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P-even and -odd asymmetries on ^{117}Sn at the vicinity of the p-resonance E_p=1.33 eV

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Abstract

A self consistent description of angular correlations in neutron induced reactions is required for quantitative analysis of parity violating (PV) and time reversal invariance violating (TRIV) effects in neutron nucleus scattering. The 1.33 eV p-wave compound resonance in ^{117}Sn is one of the few p-wave resonances where enough measurements have been performed to allow a nontrivial test of the internal consistency of the theory. We present the results of a global analysis of the several different asymmetries and angular distribution measurements in (n, γ) reactions on the 1.33 eV p-wave resonance in ^{117}Sn conducted over the last few decades. We show that the compound resonance mixing theory can give an internally consistent description of all observations made in this system to date within the experimental measurement errors. We also confirm the conclusions of previous analyses that a subthreshold resonance in ^{117}Sn dominates correlations related to s-p mixing, and discuss the implications of these results for future searches for TRIV in this system.

I. INTRODUCTION

The angular distributions in (n, γ) reactions on the 1.33 eV p-wave resonance in ^{117}Sn measured in different experiments over the last few decades have been a subject of discussions due to reported inconsistencies in descriptions of experimental data. In 1984, Alfimenkov *et al.* [1] measured the left-right asymmetry in radiative neutron capture at the vicinity of ^{117}Sn 1.33 eV p-wave resonance. One year later this group measured the (n, γ) forward-backward asymmetry [2] at the same resonance. However, the analysis of these data could not consistently describe the experimental results using theoretical descriptions of (n, γ) correlations [3] (see for details [4]). This analysis was revisited by other authors [5, 6], but they also could not consistently describe all observable parameters. It should be noted that in the above analyses a two-level approximation was used with a p-wave resonance at 1.33 eV and a negative s-wave resonance at -29.2 eV (the importance of multi resonance analysis was pointed out in [7]).

In this paper we show that a resonance description of neutron radiative capture [3]

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with three resonances can give an internally consistent description of the experimental data reerred to above. This not only resolves this particular problem for the interpretation of angular correlations in low energy neutron radiative capture, but gives an assurance in the measurements of nuclear spectroscopic parameters required for new experiments in a search for time reversal invariance violation (TRIV) in neutron scattering.

The search for new sources of TRIV is one of the highest priorities in nuclear, particle and astrophysics. New sources of CP/T violation beyond the Standard Model are needed to explain the observed matter-antimatter asymmetry of the universe. Theoretical progress to identify the large number of possible sources for T violation has made it very clear that any single type of T violation search cannot be equally sensitive to all possible mechanisms. Therefore it is important to pursue possible experiments in different systems which can provide sufficient sensitivity to discover something new in physics or to improve the current limits.

One of the possible experiments with a high sensitivity to TRIV is related to neutron scattering at p-wave compound resonances, where TRIV effects can be observed as asymmetry in polarized neutron transmission through polarized nuclear targets. Multiple papers [8–12] have suggested that TRIV searches in complex nuclei have the potential to improve the current experimental limit from electric dipole moment (EDM) experiments for parity-odd (P-odd) and time-reversal -odd (T-odd) interactions beyond the Standard Model (BSM). Also, neutron scattering experiments on complex nuclei can improve on the existing experimental upper bounds on P-even/T-odd BSM interactions by about three orders of magnitude [13, 14]. The opportunity to have different nuclear systems to search for TRIV helps in providing assurance that possible "accidental" cancellation of T violating effects due to unknown structural factors related to the strong interactions in particular systems can be avoided. It may also possess different sensitivity to many possible new sources of T violation BSM [15–18].

The basic approach for TRIV experiments in neutron scattering on heavy nuclei involves the measurement of T-odd correlations in the neutron forward scattering, such as $\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I})$ where $\vec{\sigma}_n$ is the spin of the neutron, $\vec{k}_n$ is the neutron momentum, and $\vec{I}$ is the spin of the nucleus. This correlation violates P- and T- invariance and is free from so-called final state effects, which in other processes may mimic TRIV [8, 9, 11]. These TRIV effects are directly related to the P violating effects by a simple spin dependent factor [19]. P violating effects in n-A resonances in several heavy nuclei were measured by the TRIPLE collaboration at LANSCE a couple of decades ago, following earlier work and discoveries of large amplifications of P-odd effects on p-wave neutron-nucleus resonances at other laboratories (see, for example [20] and references therein). The dozens of measurements of P-odd asymmetries through the neutron helicity dependence of the cross section were analyzed and interpreted in terms of the mixing of opposite parity components of s- and p-resonances through the parity-odd components of the electroweak interaction. For the great majority of the p-wave resonances where large parity-odd asymmetries were measured, however, there is no other experimental data available on other types of angular correlations beyond the P-odd cross section helicity dependence and the p-wave resonance energy and total width. The theory of resonance mixing has implications for both P-even and P-odd observables. Therefore, to determine additional parameters of the resonances, it is useful to expand the range of observables under analysis to include P-even angular correlations and angular correlations in neutron radiative capture.

The 1.33 eV p-wave resonance in the ^{117}Sn nucleus is one of the most interesting candidates for a time reversal test in polarized neutron transmission through a polarized nuclear target, because a rather large P-odd effect has been measured at this resonance. Also, the $I = 1/2$ spin of ^{117}Sn is a great advantage for TRIV test because spin 1/2 systems do not contain admixture of higher degrees tensor polarizations, which can lead to systematic errors in neutron spin interactions and make the buildup of large ensembles of highly-polarized ^{117}Sn nuclei more difficult due to spin relaxation from interaction with electric field gradients. A large value of polarization of ^{117}Sn nuclei can be produced by a new technique called SABRE [21–23]. SABRE involves transfer of the spin order from parahydrogen molecules to another pair of atoms in groups of four atoms with asymmetric spin couplings as the molecules are transiently adsorbed onto certain molecular catalysts. In principle this process can maintain a large steady-state ^{117}Sn polarization over the timescales needed for a TRIV search.

Before presenting our detailed analysis of the data on this system we present a brief summary of some of the long history of this subject and a review of the aspects most relevant to our work.

II. FORMALISM FOR P-ODD AND P-EVEN (N, γ) ANGULAR DISTRIBUTION ON P-WAVE NEUTRON-NUCLEUS RESONANCES.

A. P-odd effects.

Parity-violating effects have been observed since the 1960s in nuclear reaction experiments. The anisotropy in γ-ray emission after the capture of transversely polarized thermal neutrons in ^{113}Cd in the P-odd correlation $\vec{\sigma}_n \cdot \vec{k}_\gamma$ was measured in a pioneering experiment [24] (see also [25]). In this correlation $\vec{\sigma}_n$ is the neutron spin and $\vec{k}_\gamma$ the γ-ray momentum. This P-odd asymmetry was enhanced by a factor of 10^3 compared to the size expected in nucleon-nucleon interactions. In 1980s even larger P-odd effects were measured in transmission of polarized neutrons through heavy nuclear targets (see, for example [20] and references therein), which show the enhancements of P-odd effects by about six orders of magnitude. Flambaum and Shuskov [26, 27], and later Bunakov and Gudkov [10, 28] explained this 10^6 enhancement of P-odd effects as a result of a dynamical and resonance enhancements in the vicinity of compound p-wave resonance. Their formalisms imply that the resonance-resonance mixing makes the most important contribution to the enhanced P-odd effects at very low neutron energies ($E_n \approx 1$ eV or $kR \ll 1$) for medium and heavy nuclei, where the neutron binding energy is approximately equal to the compound nucleus excitation energy. For such low neutron energies it is only necessary to consider s- and p-wave neutron-nucleus resonances (with $l = 0, 1$) [10].

Typical P-odd observables for neutron transmission experiments and (n,γ) reactions are the longitudinal polarization (Eq. 1), the spin rotation angle for transversely polarized neutrons (Eq. 2) and the asymmetry in the emission of γ-rays in the direction $\vec{\sigma}_n$ in radiative capture (Eq. 3):

$$P = \frac{\sigma_{tot}^{-} - \sigma_{tot}^{+}}{\sigma_{tot}^{+} + \sigma_{tot}^{-}} = \left(\frac{1}{2\sigma_{tot}}\right)\frac{4\pi}{k}\mathfrak{Im}(f_{-} - f_{+}), \tag{1}$$

$$\frac{d\phi}{dz} = \frac{2\pi\, N}{k}\mathfrak{Re}(f_{-} - f_{+}), \tag{2}$$

$$\alpha_{n\gamma} = \left(\frac{d\sigma_{n\gamma}^{\uparrow\uparrow}}{d\Omega} - \frac{d\sigma_{n\gamma}^{\uparrow\downarrow}}{d\Omega}\right) \Big/ \left(\frac{d\sigma_{n\gamma}^{\uparrow\uparrow}}{d\Omega} + \frac{d\sigma_{n\gamma}^{\uparrow\downarrow}}{d\Omega}\right), \tag{3}$$

where $\sigma_{tot}^{+(-)}$ is the total cross-section for a neutron beam with positive (negative) helicity $\vec{\sigma}_n \cdot \vec{k}_n$, k is the neutron wave-number, $f_{+(-)}$ is the forward scattering amplitude function for positive (negative) neutron helicity, N is the nuclear number density of the target, and $d\sigma_{n\gamma}^{\uparrow\uparrow(\uparrow\downarrow)}/d\Omega$, the cross section in the direction $\vec{\sigma}_n$ (-$\vec{\sigma}_n$).

To illustrate the mechanism of parity violation in compound resonances we can consider P-odd part of elastic scattering amplitude for transmission of polarized neutron through non-polarized target [29]:

$$\frac{e^{i\delta_p}\gamma_p^n}{\sqrt{2\pi}} \frac{1}{(E-E_p)+i\Gamma_p/2} \langle\Phi_p| V_W |\Phi_s\rangle \frac{1}{(E-E_s)+i\Gamma_s/2} \frac{e^{i\delta_s}\gamma_s^n}{\sqrt{2\pi}}. \tag{4}$$

It shows the capture of the p-wave neutron due to strong interaction with the subsequent p-resonant compound nucleus formation. Under the influence of the P-odd weak interaction (V_W) a mixing transition occurs between resonant compound states with opposite parity of the compound nucleus. This state then decays due to strong interaction.

Considering this mechanism, we can obtain the explicit energy dependence in two-level approximation for Eqs. (1) to (3) [28]:

$$P = \left(\frac{1}{2\sigma_{tot}}\right) \frac{4\pi}{k^2} v \sqrt{\Gamma_s^n \Gamma_p^n}\ \frac{(E-E_s)\Gamma_p + (E-E_p)\Gamma_s}{[s][p]}, \tag{5}$$

$$\frac{d\phi}{dz} = \frac{4\pi N}{k^2} v \sqrt{\Gamma_s^n \Gamma_p^n} \frac{(E-E_s)(E-E_p) - \Gamma_s\Gamma_p/4}{[s][p]}, \tag{6}$$

$$\alpha_{n\gamma} = \left(\frac{1}{2\sigma_{tot}}\right) \frac{4\pi}{k^2} v \sqrt{\Gamma_s^\gamma \Gamma_p^\gamma}\ \frac{\Gamma_s^n(E-E_p) - \Gamma_p^n(E-E_s)}{[s][p]}, \tag{7}$$

with $[s,p] = (E-E_{s,p})^2 + \Gamma_{s,p}^2/4$, the corresponding Breit–Wigner denominators.

