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2023 年度高エネルギー加速器研究機構物質構造科学研究所 中性子共同利用 S1 型実験課題申請書 Application form for S1 type research project

物質構造科学研究所長 殿

To Director of Institute of Materials Structure Science

申請日 2023年5月29日

0) 実験代表者情報 [Information of principal investigator]

E-mail	:	hirohiko.shimizu@nagoya-u.jp
氏名 Name	:	清水 裕彦
所属機関・部局 Affiliation	:	名古屋大学・ 理学研究科
職名 Status	:	教授
住所 Address	:	〒464-8602 愛知県名古屋市千種区不老町
電話 Tel	:	052-789-3545
ファックス Fax	:	052-789-5500

1) 基本情報 [Basic Information]

i) 実験課題の種類 [Type of project] S1型 [Type S1]

iI) 実験課題名 [Title of project]

日本語 (in Japanese) 偏極熱外中性子光学における離散的対称性の破れの研究

英語 (in English) Study of Discrete Symmetries in Polarized Epithermal Neutron Optics

iii) 研究の概要 [abstract] (500 字以内)

We propose to study the breaking of the time reversal invariance (T-violation) in the spin behavior of epithermal neutrons propagating through polarized nuclear targets to search for T-odd spin correlation terms beyond the standard model with an enhanced sensitivity. The neutron absorption process is dominated by the compound nuclear process, which is observed as well-resolved narrow resonances for incident neutrons in the energy region of eV. Recently we have studied the channel boundary in the entrance channel for ¹³⁹La, which exhibits about 10⁶ times parity-violation enhancement at the incident neutron energy of $E_n = 0.74 \,\mathrm{eV}$, and found that this process has a kinematical enhancement of T-violation visibility at the same order of magnitude as the parity-violation. The result suggests a novel search for T-violation with a meaningful discovery potential compared with other types of new physics searches via T- or CP-violation. We will apply the optical nature of neutron propagation in nuclear polarized matters to measure the T-violating effects in the forward scattering amplitude, to which the final state interaction does not contribute. In addition, this experiment is suitable to extract the isoscalar T-violating meson-nucleon coupling, which has not been selectively measured in the search for neutron electric-dipole-moment.

