \sim 1 \times 10^{-8}$, taking into account the present result. In this case, we might hope to get a non-zero P-odd effect.

We would like to underline that the recent progress in the experimental methods and facilities allows us to reliably measure non-zero asymmetry values of the order of 5×10^{-8}–10^{-7} in reactions of polarized cold neutrons with light nuclei, thus giving access to studies of weak neutral currents. However, we understand limitations of the theoretical models used and invite specialists in the field to contribute to the theoretical analysis of the problem.

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