MEASUREMENT OF THE P-ODD ASYMMETRY OF γ-QUANTA FROM THE $^{10}B(n,\alpha)^7Li^* \to Li$(g.st.) REACTION AT HEIGHTENED FREQUENCY OF NEUTRON POLARIZATION SWITCHING

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Abstract.

We present results of a measurement of P-odd asymmetry α_γ of γ-quanta emission in the nuclear reaction $^{10}B(n,\alpha)^7Li^* \to \gamma \to {}^7Li$(g.st.) with polarized cold neutrons. The experiment was carried out using a new version of the integral measuring method. The frequency of neutron spin-flip is higher in this method than the typical reactor power noise frequency; this condition decreases experimental uncertainties. The result is $\alpha_\gamma = (0.8 \pm 3.9)\cdot 10^{-8}$; the results of previous experiments and a "zero" experiment are taken into account. Using this value, we constrain the neutral current coupling constant in the framework of the cluster consideration for light nuclei $f_\pi \leq 2.4\cdot 10^{-7}$ (at 90% c.l.). This constraint does not contradict the estimation obtained from the P-odd asymmetry in the reaction $^6Li(n,\alpha)^3H$: $f_\pi \leq 1.1\cdot 10^{-7}$. However, both these constraints contradict the DDH "best value" of $f_\pi = 4.6\cdot 10^{-7}$.

Introduction.

The main prediction of the standard model of electroweak interactions is the weak neutral current. The parity violation in the nucleon-nucleon interaction in various processes with few-nucleon systems and nuclei has to include both charged and neutral currents. The weak neutral current however has not yet been observed in such interactions.

The nuclear reaction of light nuclei (A = 6-10) with polarized slow neutrons is probably the most promising candidate for the study of weak neutral current properties in nucleon-nucleon (NN) processes. Such nuclei could be described in the framework of cluster and multi-cluster models [1, 2], if the excitation energy is < 25-30 MeV. P-odd effects could thus be estimated at least for the nuclear reactions with ^{10}B and ^6Li.

Using this method the authors of refs. [3, 4] have calculated the P-odd asymmetry of γ-quanta emission in the transition $^7Li^* \to {}^7Li + \gamma$, $E_\gamma = 0.478$ MeV resulting from the reaction $^{10}B(n,\alpha)^7Li$ with polarized cold neutrons (Fig. 1.). The P-odd asymmetry can be presented in terms of the meson exchange constants [4]:

$$\alpha_\gamma = 0.16 f_\pi - 0.028 h_\rho^0 - 0.009 h_\rho^1 - 0.014 h_\omega^0 - 0.014 h_\omega^1 \ . \qquad (1)$$

Here f_π corresponds to π-meson exchange, i.e. the weak neutral current. The calculation of the asymmetry using expr. (1) and the "best values" of the meson exchange constants [5]

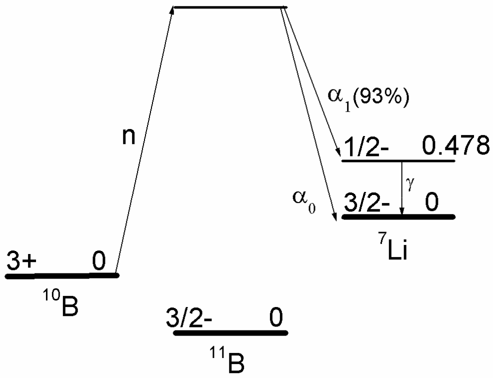

Fig. 1. Scheme of the ^{10}B(n,α)^{7}Li reaction with slow neutrons.

yields the value: $\alpha_\gamma = 1.1\cdot10^{-7}$. Note that it is dominated by f_π and would be equal to $\alpha_\gamma = 3\cdot10^{-8}$ if the weak neutral constant is zero. Two previous experiments (with a total measuring time of 47 days [6, 7]) have provided a P-odd asymmetry value in the ^{10}B(n,α)^{7}Li* → γ → ^{7}Li(g.st.) reaction equal to $\alpha_\gamma = (2.7 \pm 3.8)\cdot10^{-8}$.