In case we have strong resonances close to the considered p- and s-resonances, we have to include them which transforms the above expressions to expressions in a multi-level approximation. Often it is sufficient to consider only one s-resonance which is close to p-wave resonance (two-level approximation). However, if a second s-wave is close to p- or s-ones, the three-level approximation is required.

In 1982 Bunakov and Gudkov also found enhancements for TRIV effects in the transmission of polarized neutrons through polarized targets, which can appear through a neutron-spin-dependent difference in the total cross section and in the neutron spin rotation angle for transversely-polarized neutron transmission. [29, 30]

$$\eta = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = \left(\frac{1}{2\sigma_{tot}}\right)\frac{4\pi}{k}\mathfrak{Im}(f_\uparrow - f_\downarrow)$$
$$= -\left(\frac{1}{2\sigma_{tot}}\right)\frac{2\pi}{k^2}w\sqrt{\Gamma_s^n\Gamma_p^n}\frac{(E-E_s)\Gamma_p + (E-E_p)\Gamma_s}{[s][p]}, \tag{8}$$

$$\frac{d\chi}{dz} = \frac{4\pi N}{k}Re(f_{\uparrow\uparrow} - f_{\uparrow\downarrow})$$
$$= \frac{4\pi N}{k^2}w\sqrt{\Gamma_s^n\Gamma_p^n}\frac{(E-E_s)(E-E_p) - \Gamma_s\Gamma_p/4}{[s][p]}, \tag{9}$$

where w is the TRIV-odd mixing matrix element.

These effects are related P-odd and T-odd triple correlation $\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{I})$ and can be related to the corresponding correlation in the forward neutron elastic scattering amplitude [19, 31]:

$$f = f_0 + f_1\vec{\sigma}_n \cdot \vec{I} + f_2\vec{\sigma}_n \cdot [\vec{k}_n \times \vec{I}] + f_3\vec{\sigma}_n \cdot \vec{k}_n + ... \tag{10}$$

This P-odd and T-odd correlation causes a dependence of the neutron transmission factor on the relative orientation of the neutron spin in the direction $\vec{k}_n \times \vec{I}$ (η) and the precession of the spin with respect to the same direction (χ).

Thus one can see that the above equations show the necessity to measure all the parameters that characterize these low-lying resonances to calculate exact relations between P-odd and TRIV effects. Notice that the former expressions for P-odd and T-odd effects in two-level approximation have exactly the same energy dependence. As a consequence, we obtain [11, 19]

$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_P} = \kappa(J)\frac{w}{v}, \tag{11}$$

In ^{117}Sn ($I = 1/2$) case

$$\kappa(J) = \left[\frac{\sqrt{I}}{2(I+1)}\right]\frac{(-2\sqrt{I}\,x + \sqrt{2I+3}\,y)}{x} \qquad J = I + \frac{1}{2}, \tag{12}$$

for the coupling scheme $\hat{\vec{J}} = \hat{\vec{I}} + (\hat{\vec{l}} + \hat{\vec{s}})$ used in [3], where the total gamma width has two contributions from $j = 1/2$ and $j = 3/2$ p-wave neutron capture channels

$$\Gamma_p^n = \Gamma_{p1/2}^n + \Gamma_{p3/2}^n, \tag{13}$$

and

$$x^2 = \frac{\Gamma^n_{p1/2}}{\Gamma^n_p} \qquad \text{and} \qquad y^2 = \frac{\Gamma^n_{p3/2}}{\Gamma^n_p}. \tag{14}$$

Since $x^2 + y^2 = 1$ we can use the parametrization

$$x = cos(\phi) \qquad \text{and} \qquad y = sin(\phi). \tag{15}$$

Then the knowledge of ϕ in Eq. (15) allows to evaluate the parameter $\kappa(J)$, which relates the P-odd difference of total cross sections $\Delta\sigma_P$ proportional to the correlation $\vec{\sigma}_n \cdot \vec{k}_n$, and the TRIV ones $\Delta\sigma_{PT}$ which are proportional to $\vec{\sigma}_n \cdot [\vec{k}_n \times \vec{I}]$ in neutron transmission experiments to the ratio of corresponding nuclear matrix elements v and w [19]

The parameter $\kappa(J)$ depends only on spin factors therefore, it is clear that TRIV and P-odd effects have the same nuclear enhancement factors. Also, the direct relation between P-odd and TRIV effects shows that any inconsistency in the description of P-odd observables should be resolved to be able to fully understand and design an experiment to search for TRIV effects. With this objective is important to look for consistency in the most studied nuclei with the largest values of measured P-odd effects. At present, there are many measured P-odd and P-even effects in ^{117}Sn which provide detailed spectroscopic information for neutron resonances at very low energies.

If we measure a very large P-odd effect but $\kappa(J)$ is close to be zero, we will not be able to measure T-odd correlation at this resonance. In such a case the TRIV effect is canceled regardless the magnitude of w. But the opposite might be also true: if P-odd effect at the resonance is very small, TRIV effect can be large. Since each p-resonance has a specific value of $\kappa(J)$, for some resonances it might be large, which would make a future experiment on such a resonance more sensitive to the TRIV amplitude of interest. Therefore, before designing the TRIV experiment it is important to find a good nuclear target candidate with both a large P-odd asymmetry and a large value of the parameter $\kappa(J)$. With this objective, it is important to analyze previous experiments to characterize the low-lying p- and s-resonances with the objective to determine the value of ϕ. To achieve this goal, it is important to study P-even angular correlations in (n,γ) reactions on the same neutron resonances, because they are sensitive to the resonance parameters of interest but can possess relatively large asymmetries as they are not suppressed in size by weak interactions.

B. P-even effects in (n,γ) reactions

In 1984 Flambaum and Sushkov developed a theoretical formalism for the description of P-odd and P-even angular correlations in neutron radiative capture at very low neutron energies [3, 6]. With this formalism is possible to obtain the Eq. (7) because it also considers the resonant mechanism as the most important reaction mechanism for low neutron energies and heavy nuclei.

For an unpolarized target and in experiments where the gamma polarization is not measured, this expression becomes [5, 6]

$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{1}{2}\left[a_0 + a_1 \vec{n}_n \cdot \vec{n}_\gamma + a_2 \vec{s}_n \cdot [\vec{n}_n \times \vec{n}_\gamma] + a_3\left((\vec{n}_n \cdot \vec{n}_\gamma)^2 - \frac{1}{3}\right)\right] \\ &= a_0 + a_1 \, cos\,(\theta) + a_2 f_n sin\,(\theta)\, cos\,(\phi) + a_3\left(cos^2\,(\theta) - \frac{1}{3}\right), \end{aligned} \tag{16}$$

where $\vec{n}_{n(\gamma)}$ and $\vec{s}_n$ are unit vectors along the neutron beam (γ emission) and neutron spin direction, respectively, and f_n is the neutron polarization.

Thus for ^{117}Sn, one can define k as the neutron wave-vector, E as the neutron energy, $E_{s(p)}$ as the energy of the s(p)-resonance, $\Gamma_{s(p)}$ as the total width of the s(p)-resonance, and introducing the amplitude of the capture channel of neutrons $\gamma^n_{s(p)} = \sqrt{\Gamma^n_{s(p)}}$ with $l = 0(1)$ or $j = 1/2(3/2)$, and $\gamma^\gamma_{s(p)} = \sqrt{\Gamma^\gamma_{s(p)}}$ is the amplitude of the gamma decay channel of the compound s(p)-state.

It should be noted that the sign of the neutron width amplitude is also an important spectroscopic parameter which can be obtained only from interference terms in angular correlations. There are very few experimental results which determine the signs for the amplitudes associated with these widths for low-lying neutron resonances in any nuclei, and in particular no such information to our knowledge is available for ^{117}Sn. In the three-level approximation case (one p- and two s-resonances), we have an interference term between s-resonances in a_0 of the form [3]

$$\frac{\gamma^n_{s1}\gamma^n_{s2}\gamma^\gamma_{s1}\gamma^\gamma_{s2}\left((E - E_{s1})(E - E_{s2}) + \Gamma_{s1}\Gamma_{s2}/4\right)}{\left[(E - E_{s1})^2 + \frac{\Gamma^2_{s1}}{4}\right]\left[(E - E_{s2})^2 + \frac{\Gamma^2_{s2}}{4}\right]}. \tag{17}$$

Since the sign of every single amplitude in Eq.(17) is an important unknown parameter, the interference term could be positive (constructive interference) or negative (destructive interference).

Past efforts to obtain the signs and values for x and y measuring the P-even asymmetries in (n,γ) reactions using the left-right asymmetry ϵ^{L-R}, the forward-backward asymmetry ϵ^{F-B}, and p-wave angular anisotropy ϵ_p^a [2, 5, 6] were not successful, where:

$$\begin{aligned}\epsilon^{L-R}(E) &= \frac{\sigma(90^0,0^0,E)-\sigma(90^0,180^0,E)}{f_n[\sigma(90^0,0^0,E)+\sigma(90^0,180^0,E)]}\\ &= \frac{a_2}{a_0-a_3/3},\end{aligned} \tag{18}$$

$$\begin{aligned}\epsilon^{F-B}(E,\theta=45^0) =& \frac{\sigma(\theta=45^0,E)-\sigma(\theta=135^0,E)}{\sigma(\theta=45^0,E)+\sigma(\theta=135^0,E)}\\ =& \frac{1}{\sqrt{2}}\frac{a_1}{a_0+a_3/6},\end{aligned} \tag{19}$$

$$\begin{aligned}\epsilon^a(\theta) &= \frac{2\sigma_p(90^0,E_p)}{\sigma_p(\theta,E_p)+\sigma_p(\pi-\theta,E_p)}\\ &= \frac{U_p^2-(a_3/3)}{U_p^2+(a_3/3)\,(3\,cos^2(\theta)-1)}.\end{aligned} \tag{20}$$

From one of these observables we can obtain a pair of absolute values $|x|$ and $|y|$, but not the signs. The correct determination of both the absolute values and the signs should allow one to reproduce experimental values for these three P-even asymmetries.

These P-even asymmetries ϵ^{L-R} and ϵ^{F-B} are related with the P-even correlations in the (n,γ) expression $\vec{s}_n\cdot[\vec{n}\times\vec{\gamma}]$ and $\vec{n}_n\cdot\vec{n}_\gamma$, respectively. The explicit energy dependence of every single expansion coefficient in Eq. (16) can be found in reference [3].

On the other hand, the spectroscopic parameter

$$\begin{aligned}t_\theta^2(E_p) &= \frac{d\sigma_p(\theta,E_p)/d\Omega}{d\sigma_s(\theta,E_p)/d\Omega}\\ &= \frac{U_p^2(E_p)}{U_s^2(E_p)}\left[1+\alpha\left(cos^2(\theta)-\frac{1}{3}\right)\right],\end{aligned} \tag{21}$$

with $\alpha=-(3/\sqrt{2})xy-(3/4)y^2$ characterizes the relative contribution to the total cross section from both the s- and p-resonances measured at the p-resonance energy $\sigma_p(\theta,E_p)/\sigma_s(\theta,E_p)$ [5, 6]. It can be shown that

$$t^2(55^0, E_p) = \frac{U_p^2(E_p)}{U_s^2(E_p)} = \frac{\sigma_p^\gamma(E_p)}{\sigma_s^\gamma(E_p)} \tag{22}$$

and

$$\epsilon_p^a(\theta) = \frac{t^2(90^0, E_p)}{t^2(\theta, E_p)}. \tag{23}$$

Once the parameters of the low-lying resonances involved in the former equations are determined, we can fit the measured P-even asymmetries and should be able to find a unique ϕ value that guarantees consistency with Flambaum-Sushkov formalism.

