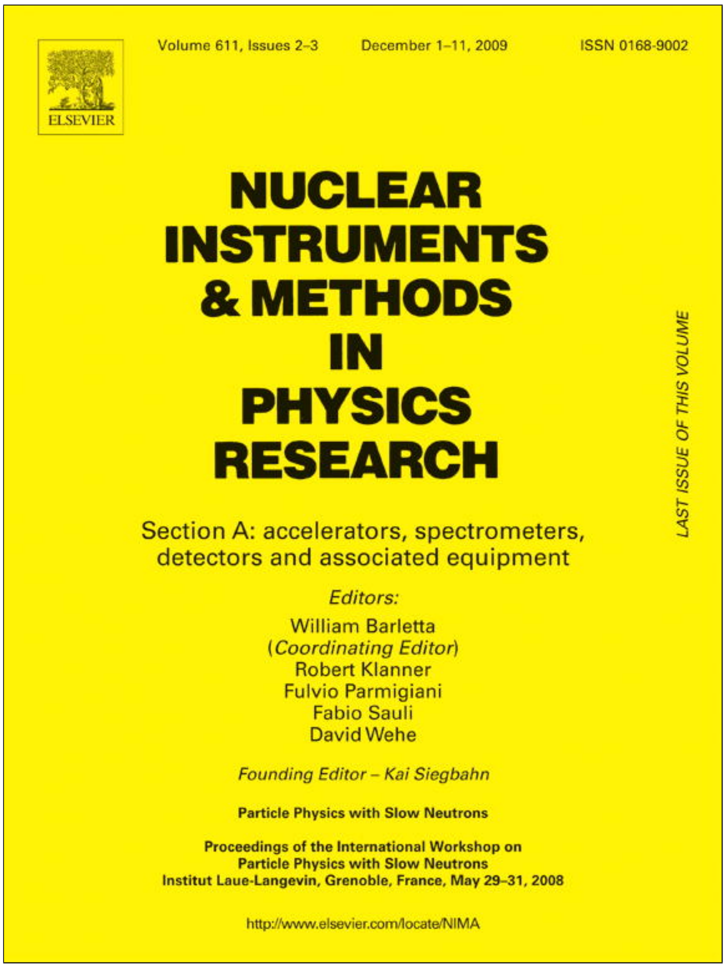

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Measurement of *P*-odd asymmetry of γ-quanta emission in the nuclear reaction ^{10}B(n,α)^{7}Li*→γ+^{7}Li(g.s.)

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ABSTRACT

We present results of measurement of the *P*-odd asymmetry $\alpha_{P\text{-odd}}$ of γ-quanta emission in the nuclear reaction ^{10}B(n,α)^{7}Li*→γ+^{7}Li(g.s.) 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 $\alpha^{^{10}\mathrm{B}}_{P\text{-odd}} = +(0.8 \pm 3.9)\times 10^{-8}$; "zero" experiments are taken into account. Using this value, we constrain the weak neutral current constant in the framework of the cluster model to $f_\pi^{^{10}\mathrm{B}} \leq 2.4\times 10^{-7}$ (at 90% c.l.). This constraint does not contradict the estimation obtained from the nuclear reaction ^{6}Li(n,α)^{3}H: $f_\pi^{^6\mathrm{Li}} \leq 1.1\times 10^{-7}$ (at 90% c.l.). However, both these constraints contradict the "best" value of the Quark model by Desplanques, Donoughe, and Holstein $f_\pi^{\mathrm{DDH}} = 4.6\times 10^{-7}$.

1. Introduction

The main prediction of the standard model of electro-weak interactions is the weak neutral current. The theoretical description of parity violation in nucleon–nucleon interactions in various processes with few-nucleon systems and nuclei includes both charged and neutral currents. However, the weak neutral current has not yet been observed in such interactions.

Reactions of light nuclei ($A = 6$–10) with polarized slow neutrons are probably the most promising candidates to study weak neutral current properties in nucleon–nucleon processes. Such nuclei can 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 ^{6}Li.

