New search for parity violation in nonresonant neutron scattering on thorium

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The parity-violating longitudinal asymmetry of the neutron scattering cross section has been measured for thorium in the off-resonance energy intervals from 30 to 300 eV. The observed result of $(0.5\pm1.6)\times10^{-6}$ is compared with theoretical predictions.

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The first experimental search for parity violation in nonresonant neutron scattering on thorium was performed by Bowman *et al.* [1] with the result $P_{off}=(0.98\pm2.17)\times10^{-5}$ for the off-resonance longitudinal asymmetry. The experiment established an upper limit for the off-resonance parity-nonconserving (PNC) effect which is three orders of magnitude smaller than the typical PNC-enhanced resonance effect $P\simeq2\times10^{-2}$ [2,3] in thorium *p*-wave resonances. The quantity P_{off} is defined as the fractional difference in the off-resonance cross section σ_+ and σ_- for positive and negative helicity neutrons:

$$P_{off}=(\sigma_+-\sigma_-)/(\sigma_++\sigma_-)\simeq(\sigma_+-\sigma_-)/2\sigma_{pot}, \quad (1)$$

where σ_{pot} is the potential scattering cross section. The definition for the resonance asymmetry P is the same except that the $\sigma^{\pm}$ are the resonance cross sections and the denominator is replaced by the *p*-wave resonance cross section $\sigma_p(E_0)$ at the resonance energy E_0. For low energy neutrons the cross sections σ_{pot} and $\sigma_p(E_0)$ have the same order of magnitude. Therefore the difference between P_{off} and P signifies different parity violation mechanisms acting in compound nuclear states and nonresonant scattering: resonant PNC effects are strongly enhanced while the neutron potential scattering shows no PNC enhancement. Recent experimental results on parity violation in neutron *p*-wave resonances were reviewed by Mitchell, Bowman, and Weidenmüller [4]. Theoretical approaches to the statistical PNC enhancement in compound nuclei were reviewed most recently by Flambaum and Gribakin [5].

Several theoretical studies addressed parity violation in neutron-nucleus potential scattering. Michel [6] and Stodolsky [7] considered a term in the neutron scattering amplitude f' due to the interference between nuclear and weak forces. Applying the DWBA method, Michel obtained the expression $f'=2\epsilon(mR)(kR)R/3$ (we omit an optional nuclear correction factor) with ϵ the dimensionless effective weak interaction parameter, m the nucleon mass (equal to 4.9 fm^{-1}, because natural units $h=c=1$ are used), R the nuclear radius, and k the neutron wave number. Using a particular transformation of the weak interaction single-particle Hamiltonian, Flambaum [8] concluded that the nuclear surface plays the major role in the PNC effect. In our notation his Eq. (14) is $f'=4\epsilon(m/k)f_p(1+f_s/2R)$. This expression simplifies to the above expression of Michel with the choice of strong interaction s- and p-wave amplitudes $f_s=-R$ and $f_p=(kR)^2R/3$, respectively. The kinematical suppression factor (kR) (for thorium $kR=1.82\times10^{-3}\sqrt{E}$, where the neutron energy E is in eV) appears in theoretical approaches and leads to the reduction of the PNC asymmetry P_{off} obtained in a measurement with low energy neutrons relative to the standard value of $\simeq10^{-7}$ for proton-proton scattering. Since the helicity dependent total elastic scattering cross sections are $\sigma_\pm=4\pi|R\pm f'|^2$, for the expected small $(f'\ll f)$ parity violation the asymmetry can be estimated as $P_{off}\simeq2f'/R$.

In addition to the dependence on neutron energy, the value of the PNC effect in the direct neutron-nucleus scattering depends on the effective weak constant ϵ which enters in the anticommutator $V_{pnc}=\epsilon\{(\boldsymbol{\sigma}\mathbf{p}),\rho(r)\}_+$ first obtained by Michel [6]. Here $\mathbf{p}$ is the neutron momentum, σ is twice the