This analysis can be complicated if there is a nearby subthreshold s-wave resonance that mixes with the p-resonance of interest. This makes the determination of the spectrometric parameters that characterize this state more difficult because of the impossibility of directly measuring this resonance. In the ^{117}Sn case there is no agreement between the reported spectrometric parameters by several authors for this negative s-resonance.

Several authors in the past tried with no success to solve this problem and find this unique ϕ value that guarantees consistency [5, 6]. These analyses were done in a two-level approximation. This problem has not been resolved up to now.

We find that using the Bunakov-Gudkov formalism it is possible to find consistency with measured P-odd effects. In 1991, Gudkov suggested an important contribution to P-even effects from a close and strong enough s-resonance at 38.8 eV [7]. This means that the analysis should be done considering a three-level approximation.

III. EXPERIMENTAL VALUES FOR SPECTROSCOPIC PARAMETERS AND P-EVEN EFFECTS FOR ^{117}SN

The nearest compound resonances to $E_p = 1.33$ eV p-wave resonance in ^{117}Sn are a positive s-resonance at 38.8 eV and a sub-threshold state (a negative s-resonance) [32, 33]. The determination of the spectroscopic parameters of this negative s-resonance is difficult because we cannot directly measure the properties of this state: it can only be inferred from information on the neutron energy dependence of the cross section near zero energy. Furthermore, we find different reported values for the resonance energy of this sub-threshold state in different global data evaluations: -29.2 eV (Table I and Ref. [32]) and -81.02 eV

TABLE I. Spectrometric parameters for ^{117}Sn+n by Alfimenkov (Refs. [36] and [37]) and Mughaghab (Ref. [32])

E_s (eV)	Γ_s^{n0} (meV)	Γ_s (meV)	Γ_s^{γ} (meV)
-29	7.33	100	2.3 ± 0.4
38.80 ± 0.05	0.67 ± 0.02	100	0.6 ± 0.2
E_p (eV)	Γ_p^n (meV)	Γ_p (eV)	Γ_p^{γ} (meV)
1.33 ± 0.01	(2.5 ± 0.2)×10^{-4}	0.148 ± 0.01	1.2 ± 0.3

TABLE II. Values for spectrometric parameters ϵ_p^a and $t_\theta^2(E_p)$ for ^{117}Sn+n by Alfimenkov (Ref. [35]) and Lyapin (Ref. [39]).

$t^2(\theta, E_p)$	θ	$\epsilon_p^a(\theta)$	θ
1.83 ± 0.18	45^0	1.18 ± 0.12	45^0
3.0 ± 0.3	90^0	1.63 ± 0.14	45^0
2.16 ± 0.22	90^0		

(Ref. [33]). The change of the position of the subthreshold resonance from -29.2 eV to -81.02 eV in the 2006 re-evaluation [32, 34] occurred despite the fact that the spectroscopic values for positive resonances had either not changed at all or changed only very slightly. We believe that this shift comes from small changes in how the data fitting procedure was reoptimized to determine some global parameters of interest in nuclear data evaluations such as level densities, Westcott g-factors, and resonance integrals parameters. It is known that in these global evaluations the negative energy resonance parameters often serve the function of "absorbing" some of these changes. Therefore this later change in the inferred value for the subthreshold resonance position in ^{117}Sn appearing in the global data evaluations may have nothing to do with the real properties of the resonance. We therefore choose to rely on data taken close to zero neutron energy, where the effects of the tail of the subthreshold resonance are the largest. Alfimenkov, Lyapin *et al.* measured P-even effects and spectroscopic parameters for these resonances in ^{117}Sn (Tables and Figs. I-II) [1, 5, 6, 35–38] in the low neutron energy regime.

In this paper we conduct an analysis to seek consistency between the theoretical formalism [3] and experimental results for these P-even asymmetries using the spectroscopic

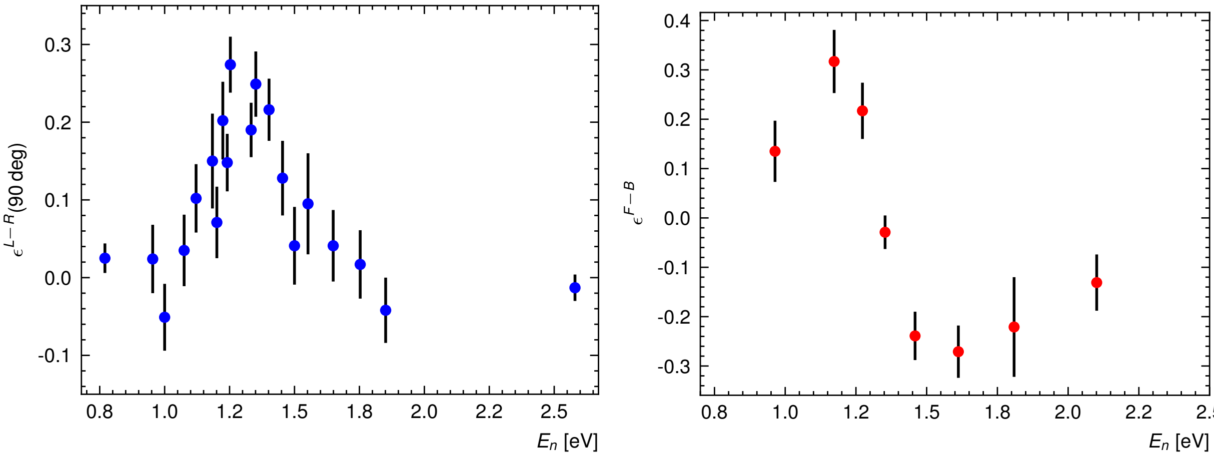

FIG. 1. Results of the asymmetry ϵ^{L-R} (left figure from Refs. [1, 5]) and ϵ^{F-B} (right figure from Refs. [2, 5]) for ^{117}Sn at the vicinity of the p-resonance $E_p = 1.33$ eV.

parameters measured by Alfimenkov, the -29.2 eV negative s-resonance by Mughabghab [32], later measurements of ^{117}Sn resonance parameters by the TRIPLE collaboration [38], and a recent measurement of an angular-dependence of the (n, γ) p-wave resonance shape [40]. Then, the self consistent description gives a unique ϕ value by reproducing experimental values for all these observables.

IV. P-EVEN EFFECTS IN ^{117}SN+n.

A. Left-right ϵ^{L-R} and forward-backward ϵ^{F-B} asymmetries

1. Two-level approximation

Taking Eqs. (18) and (19) spectroscopic parameters from Table (I) in a two-level approximation, we find ourselves in exactly the same situation reported by several authors (Refs. [2, 5, 6]). We cannot find a unique ϕ value that allows us to reproduce both experimental results on ϵ^{L-R} and ϵ^{F-B}, as can be seen in Figs. (2) and (3); for a given ϕ value, we obtain either magnitude or sign problems.

In view of the lack of information on the signs of neutron ($\gamma^n_{s(p)}$) and gamma ($\gamma^\gamma_{s(p)}$) transition amplitudes for the s(p)-compound state, we propose to assume a negative sign in Eqs. (18) and (19) to see if the additional spectroscopic data can be fit. After fitting

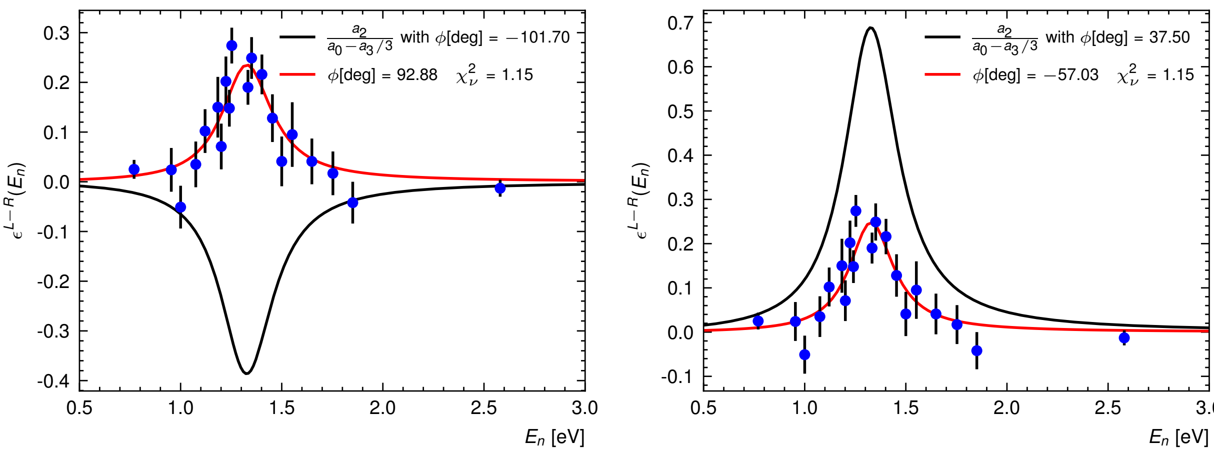

FIG. 2. Measured values for the left-right asymmetry at the vicinity of the p-resonance $E_p = 1.33$ eV for ^{117}Sn. Red curves correspond to the best fits: $\phi(^0) = -57.03$ ($\chi^2_\nu = 1.15$) and $\phi(^0) = 92.88$ ($\chi^2_\nu = 1.15$). Black curves correspond to calculated curves using obtained ϕ values from the fitting on measured F-B asymmetry values.