The P-odd effect in the nuclear reaction ^{6}Li(n,α)^{3}H has also been calculated [8] in terms of the meson exchange constants

$$\alpha_t \approx -0.45 f_\pi + 0.06 h_\rho^0 \qquad (2)$$

and measured in ref. [9, 10]: $\alpha_t = (-8.6 \pm 2.0)\cdot10^{-8}$. If the charged weak constant were equal to the DDH "best value" of $h_\rho^0 = -11.4\cdot10^{-7}$, the weak neutral constant would be equal to $f_\pi \approx (0.4 \pm 0.4)\cdot10^{-7}$, or, at 90% confidence level, to $f_\pi < 1.1\cdot10^{-7}$. However, this value is smaller than the DDH "best value" $f_\pi = 4.6\cdot10^{-7}$ [5]. This contradiction could be verified independently if the asymmetry α_γ for ^{10}B could be measured more precisely.

Experiment.

In the light of the above, we have carried out another experiment on the PF1B beam of polarized cold neutrons [11] at the Institut Laue-Langevin (ILL) in Grenoble, France. A typical scheme of experiment is shown in Fig. 2. The average neutron wavelength at the PF1B was $<\lambda_n> = 4.7$ Å. The neutron beam cross-section at the sample position was 80 × 80 mm. The total neutron flux at the sample was equal to ~ $3\cdot10^{10}$ c^{-1}. The neutron polarization was P = (92±2)%. The neutron spin $\vec{\sigma}_n$, the γ-quantum momentum $\vec{p}_\gamma$, and the neutron momentum $\vec{p}_n$ were set as follows: $\vec{\sigma}_n \| \vec{p}_\gamma \perp \vec{p}_n$. The P-odd effect could be observed in the asymmetry of the angular distribution of the γ-quanta emission:

$$\frac{dN_\gamma}{d\Omega} \sim 1 + \alpha_\gamma \cos\theta \ , \qquad (3)$$

where θ is the angle between the neutron spin and the γ-quantum momentum.

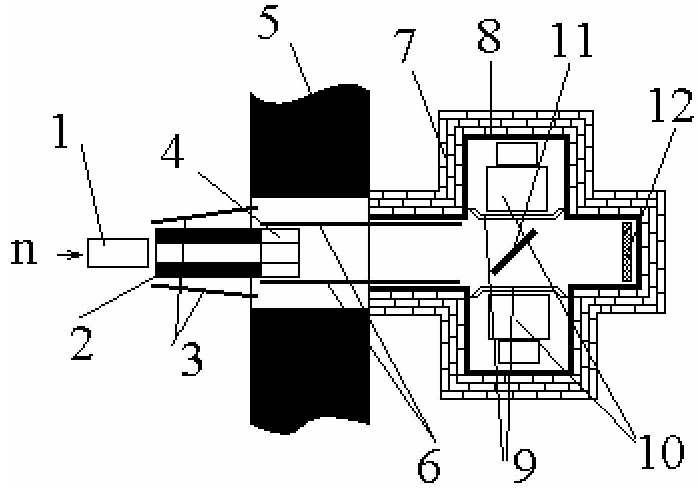

Fig. 2. A typical scheme of experiment: 1-polarizer; 2-adiabatic spin-flipper; 3,6-magnetic plates of guide field; 4-lead collimator; 5-concrete wall; 7-lead shield, 8-B4C-shield; 9-Helmgoltz coils; 10-detectors; 11-sample; 12-Li beam stop

The magnetic field guiding the neutron spin and the γ-quantum momentum was set parallel to each other with an accuracy of 10^{-2} sr. This is sufficiently precise, as the left-right asymmetry in the γ-quantum emission is zero [12]; it does not therefore contribute to the P-odd effect.

We used two detectors in the electric current mode and a method to compensate for any possible false effects described in refs. [13]. The guiding magnetic field is produced by Helmholtz coils; it is reversed periodically during the measurement.