Using this method, the authors of Refs. [3,4] have calculated the *P*-odd asymmetry of γ-quanta emission in the reaction

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

resulting from the reaction

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

with polarized cold neutrons. The *P*-odd asymmetry can be presented in terms of meson exchange constants [4]:

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

Here f_π corresponds to π-meson exchange, i.e. the weak neutral current. Using the "best values" for the exchange constants according to the quark model by Desplanques, Donoughe and Holstein (DDH) [5], Eq. (3) yields

$$^{\mathrm{DDH}}\alpha^{^{10}\mathrm{B}}_{P\text{-odd}} = 1.1\times 10^{-7}. \tag{4}$$

Note that this asymmetry is dominated by f_π and would be equal to $\alpha^{^{10}\mathrm{B}}_{P\text{-odd}} = 0.3\times 10^{-7}$, if the weak neutral constant is zero. Two experiments with a total measuring time of 47 days [6,7] have provided the *P*-odd asymmetry value

$$\alpha^{^{10}\mathrm{B}}_{P\text{-odd}} = (2.7 \pm 3.8)\times 10^{-8}. \tag{5}$$

The *P*-odd effect in the nuclear reaction

$$^6\mathrm{Li}(n,\alpha)^3\mathrm{H} \tag{6}$$

has also been calculated [8] in terms of the meson exchange constants

$$\alpha^{^6\mathrm{Li}}_{P\text{-odd}} \approx (0.06 h^0_\rho - 0.45 f_\pi) \approx -2.7\times 10^{-7} \tag{7}$$

and measured in Ref. [9]

$$\alpha^{^6\mathrm{Li}}_{P\text{-odd}} = (-8.8 \pm 2.1)\times 10^{-8} \tag{8}$$

If the charged weak constant were equal to the "best DDH value" of

$$^{\mathrm{DDH}}h^0_\rho = -11.4\times 10^{-7}, \tag{9}$$

the weak neutral constant would be

$$f_\pi^{^6\mathrm{Li}} \approx (0.4 \pm 0.4)\times 10^{-7} \tag{10}$$

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or, at 90% confidence level

$$f_\pi^{^6\mathrm{Li}} < 1.1\times 10^{-7}. \tag{11}$$

However, this value (9) is smaller than the "best DDH value" [5]

$$f_\pi^{\mathrm{DDH}} = 4.6\times 10^{-7}. \tag{12}$$

This contradiction could be verified independently if the asymmetry $\alpha_{P\text{-odd}}^{^{10}\mathrm{B}}$ is measured more precisely.

In the light of the above, we have carried out another measurement of $\alpha_{P\text{-odd}}^{^{10}\mathrm{B}}$ at the polarized cold neutron beam facility PF1B [10] at the Institut Laue-Langevin (ILL) in Grenoble, France. The average neutron wavelength at PF1B was $<\lambda_n> = 4.7\,\mathrm{Å}$. The neutron beam cross-section at the sample position was 80×80 mm, the total neutron flux at the sample $\sim 3\times 10^{10}\,\mathrm{s}^{-1}$, and the neutron polarization $P = (92\pm 2)\%$.

The detectors for the γ-quanta were placed symmetrically to the sample, at the left and the right of the transversally polarized neutron beam. This provides the following average orientation between neutron spin $\vec{\sigma}_n$, γ-quantum momentum $\vec{p}_\gamma$, and the neutron momentum $\vec{p}_n$:

$$\vec{\sigma}_n \| \vec{p}_\gamma \perp \vec{p}_n. \tag{13}$$

The magnetic guiding field for the neutron spin was created by Helmholtz coils. The accuracy of the orientation between field and detector axes was 10^{-2} sr. This is sufficient, as the left–right asymmetry in the γ-quantum emission is zero [11]; it does not therefore contribute to the P-odd effect.

The P-odd effect was observed in the asymmetry of the angular distribution of γ-quanta emission

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

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

We used two detectors in the electric current mode and a method to compensate for possible false effects described in Ref. [12]. The magnetic guiding field was 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 aluminum case measuring $160\times 180\times 5\,\mathrm{mm}^3$. The sample was covered with an aluminum foil 14 μm thick on the neutron entrance side. The total sample weight was 50 g. The sample was installed at 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. The distance between the sample centre and the centre of each detector was 75 mm.

Each γ-quanta detector consisted of an NaI(Tl) scintillator with a diameter of 200 mm and a thickness of 100 mm and a "Hamamatsu" S3204-03 photodiode sized $18\times 18\,\mathrm{mm}^2$, used to detect scintillation photons. The detectors were inserted into aluminum-alloy cases. 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-flipper were protected by boron collimators. The detectors were protected with boron rubber. We used boron for the protection, but avoided ^{6}Li, which typically contains an admixture of 10% ^{7}Li. The β-decay asymmetry of ^{8}Li (β endpoint energy 16 MeV) is as high as $\alpha_{P\text{-odd}}^{^8\mathrm{Li}} \sim 3\%$ [13]. 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 absorption in materials other than the sample does not produce P-odd asymmetry of γ-quanta emission as neutron scattering is nearly completely incoherent.