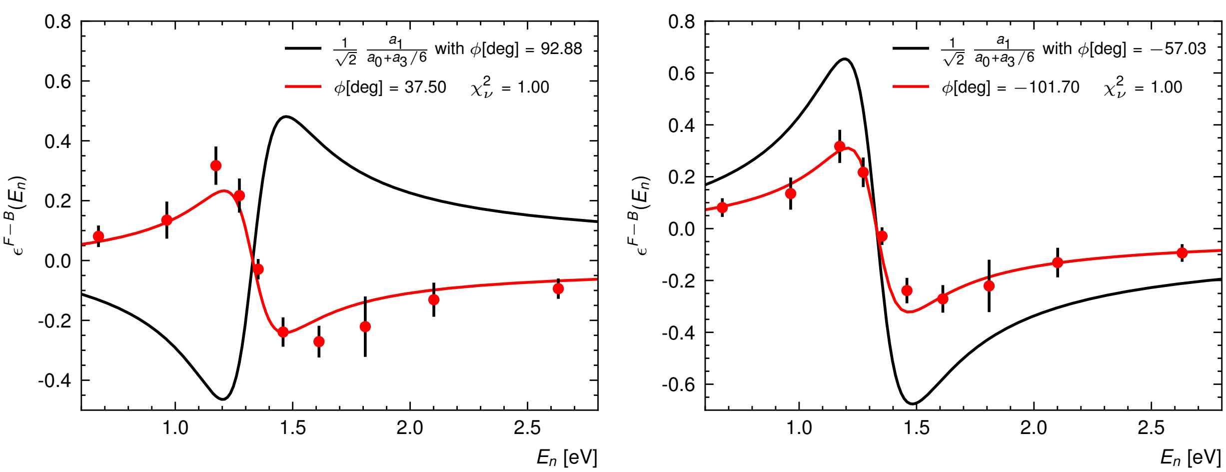

FIG. 3. Measured values for the forward-backward asymmetry at the vicinity of the p-resonance $E_p = 1.33$ eV for ^{117}Sn. Red curves correspond to the best fits: $\phi(^0) = -101.70$ ($\chi^2_\nu = 1.00$) and $\phi(^0) = 37.5$ ($\chi^2_\nu = 1.00$). Black curves correspond to calculated curves using obtained ϕ values from the fitting on measured L-R asymmetry values.

the experimental values for ϵ^{L-R} (ϵ^{F-B}) we obtain two possible values for ϕ (red curves in figures). With these ϕ values we can try to reproduce the measured values for the other asymmetry ϵ^{F-B} (ϵ^{L-R}) evaluating Eqs. (18) and (19) with the opposite sign (black curves in figures).

Taking

$$\epsilon^{F-B}(E, \theta = 45^0) = \frac{1}{\sqrt{2}} \frac{a_1}{a_0 + a_3/6} \qquad \text{and} \qquad \epsilon^{L-R}(E) = -\frac{a_2}{a_0 - a_3/3}, \tag{24}$$

we obtain Fig. (4).

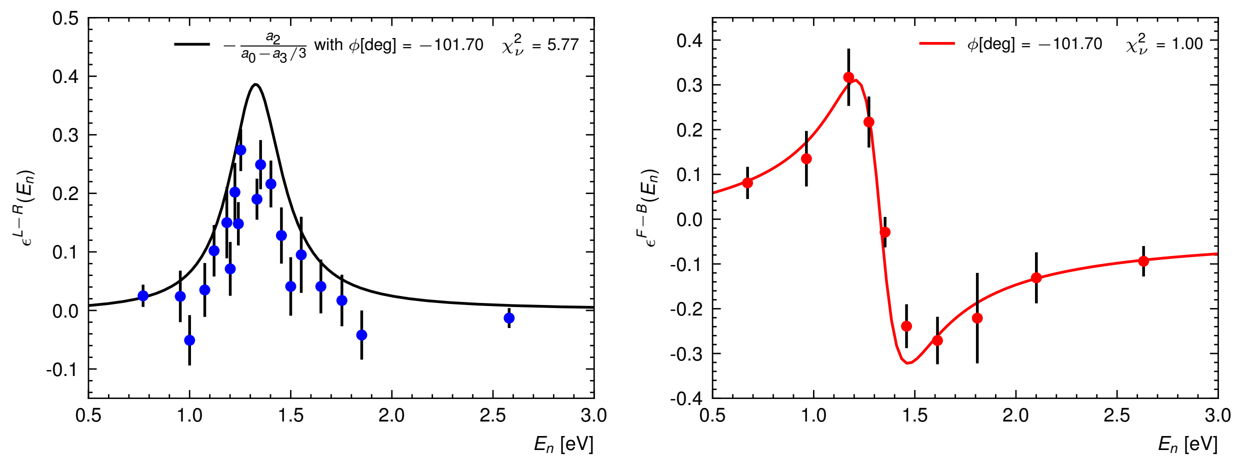

FIG. 4. Measured values for the left-right and forward-backward asymmetries at the vicinity of the p-resonance $E_p = 1.33$ eV for ^{117}Sn. Red curve corresponds to the best fit: $\phi(^0) = -101.70$ ($\chi^2_\nu = 1.00$). Black curve corresponds to the calculated curve using the fitted ϕ value from F-B asymmetry with $\chi^2_\nu = 5.77$.

From the figure we are able to reproduce experimental values for these two measured P-even asymmetries with a unique ϕ value. On the other hand, taking

$$\epsilon^{L-R}(E) = \frac{a_2}{a_0 - a_3/3} \qquad \text{and} \qquad \epsilon^{F-B}(E, \theta = 45^0) = -\frac{1}{\sqrt{2}} \frac{a_1}{a_0 + a_3/6}, \tag{25}$$

we obtain the same result. Notice here that we do not have problems with the sign of the P-even effects or their order of magnitude. In these cases the fitting of a single asymmetry gives us a value for ϕ that fits both measured observables.

In the isolated resonance regime it is common to take only one s-resonance but in the more general case we can have more than one s-resonances contributing to the P-even effect at the p-resonance energy. The mixing of the p-state with those s-resonances with the largest $\Gamma_s^{n0}/(E_s)^2$ values (the positive s-resonance at 38.8 eV and the sub-threshold state at -29.2 eV) should make the dominant contribution to the asymmetries [6]. Below we investigate whether or not the inclusion of this positive s-resonance in the fits lowers the χ^2_ν.

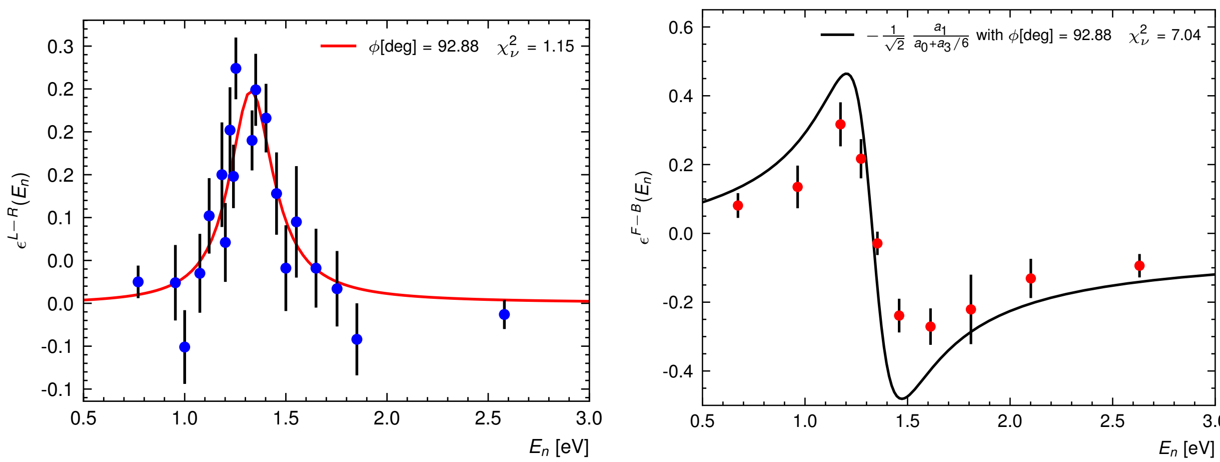

FIG. 5. Measured values for the left-right and forward-backward asymmetries at the vicinity of the p-resonance $E_p = 1.33$ eV for ^{117}Sn. Red curve corresponds to the best fit: $\phi(^0) = 92.88$ ($\chi^2_\nu = 1.15$). The black curve corresponds to the calculated curve using this fitted ϕ value from L-R asymmetry with $\chi^2_\nu = 7.04$.

2. Three-level approximation

Considering Eq. (24), spectroscopic parameters from Table (I), three-level approximation (one p- and two s-resonances) and destructive interference, we obtain Figs. (6) and (7). The value of ϕ from this fit does not change much from that obtained in the two-level approximation analysis, but the quality of the fit as measured by χ^2_ν improves noticeably. Note carefully that this success occurs in spite of the fact that we did not treat the positive resonance parameters as adjustable fit parameters: there is no change from their accepted values in the scientific literature. The only additional new undetermined "parameter" involved in this three resonance fit is the relative sign of the positive s-wave resonance term compared to that from the subthreshold resonance. As we pointed out above, such signs are not determined by other measurements and must be treated as free parameters in our case. From Fig. (7), for the interval

$$\phi \in [-93.93; -92.13], \tag{26}$$

we have

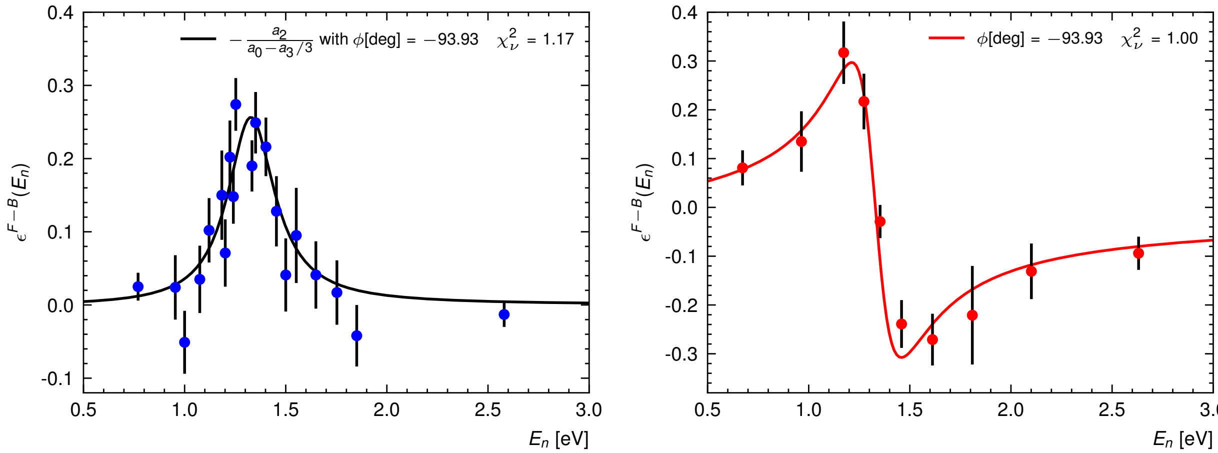

FIG. 6. Measured values for the left-right and forward-backward asymmetries at the vicinity of the p-resonance $E_p = 1.33$ eV for ^{117}Sn. Red curve corresponds to the best fit: $\phi(^0) = -93.93$ ($\chi^2_\nu = 1.00$). Black curve corresponds to the calculated curve using this fitted ϕ value from F-B asymmetry with $\chi^2_\nu = 1.17$.