2) 研究組織

実		所属	現在の専門
験	氏名	部局	学 位
(代		職	役割分担
表	清水 裕彦	名古屋大学・理学研究科	原子核素粒子物理学・博士(理学)
者		教授	全体統括
	北口 雅暁	名古屋大学 ・ 現象解析センター ・ 准教	中性子基礎物理 ・ 博士(理学) ・ 実験
		授	統括
	奥平 琢也	名古屋大学 ・ 理学研究科 ・ 助教	素粒子物理学 ・博士(理学) ・ビーム
			実験統括、 ³ He 偏極子開発
	松下 琢	名古屋大学 ・ 理学研究科 ・ 講師	低温物理 ・博士(理学) ・低温装置開
			発
	和田 信雄	名古屋大学 ・理学研究科 ・名誉教授	低温物理 ・博士(理学) ・低温装置開
			発
	吉岡 瑞樹	九州大学 ・ 理学研究院 ・ 准教授	素粒子物理学 ・ 博士(理学) ・ ガンマ
			線測定
	遠藤 駿典	日本原子力研究開発機構 ・ 原子力基礎	素粒子物理学 ・ 修士(理学) ・ 中性子
		工学研究センター ・ 研究員	ビーム実験
	岩本 修	日本原子力研究開発機構 ・ 原子力基礎	原子力工学 ・博士(工学) ・原子核共
		工学研究センター ・ グループリーダー	鳴反応解析
	木村 敦	日本原子力研究開発機構 ・ 原子力基礎	原子力工学 ・博士(工学) ・原子核共
		工学研究センター ・ 主任研究員	鳴反応解析
	酒井 健二	日本原子力研究開発機構 · J-PARC セ	素粒子物理学 ・ 博士(理学) ・ ビーム
		ンター・ 副主任研究員	ライン整備
	奥 隆之	日本原子力研究開発機構 · J-PARC セ	素粒子物理学 ・ 博士(理学) ・ ビーム
		ンター・副主任研究員	ライン整備
	篠原 武尚	日本原子力研究開発機構 · J-PARC セ	磁性物理 ・博士(理学) ・中性子ビー
		ンター・ 主任研究員	ム実験
	土川 雄介	日本原子力研究開発機構 · J-PARC セ	原子核物理・博士(理学)・中性子ビー
		ンター・研究員	ム実験
	嶋 達志	大阪大学 ・ 核物理研究センター ・ 准教	天体核物理 ・博士(理学) ・複合核理
		授	
	郡 英輝	大阪大学 ・ 核物理研究センター ・ 特任	原子核物理 ・ 博士(理学) ・ 核偏極
		准教授	
	滕岡 宏之	東京丄業大字 ・ 埋字院 ・ 准教授	原子核物理字 ・ 博士(埋字) ・ カンマ
			線測定 素粧之時開発 (開発) 「房屋層
	即沿 昌隆	ム島大字 ・ 光端物質科字研究科 ・ 助教	茶粒于物理子 ・ 博士(理子) ・ 偏極標
		山瓜上兴一田兴江古幻 板板	的開発 医乙基酶四份 (四份)
	右田 尚広	山形大字 ・ 埋字研究科 ・ 教授	原于核物理字 · 博士 (理字) · 動的核
	一一日日 王 王	山瓜上兴一田兴江市幻一水妆板	[加] [[] [[] [] [] [] [] [] [] [] [] [] []
	呂地 我之	山形入子 ・ 理子研究科 ・ 准教授	原丁核物理子 ・ 時工 (理子) ・ 動的核
	志眠 洗二	吉邦十尚 , 田尚 而你利 , 	/雁悭 「唐乙姑脑珊学」、「唐千(珊学)」、「唐乙抜
	秋到 后一	「京師八子 · 连子研究科 · 教技	原丁核初理子。
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	直田 季化		成 妻粉ヱ珈珥受 ・ 捕+ (珥受) ・ 信 攝試
	ПП <u>15</u> 1/ <u>Г</u>	米北八子 亚两内科研九州 17江功获	米松] 初珪子 侍工 (珪子) / 備極武 約 佐武
	岡村 岸引	ニュージョン 「「「「「「」」」 「「」」 「「」」 「」 「」 「」 「」 「」 「」 「	
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		高二小が 加速部の2000 の食柄 浩利学研究所 ・ 講師	
		高エネルギー加速器研究機構 ・ 物質構	原子核物理学 ・ 博十(理学) ・ ビーム
1		浩科学研究所 · 特別准教授	ライン建設
	市川 豪	高エネルギー加速器研究機構 ・ 物質構	<u>- ネーンに</u> 素粒子物理学 · 博十(理学) · ビーム
1		造科学研究所 · 特仟肋教	ライン建設
	川崎 直介	高エネルギー加速器研究機構 ・素粒子	素粒子物理学 ・博十(理学) ・低温装
1		原子核研究所 · 准教授	置のビームラインへの導入
	山形曹	理化学研究所 · 光量子光学研究領域 ·	超精密加工・博士(工学)・中性子光
		チームリーダー	