A new version of the integral measuring method was first used to measure the P-odd asymmetry in Ref. [14]; the frequency of neutron spin-flip was higher than the typical frequency of the reactor power noise.

Fig. 1 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 [15]. It has been shown [15] 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 can generally be suppressed.

A significant fraction of light is lost in the γ-detectors, as the photodiode-sensitive area is much smaller than the diameter of the NaI(Tl) crystal; we therefore had to amplify the electronic signals significantly in order to measure them. This caused a "microphone effect" in the electronic channels because of the mechanical vibration of the preamplifiers. The effect varies with different electronic channels. It is therefore 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 to measure the current. It is adapted to neutron spin-flip frequencies of 0.01–50 Hz.

The uncertainty of measurement of the P-odd effect in the nuclear reaction (1) is shown in Fig. 2 as a function of the neutron spin-flip frequency. One can see that increasing the spin-flip frequency reduces uncertainties in the single channels as well as in the subtracted signal. The decrease in uncertainty is due to the suppression of the "microphone effect".

The measurements were carried out in series of ~4 min. During standard data taking, the frequency of neutron spin-flip was 5 Hz. In order to reduce the effects of apparatus asymmetry and noise from the radio-frequency flipper, we reversed the direction of the guiding magnetic field at the sample in every series using the Helmholtz coils. We measured an equal number of series for the two field directions in analogy to Ref. [16]. This reversed the neutron spin and the sign of the measured asymmetry, respectively. The subtracted signal thus corresponds to the double asymmetry; in contrast, apparatus-related false asymmetries are

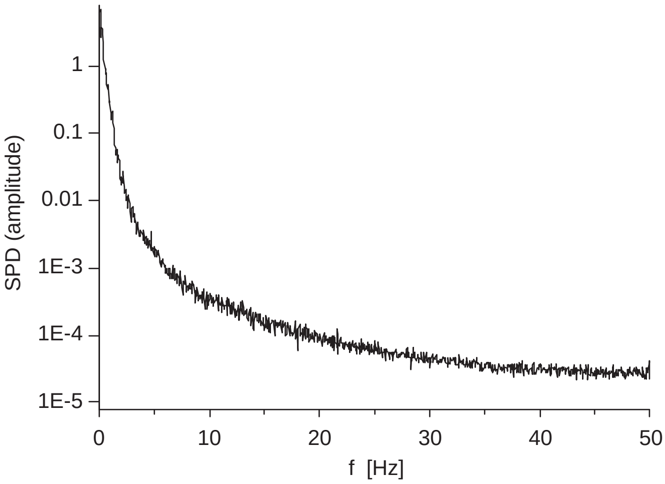

Fig. 1. Spectral density (SPD) of the ILL reactor power fluctuations (in arbitrary units) as a function of frequency, as measured during the experiment.

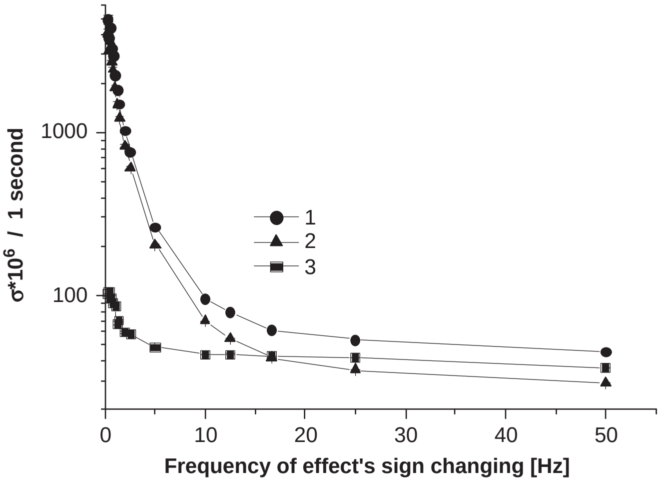

Fig. 2. The uncertainty σ of the measurement of the P-odd effect in the reaction $^{10}B(n,\alpha)^7Li^* \Rightarrow \gamma + ^7Li$(g.s.) as a function of the frequency of the neutron spin-flip. 1,2—uncertainties of the asymmetry measurement for detectors 1 and 2; 3—uncertainty of the measurement of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

subtracted. As the spin-flip frequency was not high enough to minimize the measurement uncertainty (Fig. 2), we also used a scheme of compensation for reactor power fluctuations.