The sample was produced from an amorphous powder ^{10}B; its isotopic purity was 85%. It was enclosed in an aluminium case measuring 160×180×5 mm. The sample was covered with an aluminium foil 14 μm thick on the neutron entrance side. The total sample weight was 50 g. The sample was installed in the centre of the neutron beam; the angle between the neutron beam axis and the sample surface was 45°. Most of the neutrons were absorbed by the sample; an absorption event results in the emission of an α-particle and 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 thickness of 100 mm. "Hamamatsu" S3204-03 photodiodes sized 18×18 mm were used to detect scintillation photons. The detectors were inserted into aluminium-alloy cases placed symmetrically on two opposite sides of the sample. The setup was surrounded with lead protection 15 cm thick. The internal surface of the lead shielding was covered with borated rubber or a polyethylene cover. The polarizer and the spin-flippers were protected by boron collimators. The detectors were protected with boron rubber. We used boron for the protection, but avoided ^{6}Li, as the β-decay asymmetry of ^{8}Li (the energy of 12-14 MeV results from a 10% admixture of ^{7}Li) is as high as $\alpha_{P-odd}^{^8Li} \sim 3\%$ [14]. This could compromise the results with a false P-odd effect. Background scattering (with no sample) was found to be as low as 5% compared to scattering by the sample. Neutron absorbtion in other-than-sample materials does not produce P-odd asymmetry of γ-quanta emission as the neutron scattering is nearly completely incoherent.

A new version of the integral measuring method was first used to measure P-odd asymmetry in ref. [15]: the frequency of neutron spin flip was higher than the typical frequency of the reactor power noise.

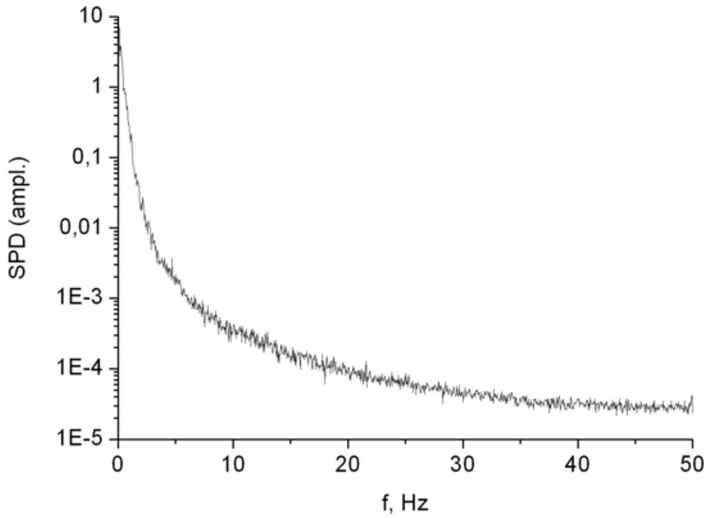

Fig. 3. SPD is a spectral density of the ILL reactor power fluctuations (in a.u.) as a function of frequency.

Fig. 3 shows the spectral density of the noise of the reactor power as a function of frequency f measured during the experiment at PF1B. Analogous distributions have been measured previously in experiments at other reactors [16]. It has been shown (ref. [16]) that uncertainty in the asymmetry measurement is only due to frequencies higher than the frequency of spin-flip. 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 γ-detectors, as the photodiode sensitive area is much smaller than the diameter of an NaI(Tl) crystal; we therefore had to enhance the electronic signals significantly in order to measure them. This caused a "microphone effect" in an electronic channel because of the mechanical vibration of the preamplifiers. The effect varies with the different electronic channels. It is therefore not subtracted by the measuring procedure described in refs. [13]. Spin-flipping with high frequency "cuts" the low-frequency non-correlated frequency of two signals and therefore reduces the corresponding uncertainty. In order to suppress the microphone effect, we built a new electronic system to measure current. It is adapted to the neutron spin-flip frequency of 0.01-50 Hz. The uncertainty of measurement of the P-off effect in the $^{10}B(n,\alpha)^7Li^* \rightarrow \gamma \rightarrow {}^7Li(g.st.)$ is shown in Fig. 4 as a function of neutron spin flip frequency. One can see that this method reduces uncertainties in single channels as well as in the subtracted signal. The decrease in uncertainty is due to the suppression of the "microphone effect".

Additionally, new system were tested with a ^{137}Cs γ-source (Fig. 5.). It should give homogeneous distribution of spectral density – "with noise". However, Fig. 5. shows a declination of spectral density for frequency more then ~ 50 Hz. The reason of it is that the system detector + preamplifier is not ideal current to voltage converter, but it works as low pass filter.

In main measurements the frequency of neutron spin flip was equal to 5 Hz. The measurements were carried out in series of ~4 minutes. In order to reduce the effects of apparatus asymmetry and radio noise, we reversed the direction of the guiding magnetic field at the sample in every series using Helmholtz coils.