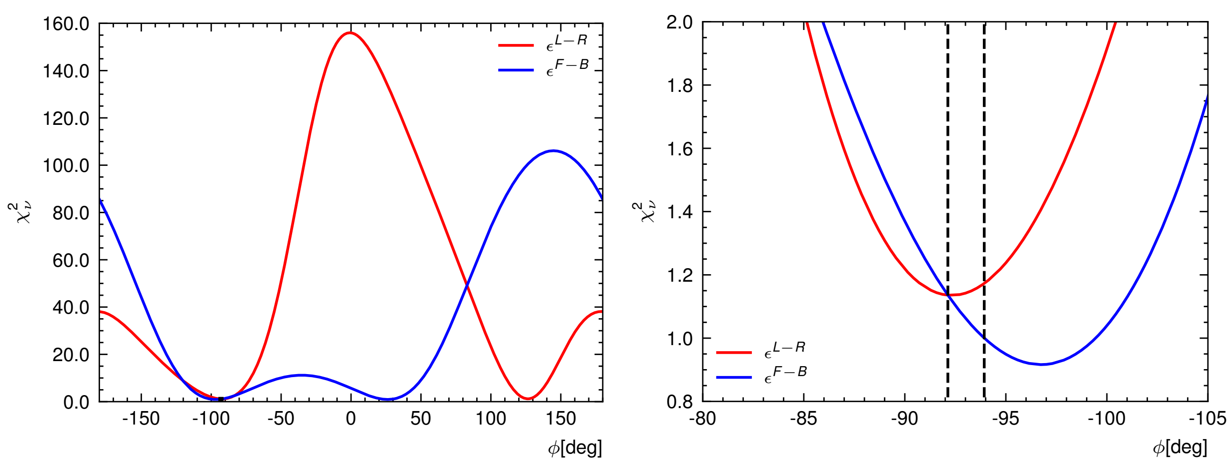

FIG. 7. χ^2_ν as a function of the parameter ϕ (a negative s-resonance at -29.2 eV, a p-resonance at 1.33 eV, a positive s-resonance at 38.8 eV and considering three-level approximation, destructive interference and spectroscopic parameters by Alfimenkov).

$$\begin{aligned} \chi^2_{\nu_{LR}} &\in [1.17; 1.14], \\ \chi^2_{\nu_{FB}} &\in [1.00; 1.14]. \end{aligned} \tag{27}$$

On the other hand, taking Eq. (25) we obtain

$$\phi \in [86.07; 87.87], \tag{28}$$

that also satisfy Eq. (27). From Figs. (8) and (9) we can see an improvement in the evaluated χ^2_ν values for ϵ^{L-R} and ϵ^{F-B}. This means that the positive s-resonance makes an important contribution to the measured asymmetries at the p-resonance energy. From the former two intervals $\phi \in \{[-93.93; -92.13] \cup [86.07; 87.87]\}$ we obtain Fig. (10)

$$\kappa \in [6.53; 12.34].$$

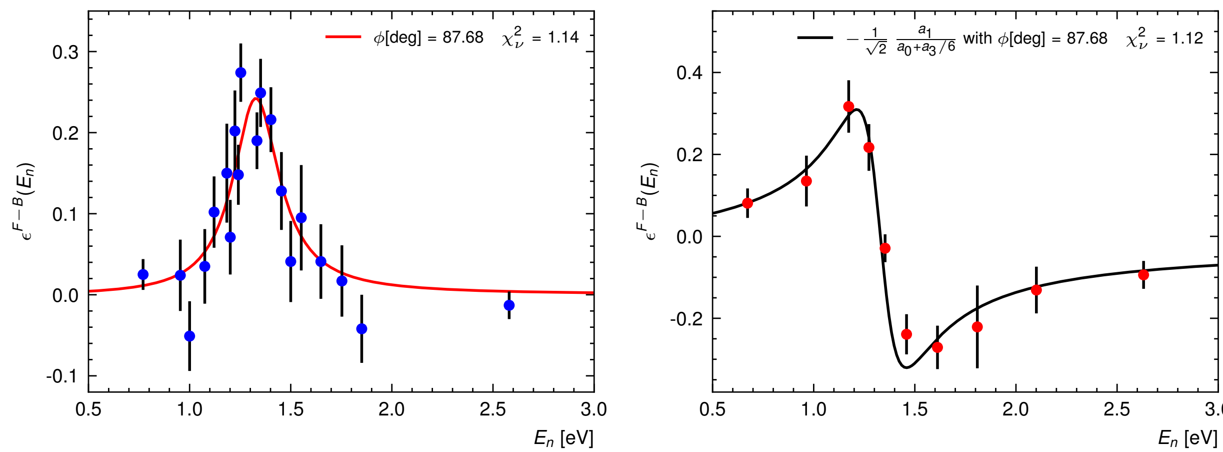

FIG. 8. Measured values for the left-right and forward-backward asymmetries at the vicinity of the p-resonance $E_p = 1.33$ eV for ^{117}Sn. Red curve corresponds to the best fit: $\phi(^0) = 87.68$ ($\chi^2_\nu = 1.14$). Black curve corresponds to the calculated curve using this fitted ϕ value from L-R asymmetry with $\chi^2_\nu = 1.12$.

The measurement of the parameter Γ_p is not an easy experimental task. Alfimenkov measured the parameter Γ^γ through (n,γ) reactions at 1.33 eV in ^{117}Sn. He reported a first value $\Gamma^\gamma_p = 0.23 \pm 0.02$ eV [41]. Since ^{117}Sn is a non-fissile nucleus and the total cross section is practically equal to the radiative capture cross section at these very low energies ($\Gamma^n \ll \Gamma^\gamma$) we can make the approximation $\Gamma_p \approx \Gamma^\gamma_p$. Later Smith *et al.* [42] reported a lower value $\Gamma^\gamma_p = 0.148 \pm 0.010$ eV which then was adopted into the next edition of Mughabghab [33]. Usually $\Gamma_p = \Gamma_s \approx 0.1$ eV [28] for most resonances. We can also find a lower value $\Gamma^\gamma_p = 0.180 \pm 0.018$ eV by Alfimenkov in references [43–45]. We fit the data using all of these values for Γ^γ_p. We obtain the best fits with $\Gamma^\gamma_p = 0.148$ eV. There

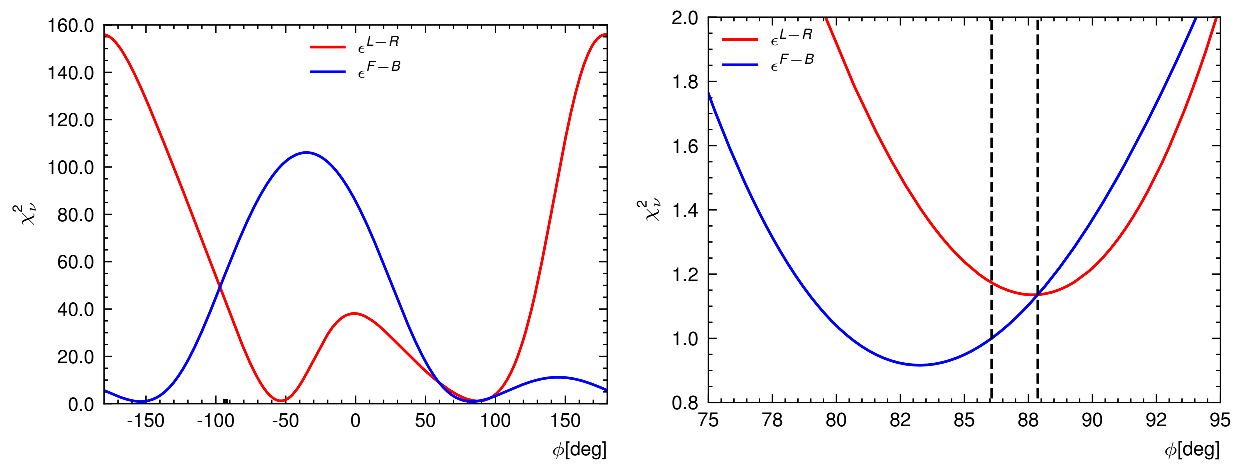

FIG. 9. χ^2/ndf as a function of the parameter ϕ (a negative s-resonance at -29.2 eV, a p-resonance at 1.33 eV, a positive s-resonance at 38.8 eV and considering three-level approximation, destructive interference and spectroscopic parameters by Alfimenkov).

are additional good reasons to believe that this narrower width is likely to be closer to the correct value based on the differences of the source and apparatus properties used in these different measurements. The beam and measurement apparatus used in [42] were a qualitative improvement over that available to [41]. The intrinsic spread of the neutron energies from the water moderator at the spallation source used in [42] is narrower than that from the neutron source used in [41], and the time resolution of both the ^{10}B-loaded liquid scintillation neutron detector used in transmission and the pure CsI gamma detector array used in (n, γ) mode in [42] were sharper than the detectors available to [41]. We suspect that these instrumental improvements could be the reason why Smith *et al.* reported a narrower resonance width Γ_p^γ. Combined with the high statistical accuracy obtained in this work, the Smith *et al.* result domiantes the reported errors on the resonance energy and width.

The recent measurements of γ-rays angle distribution with unpolarized neutrons at 1.33 eV in n+^{117}Sn [40] are consistent with the values $\phi_1 \approx -88^0$ and $\phi_2 \approx 18^0$. While the measurements of the left-right asymmetry [46, 47] reported $\phi_1 \approx -2.0^0$ and $\phi_2 \approx 40.9^0$, with the value of the left-asymmetry $A_{LR} = 1.07 \pm 0.23$. These results do not agree with each other, nor with the obtained interval in the present analysis $\phi \in \{[-93.93; -92.13] \cup [86.07; 87.87]\}$ that guarantees $\chi^2_\nu \in [1.00; 1.17]$. This indicates that more precise experiments are required to resolve the possible source of inconsistency, which is more likely related to low statistics in the previous measurements.

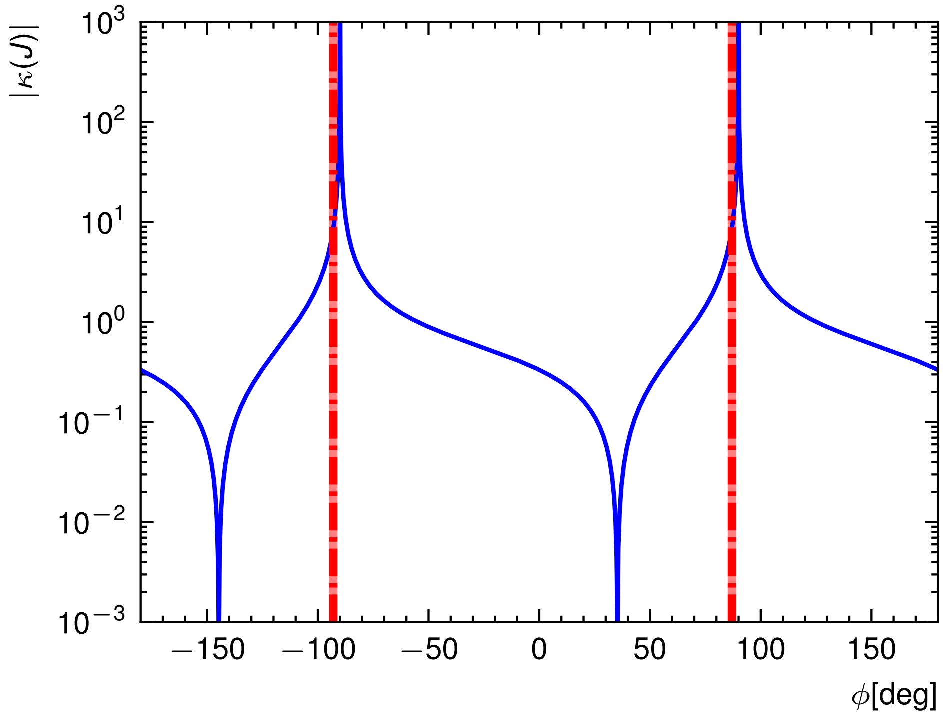

FIG. 10. Values obtained for the parameter $\kappa(J)$ (Eq. 12) in the present analysis. Since there is no constraint on $\kappa(J)$ values derived from any formalism, values between 10^{-1} and 10 can be possible.