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neutron spin, and $\rho(r)$ is the nucleon density (for simplicity we omit the isotopic-spin dependence of ϵ). This single-particle operator V_{pnc} describes the direct interaction of the neutron with the weak nuclear potential. There is no well established unique theoretical value of ϵ. Starting from the two-body weak interaction, Michel [6] estimated $\epsilon \simeq 2 \times 10^{-8}$ (the current ϵ is Michel's G''). Summarizing numerous approaches to determine the meson-nucleon weak coupling constants, Desplanques [9] recommended the value $\chi \simeq 3.5\times 10^{-6}$ for the parameter χ which describes the strength of the nucleon-nucleus weak force. Conversion from χ to ϵ (according to the relation $\epsilon = 2\pi\chi\rho/m^3$, with ρ the constant nucleon density inside the nucleus) gives $\epsilon \simeq 3.0 \times 10^{-8}$. Flambaum and Gribakin [5] advocated the use of the minimal value $\epsilon_{min} \simeq 1\times 10^{-8}$ for the neutron-nucleus interaction. In the approaches of Refs. [6] and [5] with the ϵ value recommended by Desplanques, the estimate for the longitudinal asymmetry at 100 eV would be

$$P_{off}(\text{theory}) \simeq 0.3\times 10^{-7}. \tag{2}$$

However, the existing wide range of the weak meson-nucleon coupling constants do not absolutely forbid the value of $\epsilon_{max} \simeq 4\times 10^{-7}$, which was suggested in Ref. [10] to explain the anomalous sign effect in the PNC asymmetries of the low energy neutron absorption in thorium [2]. Using the value ϵ_{max}, one obtains the highest theoretical limit

$$P_{off}^{max}(\text{theory}) \leqslant 0.4\times 10^{-6}. \tag{3}$$

In principle, an additional contribution to the asymmetry P_{off} should arise from parity violation in compound-nuclear states through the extended resonance tails. For a given *p*-wave resonance, the corresponding cross section difference $\Delta\sigma_{p,res} = (\sigma_+ - \sigma_-)_{p,res}$ is expected to decrease as $[2(E - E_0)/\Gamma]^2$, where Γ is the resonance total width. Neutron resonances in ^{232}Th are extremely narrow: $\Gamma \simeq 0.025$ eV as compared with the average spacing $D \simeq 17$ eV. With a typical value of $\Delta\sigma_{p,res} \simeq 0.3$ b [3], an estimate of a *p*-resonance contribution to P_{off} for the ''symmetric'' energy position $(E - E_0) = D/2$ between two parity-mixed resonances separated by D is $P_{off} \sim 0.3\times 10^{-7}$. As shown in Refs. [11] and [12], the PNC difference of resonance cross sections changes sign in the region between parity-mixed resonances, with the crossover point determined by the relative size of the total widths of the resonances. The larger values for energies closer to one of the resonances should cancel to first order due to this sign change.

We felt that our recent ^{232}Th data [2], which was obtained with a greatly improved experimental apparatus and good statistics, would permit us to reduce the former upper limit [1] on P_{off} by at least a factor of 10. In the present paper we report the results of the analysis of the PNC longitudinal asymmetries for energies between ^{232}Th resonances. The experimental method makes use of the measurement of the transmission asymmetry ϵ_{pnc} defined by

$$\epsilon_{pnc} = \frac{N_+ - N_-}{N_+ - N_-} = -\tanh\left(\frac{n}{2} f_n(\sigma_+ - \sigma_-)\right) \cong -n f_n \sigma_{pot} P_{off}, \tag{4}$$

where N_+ and N_- are the detector count rates for positive and negative helicity states of the longitudinally polarized neutron beam, n is the number of nuclei per cm^2 in the target, and f_n is the neutron beam polarization. Since the scaling factor between ϵ_{pnc} and P_{off} is $n f_n \sigma_{pot} = 3.16$ for our experiment, the cross section longitudinal asymmetry is obtained from the measured transmission asymmetry as

$$P_{off} = \epsilon_{pnc}/3.16. \tag{5}$$

Measurements were performed by the time-of-flight method at the Manual Lujan Jr. Neutron Scattering Center spallation neutron source [13]. An overview of our early experimental apparatus was given by Roberson *et al.* [14]. Crawford *et al.* [15] described recent improvements to the system. Here we note only details that are relevant for obtaining the asymmetry ϵ_{pnc}. A longitudinally polarized neutron beam was obtained by transmission through a polarized proton target developed by Penttilä *et al.* [16]. The cross sections σ_s and σ_t in the singlet (spin $J=0$) and the triplet (spin $J=1$) scattering states of the neutron-proton system differ considerably with σ_s much larger than σ_t. With the magnetic field at the proton target (and correspondingly the proton spins) aligned along the beam direction, the cross section σ_s leads to strong scattering of the $(-)$ helicity neutrons, and the beam exits the polarized proton target mainly in the $(+)$ helicity state. The neutron spin direction was reversed every 10 s by an adiabatic spin flipper devised by Bowman, Penttilä, and Tippens [17]. The value of the neutron beam polarization depends on the number of protons n_p per cm^2 in the proton target and the proton polarization f_p according to