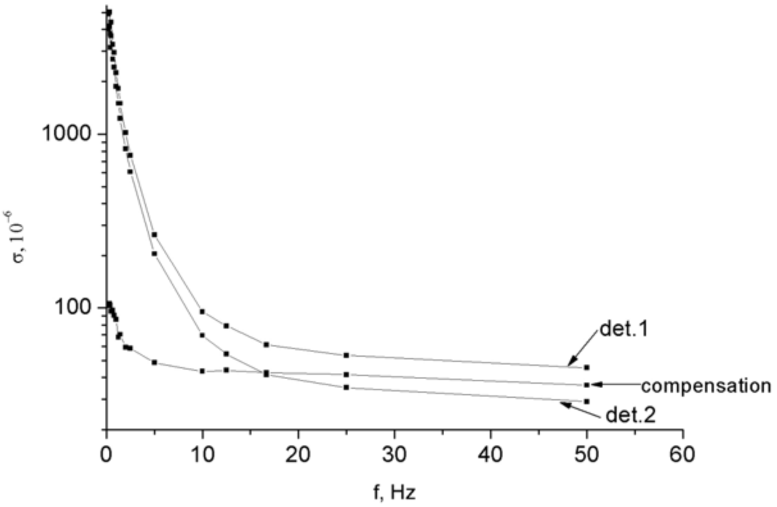

Fig. 4. The uncertainty σ of the measurement of the P-odd effect in the reaction $^{10}B(n,\alpha)^7Li^* \rightarrow \gamma \rightarrow {}^7Li(g.st.)$ as a function of the frequency of the neutron spin flip:
det.1, det. 2 – the uncertainty of the asymmetry measurement for the detectors 1, 2;
"compensation" – the uncertainty of the measurement of the subtracted signal (the reactor power fluctuations are compensated) multiplied by $*\sqrt{2}$ (for comparison with single channels).

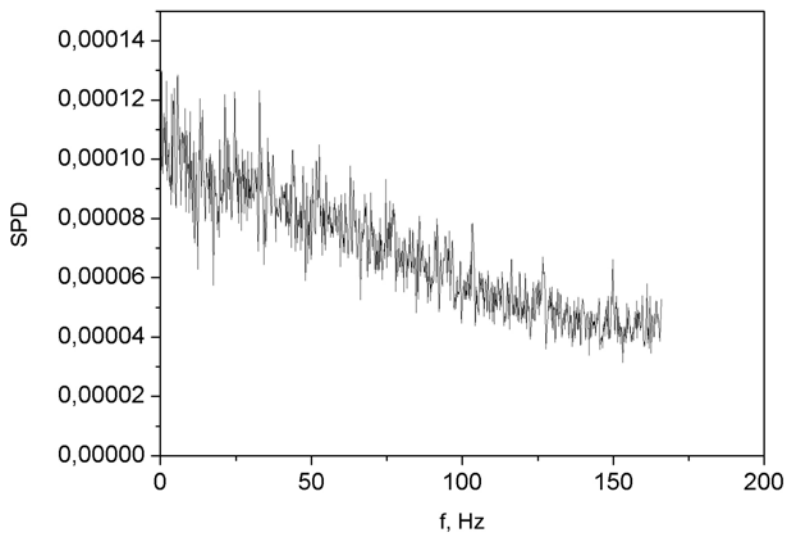

Fig. 5. SPD of signal from the ^{137}Cs source

We measured an equal number of series for two field directions in analogy to ref. [9].This reversed the neutron spin and the sign of the measured asymmetry respectively. The subtracted signal thus 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 also used the scheme of compensation for reactor power fluctuations.

After measuring the asymmetry for ~20 days we obtained the following result

$$\alpha_\gamma = (3.1 \pm 3.8) \cdot 10^{-8}.$$

It is corrected for the neutron beam polarization P and for the average cosine of the detection angle θ: $P\langle\cos\theta\rangle$ = 077. Table 1 shows the P-odd asymmetry values in the reaction $^{10}B(n,\alpha)^7Li^* \to \gamma \to ^7Li(g.s.)$ measured during two ILL runs (no cut for the data applied).

Table 1. $\alpha_{P-odd}^{^{10}B}$ asymmetry values measured during 2 runs at the ILL.

Run	$\alpha_{P-odd}^{^{10}B}$	Ref.
2001-2002	$+(2.7\pm3.8)\cdot10^{-8}$	[6, 7]
2007	$+(3.1\pm3.8)\cdot10^{-8}$	
Average	$+(2.9\pm2.7)\cdot10^{-8}$	

Test experiments.