The values of TRIV effects η and χ in Eqs. (8) and (9) are proportional to unknown TRIV matrix element w, and directly related to corresponding P-odd observables (see, for example Eq. (11)), which can be measured at the same experiment. Thus, the relations between observed P-odd effects and TRIV effects are defined by one unknown parameter $\lambda = w/v$, which is a ratio of TRIV and P-odd nuclear matrix elements calculated with exactly the same nuclear wave functions, and by parameter κ obtained in the current analysis: κ=6.53.

The exact calculations of matrix elements v and w are practically impossible due to the chaotic nature of compound resonance nuclear wave functions. However, their ratio (parameter λ) can be estimated with rather good accuracy [48–50]. It has been shown (see for example [48–54] and references therein) that different models of CP-violation lead to the possible values of the parameter λ in the wide range from 10^{-2} to 10^{-10}, which corresponds to Kobayashi-Maskawa mixing in the Standard Model.

Taking the value of $\lambda = 10^{-5}$, which will improve the current limits on EDMs and some constrains on new physics (see, for example [8, 9, 50] and references therein), and κ=6.53

for ^{117}Sn we obtain

$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_P} < 6.53 \times 10^{-5}. \tag{29}$$

Then, for possible neutron transmission experiments with time-of-flight spectrometer, assuming very intense neutron fluxes, high-efficiency polarizers, excellent energy resolution at thermal and epithermal energies, and the use of 4π absolute efficiency detector arrays, one can get an experimental sensitivity for $\Delta\sigma_{PT}/\Delta\sigma_P$ in the order of 10^{-6} [9]. Polarized neutron fluxes, in the energy range of the neutron resonance in ^{117}Sn, at the target position of the order of $10^6 - 10^7$ neutrons·s are currently achievable at LANSCE and JPARC [55–57] with ^{3}He spin-filters polarization of the order of 70% and neutron transmission between 40 and 50%. Therefore, an uncertainty of the order of 10^{-6} in TRIV cross section can be achieved for ^{117}Sn, in 10^7 s (see Ref. [9] and Fig. (11)). On the other hand, experimental sensitivity of 10^{-5} can be obtained in 10^5 s. These results show that TRIV experiment with ^{117}Sn is very complementary to the ongoing experiments for EDM measurements.

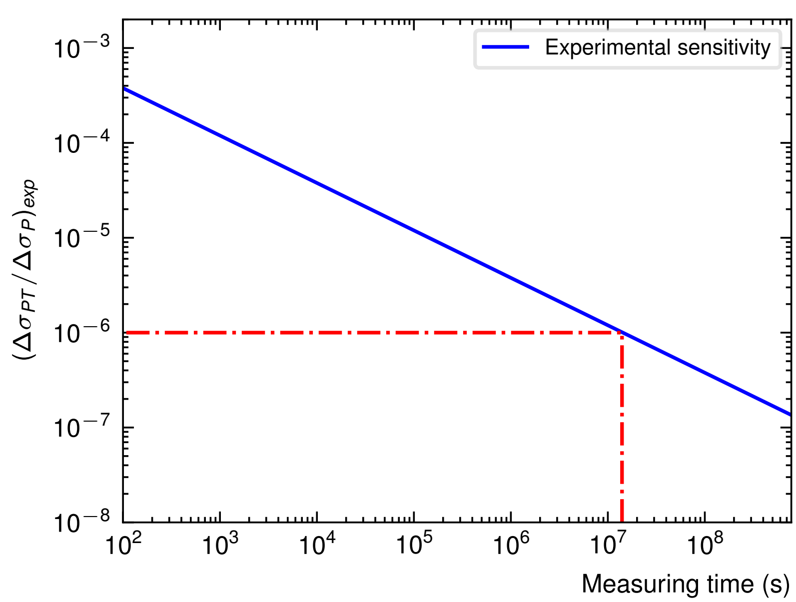

FIG. 11. Estimated experimental sensitivity of the TRIV experiment with ^{117}Sn.

B. P-component angular anisotropy ϵ_p^a and $t^2(\theta, E_p)$

In Table (I) values for ϵ_p^a were obtained using Eq. (23) and measured values for $t_p^2(\theta)$. Taking into account directly experimental values for $t_p^2(45^0)$, $t_p^2(55^0)$, $t_p^2(90^0)$ and evaluated ones for $t_{cal}^2(\theta, E_p)$ from spectroscopic parameters from Table (I) we obtain Figs. (12) and (13).

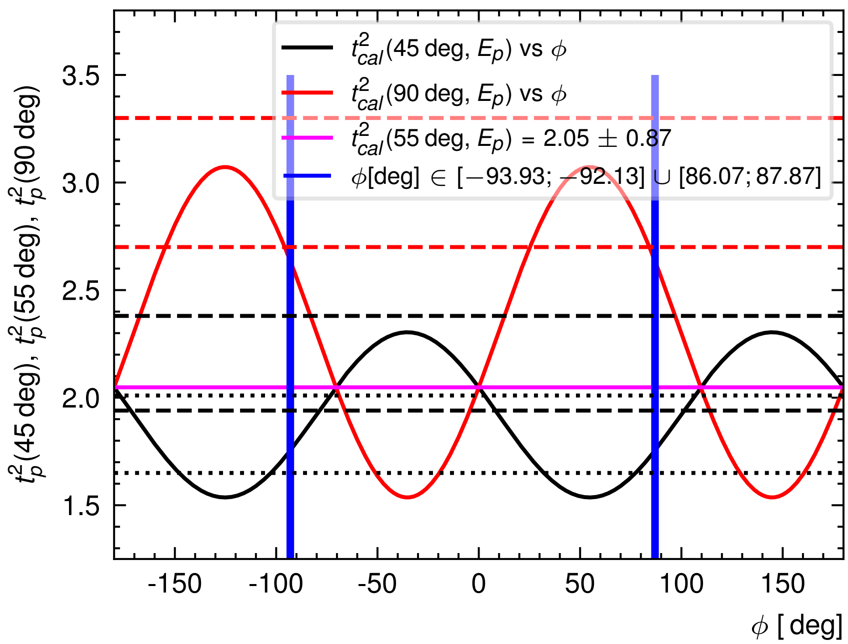

FIG. 12. Calculated values for spectroscopic parameters $t^2_{45^0}(E_p)$, $t^2_{55^0}(E_p)$ and $t^2_{90^0}(E_p)$ using three-level approximation, destructive interference, Flambaum-Sushkov formalism, and values by Alfimenkov. Experimental values $t^2_{exp}(90^0, E_p) = 3.0 \pm 0.3$ (red dashed line), $t^2_{exp}(45^0, E_p) = 2.16 \pm 0.22$ (black dashed line) and $t^2_{exp}(45^0, E_p) = 1.83 \pm 0.18$ (black dotted line) are also shown. There is agreement between the calculated and experimental values if we take into account the values for ϕ from ϵ^{L-R} and ϵ^{F-B}.

From these figures we can see that ϕ is consistently determined from ϵ_p^{L-R} and ϵ_p^{F-B} data when analyzed in the three-level approximation (destructive interference) and Flambaum-Sushkov formalism. In this case, we have agreement considering only the value $\epsilon_p^a = 1.63 \pm 0.14$. The fact that we obtain the best result in three-level approximation means that the positive s-resonance at 38.8 eV has an important contribution to the asymmetries at the p-resonance energy $E_p = 1.33$ eV in ^{117}Sn.

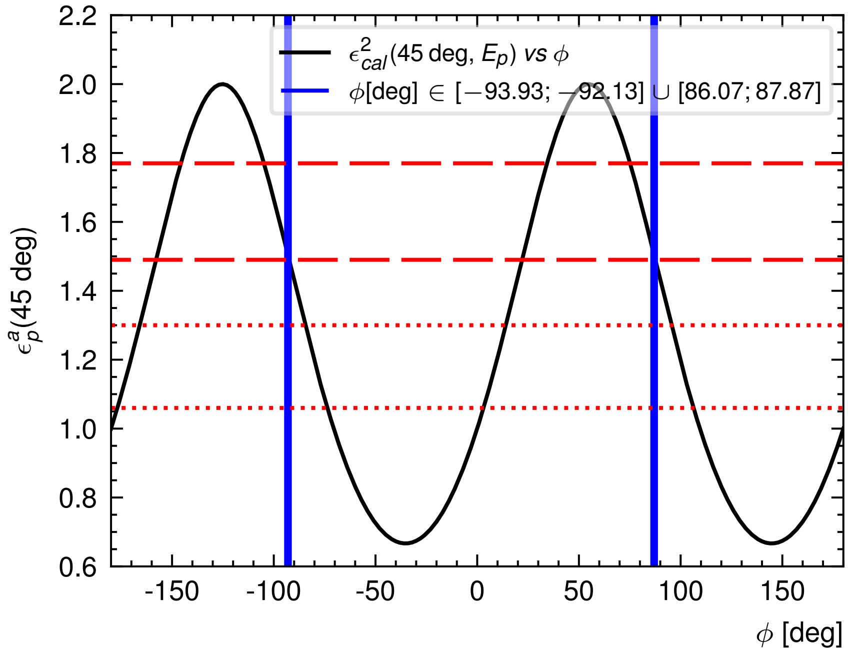

FIG. 13. Experimental and theoretical values for the spectroscopic parameter $\epsilon_p^a(45^0)$ using three-level approximation, destructive interference, Flambaum-Sushkov formalism and values by Alfimenkov. Experimental values $\epsilon^2_{exp}(45^0, E_p) = 1.63 \pm 0.14$ (red dashed line) and $\epsilon^2_{exp}(45^0, E_p) = 1.18 \pm 0.12$ (red dotted line) are also shown. There is agreement between the calculated and experimental values if we take into account the values for ϕ from ϵ^{L-R} and ϵ^{F-B}.

It would be no surprise if the addition of more fitting parameters to a theoretical model lowers the chi-squared value of the fit to the data. We emphasize again that in this study we always consider only one fitting parameter ϕ both in two- and three-level approximation.

Above we presented our arguments for why we chose to base our main analysis of the data using the subthreshold resonance parameters from the measurements of Alfimenkov, whose values come directly from data in the low-energy neutron range of interest. Nevertheless, we also analyzed the data with values from two different global data evaluations (1981 and 2006 from Mughabghab) which as noted below possess very different values for the subthreshold resonance. We were not able to obtain consistency between experimental and evaluated values for $t^2(E_p, 45^0)$, $t^2(E_p, 55^0)$ and $t^2(E_p, 90^0)$ in two-level approximation from either data evaluation, nor was it possible to succeed with spectroscopic values from the 1981 Mughaghab series in three-level approximation. But we could get an internally consistent analysis from the 2006 Mughaghab series in three-level approximation (destructive interference). In this case, we obtain

$$\phi = -96.14 \quad \text{and} \quad 83.86, \tag{30}$$

and

$$\begin{aligned} \chi^2_{\nu_{LR}} &= 1.59, \\ \chi^2_{\nu_{FB}} &= 1.00. \end{aligned} \tag{31}$$

These values are not far away from those reported in Eqs. (26) and (28). In this article we only presented our best results (taking values by Alfimenkov). Alfimenkov's values come directly from his own data in the low-energy neutron range of interest. Clearly, more experiments would be very valuable to better constrain the spectroscopic parameters in this system, especially for the resonant sub-threshold state in ^{118}Sn whose properties are clearly important to describe the data.