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

$$^{raw}\alpha^{^{10}B}_{P\text{-odd}} = +(3.1 \pm 3.8) \times 10^{-8}. \tag{15}$$

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

$$P\langle\cos(\theta)\rangle = 0.77. \tag{16}$$

Table 1 shows the P-odd asymmetry values in the reaction $^{10}B(n,\alpha)^7Li^* \rightarrow \gamma + ^7Li$(g.s.) measured during two ILL runs (no further corrections to the data applied).

In the nuclear reaction in Eq. (6) with ^6Li [9], a "zero" experiment was carried out. Aluminum foil was used to cover the sample to prevent the charged particles from penetrating into the ionization chamber. We cannot carry out an analogous experiment in the integral current mode with the ^{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 experiments.

One test consisted performing measurements without ^{10}B sample but with only the aluminum foil that normally covers the sample. In this configuration the neutron beam penetrates the material behind the sample position and produces γ-quanta, which is not the case in the measurement with ^{10}B sample. 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 ^{10}B sample. The measurement with the aluminum foil provided the result

$$\alpha^0_{\text{test}} = (0.6 \pm 4.0) \times 10^{-8}. \tag{17}$$

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 by the ^{10}B sample, the false effects are greatly enhanced. Graphite is an "ideal" scatterer. Its absorption cross-section for thermal neutrons is $\sigma_{n\gamma} = 3.8 \times 10^{-3}$ b only, but its scattering cross-section is $\sigma_s = 4.8$ b. A target of natural graphite scattered ~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

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

Run	$^{raw}\alpha^{^{10}B}_{P\text{-odd}}$	Ref.
2001–2002	$+(2.7 \pm 3.8) \times 10^{-8}$	[6,7]
2007	$+(3.1 \pm 3.8) \times 10^{-8}$	This work
Average	$+(2.9 \pm 2.7) \times 10^{-8}$	

$$\alpha^{\text{graphite}}_{\text{test}} = (1.7 \pm 1.9) \times 10^{-6}. \tag{18}$$

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 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:

$$\alpha^{\text{calc}}_{\text{scat.}^{10}B} = (2.7 \pm 3.0) \times 10^{-9}. \tag{19}$$

Obviously, the corresponding correction is small.

Besides, ~0.002 of the neutrons scatter in the air in the vicinity of the sample. The corresponding false effect, estimated in analogy to Eq. (19), is

$$\alpha^{\text{calc}}_{\text{scat.air}} = (3.5 \pm 3.9) \times 10^{-8}. \tag{20}$$

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

The estimation resulting from the different "zero" experiments is

$$\alpha^{\text{total}}_0 = (2.1 \pm 2.8) \times 10^{-8}. \tag{21}$$

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

$$\alpha^{\text{calc}}_{\text{impurity}} < 10^{-8}. \tag{22}$$

The small size of this effect is explained by the large cross-section of neutron absorption in ^{10}B, 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:

$$\alpha_{\text{noise}} < 10^{-8}. \tag{23}$$

Subtracting the result of the "zero" measurement from the average raw asymmetry (Table 1), we obtain the final result

$$\alpha^{^{10}B}_{P\text{-odd}} = (0.8 \pm 3.9) \times 10^{-8}. \tag{24}$$

Using this value, Eqs. (3) and (9), we estimate the weak neutral current constant in a fashion similar to our estimations in Ref. [9]

$$f^{^{10}B}_{\pi} = -(1.5 \pm 2.4) \times 10^{-7}, \tag{25}$$

or, at 90% confidence level

$$f^{^{10}B}_{\pi} < 2.4 \times 10^{-7}. \tag{26}$$

We intend to increase the accuracy in future experiments, taking advantage of the new system of measurement of the detector current, which provides experimental uncertainty close to the best possible statistical value.

However, the existing data are already sufficiently precise to be able to state that the weak neutral current constant in the reaction $^{10}B(n,\alpha)^{7}Li^{*}\rightarrow\gamma+^{7}Li$(g.s.) Eq. (1) is smaller than the "best DDH value" Eq. (12).

As mentioned above, the constraint for the weak neutral constant obtained in the reaction with ^{6}Li [9] in the framework of the cluster model [8], $f_{\pi}^{^{6}Li}<1.1\times10^{-7}$ (Eq. (11)), is also smaller than the "best DDH value".

2. Conclusion

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 "best DDH value" $f_{\pi}^{DDH}=4.6\times10^{-7}$.

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