An appropriate "zero" experiment is described in [10] for measurements with ^{6}Li. Aluminium foil was used to cover the sample, to prevent the charged particles penetrating from the sample to the ionization chamber. We cannot carry out an analogous experiment in the integral current mode with a ^{10}B sample, as the γ-quanta from the neutron reaction with boron cannot be separated from those from other reactions with impurity nuclei. We therefore performed two other kinds of test experiment.

One test consisted in performing measurements with an aluminium foil covering the sample, or with no sample in the neutron beam. In these circumstances the neutrons interact with the material behind the sample position and produces mainly γ-quanta (in the main experiment the neutrons are otherwise absorbed by the sample). This is not a true "zero" test, but a check for false P-odd asymmetry related to the construction material of set-up. The statistical accuracy of such measurements is not higher than in the main experiment. The measurement with the aluminium foil provided the result:

$$\alpha_{test}^{0} = (0.6 \pm 4.0)\cdot10^{-8}.$$

The second test involves replacing the ^{10}B sample with a different target sample which has high neutron scattering cross section and low (n,γ) cross section. The scattered neutrons can be absorbed by the apparatus materials and emit γ-quanta. If γ-quanta emission in impurities in the apparatus materials is P-odd asymmetric, the corresponding false P-odd asymmetry is greatly enhanced (thanks to the highly enhanced flux of the scattered neutrons). Graphite is an "ideal" scatterer. Its absorption cross-section is $\sigma_{n\gamma} = 3.8\cdot10^{-3}$ b; its scattering cross-section is σ_S = 4.8 b. We used a target of natural graphite scattered ~43% neutrons; these scattered neutrons were absorbed by the apparatus materials. 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

$$\alpha_{test}^{graph} = (1.7 \pm 1.9) \cdot 10^{-6}.$$

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

$$\alpha_{scatB} = (2.7 \pm 3.0) \cdot 10^{-9} .$$

As it is seen, the corresponding correction is small.

Besides, ~0.002 of neutrons scatters in the air in the vicinity of the sample. An additional false effect, in analogy to the estimation for boron scatter, is equal to:

$$\alpha_{scat.air} = (3.5 \pm 3.9) \cdot 10^{-8} .$$

This is the most significant possible admixture to the measured P-odd effect.

The estimation resulting from the "zero" experiment is:

$$\alpha_0^{tot} = (2.1 \pm 2.8) \cdot 10^{-8} .$$

The false P-odd effect caused by eventual impurities in the ^{10}B sample is estimated at

$$\alpha_{imp}^{est} < 10^{-8} .$$

The small size of this effect is explained by the large cross-section of neutron absorption, the small fraction of impurities (~10^{-5}), and the small asymmetry values of the reactions with the impurities.

We also measured the possible false P-odd effect caused by parasite electromagnetic signals. The effect was small in all measurements:

$$\alpha_{noise} < 10^{-8} .$$

Results and discussion.

Finally, the coefficient of P-odd asymmetry is equal to:

$$\alpha_{\gamma} = (0.8 \pm 3.9) \cdot 10^{-8} ,$$

taking into account the background/test measurements.

Using this value, eq. (1) and supposing that other weak coupling constants are equal to the DDH "best values", we estimated the weak π-meson constant in a fashion similar to our estimations in ref. [10]:

$$f_{\pi} = -(1.5 \pm 2.4) \cdot 10^{-7} ,$$

or, at 90% confidence level:

$$f_{\pi} < 2.4 \cdot 10^{-7}.$$

We intend to increase the accuracy in future experiments, taking advantage of the new system of measurement of detector current, which provides experimental uncertainty close to the best possible statistical value. However, the existing data is already sufficiently precise to be able to state that the weak neutral current constant in the reaction ^{10}B(n,α)^{7}Li* → γ → ^{7}Li(g.st.) is smaller than the DDH "best value". As mentioned above, the constraint for the weak neutral constant obtained in the reaction with ^{6}Li [10] in the framework of the cluster model [8] $f_{\pi} < 1.1 \cdot 10^{-7}$ is also smaller than the DDH "best value".

Finally, we can conclude that the two measured constraints (with ^{10}B and ^{6}Li) for the weak neutral constant agree with each other but contradict the DDH "best value" $f_{\pi} = 4.6 \cdot 10^{-7}$.

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