$$f_n = \tanh[f_p n_p(\sigma_s - \sigma_t)/2], \tag{6}$$

which we used in monitoring f_n-changes by observing the proton polarization signal continuously with a nuclear magnetic resonance technique. The absolute value of the neutron polarization $f_n = 72\pm 4\%$ was determined with the use of the large and well known ^{139}La longitudinal asymmetry $P(E_0 = 0.74$ eV) in a separate measurement with a lanthanum target, as discussed by Yuan *et al.* [18]. The thorium sample thickness was $n = 3.40\times 10^{23}$ nuclei/cm^2.

Neutrons transmitted through the sample were detected at 56.7 m by a large area ^{10}B-loaded liquid scintillation detector, as described by Yen *et al.* [19]. The scintillator was segmented into 55 cells with each cell viewed by a photomultiplier. It was important to discriminate against the single photoelectron pulses from photomultipliers. However, it was impractical to use 55 multiscalers. Therefore the signal processing circuit was designed to operate in a hybrid digital-current mode. The photomultiplier signals were individually discriminated by 300-MHz discriminators and then linearly summed in a signal combiner. The voltage output from the signal-combiner was digitized by a transient recorder with

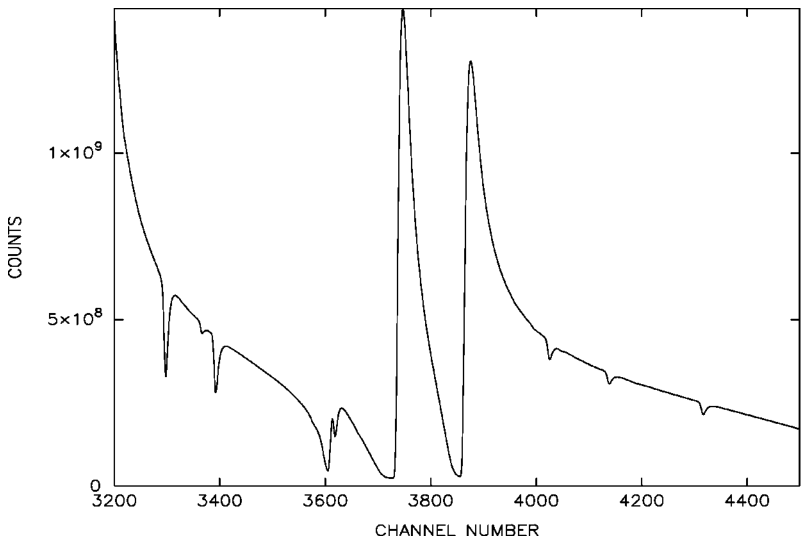

FIG. 1. Time-of-flight spectrum of thorium in the energy range 83–164 eV. The detector counts are the transient recorder readings with a channel width of 100 ns.

the associated data acquisition electronics which provided time-of-flight analysis in 8192 channels. In order to determine the ratio between the transient recorder readings (corresponding to the current from the detector) and the number of true neutron captures in the detector, we measured the amplitude to digital conversion ratio (ADC)—the response of the transient recorder to the known frequency of pulses generated with a pulser. The result (ADC=21.4) was in agreement with analysis of the statistical fluctuations of the current and with direct measurement of the count rate using a multiscaler which was performed at reduced beam intensity. The N_+ and N_- detector yields in 8192 channels of 100 ns width were accumulated in 30-min ''runs'' and stored on a disk in nonflipped and flipped data areas. For this analysis, 147 runs selected as good data were summed in two areas of one file for subsequent analysis using Eq. (4).