V. SEEKING FOR CONSISTENCY BETWEEN BUNAKOV-GUDKOV FORMALISM AND MEASURED P-ODD ASYMMETRIES IN ^{117}SN+n.

We now turn to the measurements of P-odd effects near the 1.33 eV p-wave resonance of ^{117}Sn to see if the existing data is internally consistent with the resonance parameters that describe the P-even data.

From the P-odd reaction amplitudes we obtain in two-level approximation at the thermal energy

$$\frac{P(E_p)}{P(E_{th})} = 4\frac{\sigma_{tot}(E_{th})}{\sigma_{tot}(E_p)}\frac{(E_p - E_s)\Gamma_p\left[(E_{th} - E_s)^2 + \Gamma_s^2/4\right]\left[(E_{th} - E_p)^2 + \Gamma_p^2/4\right]}{\left[(E_{th} - E_s)\Gamma_p + (E_{th} - E_p)\Gamma_s\right]\left[(E_p - E_s)^2 + \Gamma_s^2/4\right]\Gamma_p^2}. \tag{32}$$

At the p-resonance energy we have

$$\frac{P(E_p)}{d\phi/dz(E_{th})} = \frac{2}{N\sigma_{tot}(E_p)}\frac{(E_p - E_s)\Gamma_p\left[(E_{th} - E_s)^2 + \Gamma_s^2/4\right]\left[(E_{th} - E_p)^2 + \Gamma_p^2/4\right]}{\left[(E_{th} - E_s)(E_{th} - E_p) - \Gamma_s\Gamma_p/4\right]\left[(E_p - E_s)^2 + \Gamma_s^2/4\right]\Gamma_p^2}. \tag{33}$$

In this case we eliminate the spin factors dependence (because both P and $d\phi/dz$ share the same spin factor) and the weak-mixing represented by v which means that we should be able to compare well with the P-even results.

c c c c

TABLE III. Calculated values for P-odd effects (P, $d\phi/dz$ and α_{n,γ_0}) at the thermal and p-resonance energy for ^{117}Sn.

P_p (10^{-3})	P_{th} (10^{-6})	$\alpha_{n,\gamma_{0_{th}}}$ (10^{-4})	$d\phi_{th}/dz$ (10^{-6}) (rad/cm)
$-(3.0 \pm 0.13)$	$-(10 \pm 0.69)$	$-(7.6 \pm 0.92)$	$-(48.4 \pm 1.94)$

To obtain the former two equations we need to take into account the contribution from the nearest s- and p-resonances and the scattering potential in the total cross section expression [58]

$$\sigma_{tot}(E) = \frac{\pi}{k^2}\frac{\Gamma_s^n \Gamma_s}{(E-E_s)^2 + \Gamma_s^2/4} + \frac{\pi}{k^2}\frac{\Gamma_p^n \Gamma_p}{(E-E_p)^2 + \Gamma_p^2/4} + (kR)^2. \tag{34}$$

Taking the spectrometric parameters reported in Table (I), $\sigma(E_{th}) = 4$ b, $\sigma(E_p) = 1.8$ b, $N = 3.7 \cdot 10^{22}$ cm^{-3}, $d\phi/dz(E_{th}) = (-36.7 \pm 2.7) \cdot 10^{-6}$ rad/cm and the average $P(E_{th}) = (6.7 \pm 0.5) \cdot 10^{-6}$ from reference [43] and evaluating these equations we obtain

$$P(E_p) = (4.7 \pm 0.4) \times 10^{-3} \quad \text{and} \quad P(E_p) = (9.2 \pm 0.7) \times 10^{-3},$$

respectively. These calculated values agree with the experimental values reported in Table (IV).

To estimate the weak matrix element v for heavy and medium-heavy nuclei we can use the phenomenological equation [58]

$$v \sim 10^{-4}\sqrt{\bar{D}\,[\mathrm{eV}]}, \tag{35}$$

where $\bar{D}$ is the average distance between compound resonances. In the following calculations we use $\bar{D} = 48 \pm 6$ eV [32] to evaluate some P-odd asymmetry for ^{117}Sn.

Taking spectroscopic parameters from Table (I) we calculate values for these P-odd effects shown in Table (III). In order to compare absolute values we need to consider the exact expressions for spin factors.

In Table (IV) we can see measured values for these asymmetries reported in several references. On the sign of these measured asymmetries we observe that it is very common to

TABLE IV. Measured P-odd asymmetries at resonant and thermal energies.

$\alpha_{n,\gamma_{th}} (10^{-4})$		P_{th} (10^{-6})	
8.1 ± 1.3	[59]	-(6.2 ± 0.7)	[28, 43]
4.4 ± 0.6	[60, 61]	11.2 ± 2.6	[43]
-(4.1 ± 0.8)	[59]	6.9 ± 0.8	[43]
8.9 ± 1.5	[62]	9.8 ± 4.1	[63]
8.5 ± 1.5	[58]	16.0 ± 2.1	[28]
		-(9.78 ± 4.08)	[28]
$d\phi_{th}/dz$ (10^{-6}) (rad/cm)		P_p (10^{-3})	
-36.7 ± 2.7	[43, 60]	-(4.5 ± 1.3)	[60, 63]
-38.6 ± 6.8	[64]	7.7 ± 1.3	[38, 43]
		7.9 ± 0.4	[38]

find discrepancies between references that cite the same experimental reported value. Our reported values in Table (III) agree pretty well with those shown in Table (IV).

VI. CONCLUSIONS

Our analysis shows that a resonance description of neutron radiative capture [3] can describe all of the data taken so far at the 1.33 eV resonance in ^{117}Sn, which is one of the most extensively studied p-wave compound nuclear resonance to date. We observed an essential improvement in the fit of the experimental data without additional free parameters when we use the three-level approximation with destructive interference. This shows that the s-wave resonance at 38.8 eV is important to describe the P-even effects at the vicinity of p-wave resonance in ^{117}Sn, which are dominant by the mixing with the subthreshold s-wave resonance. It should be noted that to improve the accuracy of the measured resonance parameters the further analysis of new observables involving gamma circular polarization and the ^{117}Sn nuclear polarization is highly desirable. However, even at this stage our results show the assurance in understanding spectroscopic parameters which are required for future experiments for the search of TRIV in neutron scattering on ^{117}Sn target. The reasonably large value of the parameter κ makes ^{117}Sn a good candidate for a TRIV test.

We plan to apply a similar analysis for other candidates for the targets for TRIV experiments such as ^{139}La, ^{81}Br, ^{131}Xe, when more experimental data will be available.

VII. ACKNOWLEDGMENT

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[1] V. Alfimenkov, S. Borzakov, V. Tkhuan, Y. Mareev, L. Pikel'ner, I. Frank, A. Khrykin, and I. Sharapov, Left-right asymmetry in the gamma emission at a P-parity-breaking neutron resonance of ^{117}Sn, JETP Lett. (Engl. Transl.); (United States) **39:8** (1984).

[2] V. P. Alfimenkov, S. B. Borzakov, Y. Mareev, L. B. Pikel'ner, A. S. Khrykin, and E. Sharapov, *Correlations in gamma-quanta angular distribution at neutron capture in* ^{117}*Sn p-resonance region*, Tech. Rep. (USSR, 1985) iNIS-SU–357.

[3] V. V. Flambaum and O. P. Sushkov, Angular and polarization correlations in the (n, γ) reaction, Nucl. Phys. A **435**, 352 (1985).

[4] V. Alfimenkov, S. Borzakov, Y. D. Mareev, L. Pikelner, V. Skoy, A. Khrykin, and E. Sharapov, P-even effects in a direct γ transition following neutron capture in ^{113}Cd around Ep= 7 eV resonance, in *AIP Conference Proceedings*, Vol. 238 (American Institute of Physics, 1991) pp. 811–813.

[5] V. R. Skoi and E. I. Sharapov, P-odd angular correlations in resonance (n,γ) reactions, Fiz. Elem. Chastits At. Yadra **22**, 1400 (1991).

[6] A. L. Barabanov, Angular anisotropy of γ rays in the (n,γ) reaction near the p resonance, Physics of Atomic Nuclei **55**, 1513 (1992).

[7] V. P. Gudkov, About the resonance approximation in neutron induced reactions, Zeitschrift für Physik A Hadrons and Nuclei **340**, 1 (1991).

[8] V. Gudkov and Y.-H. Song, Discover potential in a search for time-reversal invariance violation in nuclei, Hyperfine Interact. **214**, 105 (2013).

[9] J. D. Bowman and V. Gudkov, Search for time reversal invariance violation in neutron transmission, Phys. Rev. C **90**, 065503 (2014).

[10] V. E. Bunakov and V. P. Gudkov, Parity Violation and Related Effects in Neutron Induced Reactions, Nucl. Phys. A **401**, 93 (1983).

[11] V. Gudkov, On CP violation in nuclear reactions, Physics Reports **212**, 77 (1992).

[12] A. Beda and V. Skoy, Current status of research on T invariance in neutron-nuclear reactions, Phys. Part. Nuclei **38**, 775 (2007).

[13] V. P. Gudkov, Theory of T violating P conserving effects in neutron induced reactions, Nucl.Phys. **A524**, 668 (1991).

[14] Y.-H. Song, R. Lazauskas, and V. Gudkov, Time Reversal Invariance Violating and Parity Conserving effects in Neutron Deuteron Scattering, Phys.Rev. **C84**, 025501 (2011).

[15] M. Pospelov, Best values for the CP odd meson nucleon couplings from supersymmetry, Phys. Lett. B **530**, 123 (2002), arXiv:hep-ph/0109044.

[16] M. Pospelov and A. Ritz, Electric dipole moments as probes of new physics, Annals of Physics **318**, 119 (2005), special Issue.

[17] Y.-H. Song, R. Lazauskas, and V. Gudkov, Time reversal invariance violating and parity conserving effects in neutron-deuteron scattering, Phys. Rev. C **84**, 025501 (2011).

[18] Y.-H. Song, R. Lazauskas, and V. Gudkov, Nuclear electric dipole moment of three-body systems, Phys. Rev. C **87**, 015501 (2013).

[19] V. Gudkov and H. M. Shimizu, Nuclear spin dependence of time reversal invariance violating effects in neutron scattering, Phys. Rev. C **97**, 065502 (2018).

[20] G. Mitchell, J. Bowman, S. Penttilä, and E. Sharapov, Parity violation in compound nuclei: experimental methods and recent results, Physics Reports **354**, 157 (2001).

[21] R. Adams, J. Aguilar, K. Atkinson, M. Cowley, P. Elliott, S. Duckett, G. Green, I. Khazal, J. Lopez-serrano, and D. Williamson, Reversible interactions with para-hydrogen enhance NMR sensitivity by polarization transfer, Science **323**, 1708 (2009).