The analysis was performed for neutron energies between 30 and 300 eV. The available energy interval was limited at low energy by the finite number of time-of-flight (TOF) channels and at high energy by resolution-broadening of the resonances. An example of the measured time-of-flight spectrum for the region between 3200 and 4500 channels is shown in Fig. 1. To define off-resonance intervals for the analysis, we excluded regions around all *p*-wave and *s*-wave resonances. This procedure was straightforward for narrow *p*-wave resonances. For *s*-wave resonances interference minima and maxima extended outside the standard resonance shape, that is broad structures appear due to interference between the resonance and potential scattering amplitudes, which makes the total cross section different from the potential cross section in limited regions on both sides of the *s*-wave resonance. Therefore regions around *s*-wave resonances were excluded when the observed cross section differed from the potential cross section by two barns or more (the value of the potential cross section for ^{232}Th is 12.9 b [20]). After this selection process, there remained some relatively broad intervals and several narrow TOF intervals of about 30 channels each. The integrated count rate in each of the smaller intervals was about $\sim 10^9$. We chose this number as a unit for our statistical analysis. The broad intervals were subdivided into regions with count rates of about one unit. This procedure yielded 20 intervals with widths of ~ 2 eV at low energy, ~ 5 eV for the middle energies, and ~ 8 eV at high energy. The detector counts N_+ and N_- of data areas for positive and negative helicity states were summed for the channel regions (T_i, T_f), and the transmission asymmetry of Eq. (2) ϵ_{pnc} and its statistical error $\Delta\epsilon_{pnc}$ were calculated for corresponding energy regions (E_i, E_f). The results are listed in Table I.

All measured values are consistent with a zero off-resonance transmission asymmetry within the limits of the statistical accuracy which is $\sim 2.5 \times 10^{-5}$ for an individual data region. At the same level of accuracy, there is no energy dependence in the 20 energy regions analyzed. Therefore we simply calculated the weighted average with the weighting

TABLE I. Nonresonance longitudinal transmission asymmetries ϵ in ^{232}Th.

Region	E_i (eV)	E_f (eV)	T_i	T_f	$10^5\epsilon_{pnc}$	$10^5\Delta\epsilon_{pnc}$
1	30.71	32.89	7400	7150	2.51	2.32
2	33.36	36.36	7100	6800	-2.62	1.94
3	38.59	40.79	6600	6420	1.50	2.24
4	41.30	43.73	6380	6200	1.30	2.11
5	50.83	52.83	5750	5640	-2.04	2.16
6	52.85	54.56	5639	5550	0.73	2.24
7	54.57	56.57	5549	5450	1.57	1.96
8	81.12	89.15	4550	4340	-3.18	2.21
9	90.81	96.55	4300	4170	-1.30	2.30
10	105.70	109.23	3985	3920	-2.40	2.28
11	109.29	111.21	3919	3885	1.20	2.49
12	116.23	117.77	3800	3775	-0.21	2.52
13	136.96	143.43	3500	3420	-1.17	2.60
14	155.91	161.76	3280	3215	1.57	1.90
15	179.54	187.53	3056	2990	4.43	2.84
16	213.77	218.89	2800	2767	-1.14	2.42
17	243.14	248.78	2625	2595	3.78	2.34
18	255.61	260.45	2560	2536	-1.45	3.54
19	274.52	282.44	2470	2435	2.17	2.50
20	290.71	299.35	2400	2365	-2.05	3.06

coefficients taken as the inverse statistical variance. The measured value is $\epsilon=(0.16\pm0.52)\times10^{-5}$ with a corresponding chi-squared value per degree of freedom $\chi^2=0.79$. This result is normal from a statistical viewpoint, since the probability of observing such a value of χ^2 for the $\nu=19$ distribution is about 70%. Applying Eq. (5) we obtain our final result:

$$P_{off}=(0.5\pm1.6)\times10^{-6}. \tag{7}$$

In conclusion, the measured result represents a more than tenfold reduction in the former [1] upper limit for the off-resonance parity violation. In addition this result is obtained at a higher neutron energy, which is considered to be more sensitive for testing the PNC effect in neutron potential scattering. The effective energy for which the present result was determined is about 100 eV, since the analysis averaged over a nearly equal number of regions above and below 100 eV which have statistically equivalent data. Therefore it is reasonable to compare the experimental result with the theoretical estimates for 100 eV. The observed experimental upper limit is significantly above the highest theoretical limit of Eq. (3). A motivation for performing the present analysis was to test these theoretical estimates. We conclude that the parity violation in the off-resonance scattering has no unexpected enhancement mechanism. Because of the kinematical reduction of the PNC effect in potential scattering, determination of the nonresonant PNC effect has better prospects if performed at a higher energy, e.g., up to 20 keV. The other difficulty is caused by the presence of large *s*-wave resonances that interfere with the potential scattering. Therefore the ideal test would be on targets, such as ^{208}Pb or ^{209}Bi that have no dominating *s*-wave resonances in the energy region of interest.

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