[22] D. P. Nikolaou, P. B. M. Goodson, and P. E. Y. Chekmenev, NMR hyperpolarization techniques for biomedicine, Chemistry **21(8)**, 3156 (2015).

[23] A. M. Olaru, A. Burt, P. J. Rayner, S. J. Hart, A. C. Whitwood, G. G. R. Green, and S. B. Duckett, Using signal amplification by reversible exchange (SABRE) to hyperpolarise ^{119}Sn and ^{29}Si NMR nuclei, Chem. Commun. **52**, 14482 (2016).

[24] Y. G. Abov, P. A. Krupchtsky, and U. A. Oratovsky, Yad. Fiz. **1**, 479 (1965).

[25] V. M. Lobashov, V. L. Nazarenko, L. P. Saenko, L. M. Smotritskii, and G. I. Kharkevich, JETP Letters **3**, 268 (1966).

[26] V. V. Flambaum and O. P. Sushkov, On the Possibility to Observe Parity Violation in Neutron Optics, JETP Lett. **32**, 352 (1980).

[27] O. P. Sushkov and V. V. Flambaum, Parity Breaking In The Interaction Of Neutrons With Heavy Nuclei, Sov. Phys. Usp. **25**, 1 (1982).

[28] V. Bunakov and V. Gudkov, Parity non-conservation effects in neutron elastic scattering reactions, Zeitschrift für Physik A Atoms and Nuclei **303**, 285 (1981).

[29] V. Bunakov and L. Pikelner, Parity and time reversal violation in neutron-nucleus reactions, Progress in Particle and Nuclear Physics **39**, 337 (1997).

[30] V. E. Bunakov and V. P. Gudkov, Enhancement of T-noninvariant effects in neutron-induced nuclear reactions, Z. Phys. A **308**, 363 (1982).

[31] V. Gudkov and H. M. Shimizu, Neutron spin dynamics in polarized targets, Phys. Rev. C **102**, 015503 (2020).

[32] S. Mughabghab, M. Divadeenam, and N. Holden, Neutron cross sections, vol. la, acad, Press, NY (1981).

[33] S. Mughabghab, *Atlas of neutron resonances: resonance parameters and thermal cross sections Z= 1-100* (2006).

[34] S. F. Mughabghab, Thermal neutron capture cross sections resonance integrals and g-factors (2003).

[35] V. P. Alfimenkov, S. B. Borzakov, Y. D. Mareev, L. B. Pikelner, I. M. Frank, A. S. Khrykin, and E. I. Sharapov, Polarization and angular correlations in the ^{117}Sn(n,γ) reaction near the 1.33 eV p-wave resonance, Radiation Effects **94**, 263 (1986), https://doi.org/10.1080/00337578608208388.

[36] V. Alfimenkov, S. Borzakov, V. Van Thuan, Y. Mareev, L. Pikelner, A. Khrykin, and E. Sharapov, Parity nonconservation in neutron resonances, Nuclear Physics A **398**, 93 (1983).

[37] V. Alfimenkov, S. Borzakov, V. V. Thuan, and Y. D. Mareev, γ-ray spectra from the neutron resonances ^{81}Br, ^{117}Sn, ^{139}La violating the space parity, Yad. Fiz. **39**, 1057 (1984).

[38] D. A. Smith, J. D. Bowman, B. E. Crawford, C. A. Grossmann, T. Haseyama, M. B. Johnson, A. Masaike, Y. Matsuda, G. E. Mitchell, V. A. Nazarenko, S. I. Penttila, N. R. Roberson, S. J. Seestrom, E. I. Sharapov, L. M. Smotritsky, S. L. Stephenson, S. Tomsovic, and V. W. Yuan, Parity violation in neutron resonances of ^{117}Sn, Phys. Rev. C **64**, 015502 (2001).

[39] D. I. Lyapin, I. M. Salamatin, and S. A. P., Communication R3-90-125, JINR (1990).

[40] J. Koga, S. Takada, S. Endo, H. Fujioka, K. Hirota, K. Ishizaki, A. Kimura, M. Kitaguchi, Y. Niinomi, T. Okudaira, K. Sakai, T. Shima, H. M. Shimizu, Y. Tani, T. Yamamoto, H. Yoshikawa, and T. Yoshioka, Angular distribution of γ rays from the p-wave resonance of ^{118}Sn, Phys. Rev. C **105**, 054615 (2022).

[41] V. Alfimenkov, S. Borzakov, V. Van Thuan, Y. Mareev, L. Pikelner, A. Khrykin, and E. Sharapov, Parity nonconservation in neutron resonances, Nuclear Physics A **398**, 93 (1983).

[42] D. A. Smith, J. D. Bowman, B. E. Crawford, C. A. Grossmann, T. Haseyama, M. B. Johnson, A. Masaike, Y. Matsuda, G. E. Mitchell, V. A. Nazarenko, S. I. Penttila, N. R. Roberson, S. J. Seestrom, E. I. Sharapov, L. M. Smotritsky, S. L. Stephenson, and V. Yuan, Neutron resonance spectroscopy of ^{117}Sn from 1 eV to 1.5 keV, Phys. Rev. C **59**, 2836 (1999).

[43] A. L. Barabanov, P-odd effects in interactions of neutrons with ^{117}Sn and ^{139}La and the positions of negative resonances, Soviet Journal of Nuclear Physics **54**, 941 (1991).

[44] V. Bunakov and L. Pikelner, Parity and time reversal violation in neutron-nucleus reactions, Progress in Particle and Nuclear Physics **39**, 337 (1997).

[45] Alfimenkov, Correlations in gamma-quanta distribution at neutron capture in ^{117}Sn p-resonance region, JINR Rapid Communications (1985).

[46] S. Endo, T. Okudaira, R. Abe, H. Fujioka, K. Hirota, A. Kimura, M. Kitaguchi, T. Oku, K. Sakai, T. Shima, H. M. Shimizu, S. Takada, S. Takahashi, T. Yamamoto, H. Yoshikawa, and T. Yoshioka, Measurement of the transverse asymmetry of γ rays in the $^{117}\mathrm{Sn}(n,\gamma)^{118}\mathrm{Sn}$ reaction, Phys. Rev. C **106**, 064601 (2022).

[47] S. Endo, private communication (2023).

[48] V. P. Gudkov, On the test of CP violation models in neutron reactions, Phys.Lett. **B243**, 319 (1990).

[49] I. Towner and A. Hayes, P, T violating nuclear matrix elements in the one meson exchange approximation, Phys.Rev. **C49**, 2391 (1994).

[50] P. Fadeev and V. V. Flambaum, Time-reversal invariance violation in neutron-nucleus scattering, Phys. Rev. C **100**, 015504 (2019).

[51] V. E. Bunakov and V. P. Gudkov, ON THE ESTIMATES OF THE CP VIOLATION NUCLEON-NUCLEON INTERACTION, LENINGRAD-85-1064 (1985).

[52] P. Herczeg, T violating effects in neutron physics and cp violation in gauge models, in *Tests of Time Reversal Invariance in Neutron Physics*, edited by N. R. Roberson, C. R. Gould, and J. D. Bowman (World Scientific, Singapore, 1987) pp. 24–53.

[53] P. Herczeg, T VIOLATION IN NUCLEAR INTERACTIONS: AN OVERVIEW, in *Workshop on Cooling of X-Ray Monochromators on High Power Beamlines* (1988).

[54] V. P. Gudkov, The Weinberg gluonic operator and the CP odd nucleon coupling constant, Z.Phys. **A343**, 437 (1992).

[55] N. Roberson, C. Bowman, J. Bowman, P. Delheij, C. Frankle, C. Gould, D. Haase, J. Knudson, G. Mitchell, R. Mortensen, S. Penttilä, H. Postma, S. Seestrom, J. Szymanski, S. Wender, S. Yoo, V. Yuan, and X. Zhu, An apparatus and techniques of tests for fundamental symmetries in compound-nucleus scattering with epithermal polarized neutron beams, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **326**, 549 (1993).

[56] M. Kitaguchi, Neutron Experiments at J-PARC, in *Proceedings of The 4th KMI International Symposium — PoS(KMI2019)*, Vol. 356 (2019) p. 006.

[57] M. Kitaguchi, K. Asahi, S. Endo, C. Haddock, M. Hino, K. Hirota, T. Ino, I. Ito, T. Iwata, J. Koga, Y. Miyachi, T. Momose, N. Oi, T. Okudaira, K. Sakai, T. Shima, H. Shimizu, S. Takada, Y. Yamagata, and T. Yoshioka, Fundamental physics using high-performance optics (2018).

[58] V. Bunakov and V. Gudkov, Parity violation and related effects in neutron-induced reactions, Nuclear Physics A **401**, 93 (1983).

[59] V. Bunakov and L. Pikelner, Parity and time reversal violation in neutron-nucleus reactions, Progress in Particle and Nuclear Physics **39**, 337 (1997).

[60] M. Forte, B. R. Heckel, N. F. Ramsey, K. Green, G. L. Greene, J. Byrne, and J. M. Pendlebury, First measurement of parity-nonconserving neutron-spin rotation: The tin isotopes, Phys. Rev. Lett. **45**, 2088 (1980).

[61] H. Benkoula, J. Cavaignac, J. Charvet, D. Koang, B. Vignon, and R. Wilson, Evidence of parity violation in neutron capture by ^{117}Sn, Physics Letters B **71**, 287 (1977).

[62] O. P. Sushkov and V. V. Flambaum, Parity breaking in the interaction of neutrons with heavy nuclei, Soviet Physics Uspekhi **25**, 1 (1982).

[63] V. S. Olkhovsky and A. K. Zaichenko, A possible way to the explanation of the parity violation effects in the scattering of neutrons by nuclei, Phys. Lett. B **130**, 127 (1983).

[64] B. Heckel, N. Ramsey, K. Green, G. Greene, R. Gähler, O. Schaerpf, M. Forte, W. Dress, P. Miller, R. Golub, J. Byrne, and J. Pendlebury, A measurement of parity non-conserving neutron spin rotation in lead and tin, Physics Letters B **119**, 298 (1982).

[65] G. Mitchell, J. Bowman, S. Penttilä, and E. Sharapov, Parity violation in compound nuclei: experimental methods and recent results, Physics Reports **354**, 157 (2001).

[66] V. Flambaum and G. Gribakin, Enhancement of parity and time-invariance violating effects in compound nuclei, Progress in Particle and Nuclear Physics **35**, 423 (1995).

[67] V. Flambaum and O. Sushkov, Theory of neutron reactions and weak interaction in heavy nuclei, Nuclear Physics A **412**, 13 (1984).

[68] A. L. Barabanov, Semiclassical analysis of angular correlations in an (n, γ) reaction near a p-wave resonance, Physics of Atomic Nuclei **55**, 1039 (1992).

[69] V. Gudkov, *Parity violation in neutron induced reactions*, Tech. Rep. (National Lab. for High Energy Physics, 1991).

[70] A. L. Barabanov, E. I. Sharapov, V. R. Skoy, and C. M. Frankle, Testing T-odd, P-even interactions with γ rays from neutron p-wave resonances, Phys. Rev. Lett. **70**, 1216 (1993).

[71] V. V. Flambaum and A. J. Mansour, Parity and time-reversal invariance violation in neutron-nucleus scattering, Phys. Rev. C **105**, 015501 (2022).