氏 名	所属	現在の専門・学位
	部局・職	役割分担
W.M.Snow	Indiana University · Department of	素粒子物理学 · Ph.D. · 米国側代表
	Physics · Professor	
C.Auton	Indiana University · Department of	素粒子物理学 · B.Sc. · 中性子ビーム
	Physics · Student	実験、レーザー核偏極
J.Carini	Indiana University · Department of	素粒子物理学 · B.Sc. · 中性子ビーム
	Physics · Student	実験、レーザー核偏極
J Curole	Indiana University · Department of	素粒子物理学 · BSc · 中性子ビーム
0.0 01010	Physics · Student	実験 レーザー核偏極
K Dickerson	Indiana University · Department of	素粒子物理学 · B Sc · 由性子ビーム
IX.DICKCISOII	Physics · Student	宝晗 レーザー核信極
I Doskow	Indiana University · Department of	表験、アーク 夜福堡 表粒子物理学 · B Sc · 由性子ビーム
J.DOSKOW	Physics • Student	宇殿 レーザー核信極
Н Г и	Indiana University : Department of	夫級、レージ 仮備型 妻粒子物理学 · B Sa · 由粧子ビーム
11.Lu	Department of Department of Department of	余粒」初程子 D.SC. 千圧」と ム 宇殿 レーザー核信柄
C Otoro	Indiana University - Department of	天殿、レーリー 核価型
G.Otero	Department of Department of	条粒丁物理子 · D.5C. · 中性丁ピーム
T T 7 1	Physics · Student	夫駅、レーリー修備型
J. Vanderwerp	Indiana University · Department of	茶粒于物理子 · B.Sc. · 中性于ヒーム
C III	Physics · Student	実験、レーザー核偏極
G.Visser	Indiana University · Department of	素粒子物理子 · B.Sc. · 甲性子ヒーム
	Physics · Student	実験、レーサー核偏極
V.Gudkov	South Carolina University · Department	素粒子埋論 · Ph.D. · 原子核埋論
	of Physics • Professor	
J.D.Bowman	Oak Ridge National Laboratory · ·	原子核物埋字 · Ph.D. · 実験設計
	Researcher	
S.Penttilà	Oak Ridge National Laboratory · ·	原子核物埋学 · Ph.D. · 動的核偏極
	Researcher	
P.Jiang	Oak Ridge National Laboratory · ·	原子核物理学 · Ph.D. · 実験設計
	Researcher	
C.Crawford	University of Kentucky · Department	原子核物理学 · Ph.D. · 熱外検出器
	of Physics • Professor	
B.Plaster	University of Kentucky · Department	原子核物埋学 · Ph.D. · 熱外検出器
	of Physics • Professor	
H.Dhahri	University of Kentucky · Department	原子核物埋字 · Ph.D. · 熱外検出器
	of Physics • Professor	
D.Schaper	Los Alamos National Laboratory · ·	原子核物埋学 · Ph.D. · 中性子ビーム
	Reseracher	実験
B.M.Goodson	Southern Illinois University · · Pro-	原子物理学 · Ph.D. · レーザー核偏極
	fessor	
R.Maruhin	Middle Tennessee State Univ. • • Pro-	素粒子原子核物理学 · Ph.D. · 熱外検
	fessor	出器
J.Fry	Eastern Kentucky Univ. • • Professor	素粒子原子核物理学 · Ph.D. · 熱外検
		出器
I.Novikov	Western Kentucky Univ. • • Professor	素粒子原子核物理学 · Ph.D. · 熱外検
		出器
L.Barron-Palos	Universidad Nacional Autonoma de	素粒子原子核物理学 · Ph.D. · 中性子
	Mexico \cdot · Professor	ビーム実験
A.Perez-Martin	Universidad Nacional Autonoma de	素粒子原子核物理学 · Ph.D. · 中性子
	Mexico · · Professor	ビーム実験
M.Veillette	Berea Colledge · · Professor	原子核物理学 · Ph.D. · 中性子ビーム
		実験
P.Hautle	Paul Scherrer Institut • • Researcher	原子核物理学 · Ph.D. · 動的核偏極
P.King	Ohio University · · Professor	原子物理学 · Ph.D. · 熱外検出器
E.Babcock	Juelich · · Researcher	原子核物理学 · Ph.D. · 中性子ビーム
		実験
M.Barlow	Nottingham \cdot · Researcher	原子核物理学 · Ph.D. · 中性子ビーム
	-	実験
A.Komives	DePauw University · · Researcher	原子核物理学 · Ph.D. · 原子核理論

氏 名	所属	現在の専門・学位
	部局・職	役割分担
J.Tang	中国科学技術大学 · · Professor	原子核物理学 · Ph.D. · 中国側代表
R.R.Fan	中国科学院高能物理研究所 · CSNS ·	原子核物理学 · Ph.D. · P 非対称研究
	Researcher	
X.Tong	中国科学院高能物理研究所 · CSNS ·	原子核物理学 · Ph.D. · レーザー核偏
	Researcher	極
J.Wei	中国科学院高能物理研究所 · CSNS ·	原子核物理学 · Ph.D. · P 非対称研究
	Researcher	
G.Y.Luan	中国科学院高能物理研究所 · CSNS ·	原子核物理学 · Ph.D. · P 非对称研究
	Researcher	

氏 名	所属	現在の専門・学位
	部局・職	役割分担
高橋 大輔	足利大学 ・ 工学部 ・ 准教授	低温物理 ・ 博士(理学) ・ 低温装置
石黒 亮輔	日本女子大学 ・ 理学部 ・ 准教授	低温物理 ・ 博士(理学) ・ 低温装置
百瀬 孝昌	University of British Columbia · De-	原子物理学 ・博士(理学) ・レーザ核
	partment of Physics ・ 教授	偏極

氏 名	所属	現在の専門・学位
	部局・職	役割分担
藤家 拓大	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学 ・ 修士(理学) ・ 中性子
		ビーム実験
伊藤 茂康	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学 ・ 修士 (理学) ・ 中性子
		ビーム実験
中部 倫太郎	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学 ・ 修士 (理学) ・ 中性子
		ビーム実験
井出 郁央	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学 ・ 修士 (理学) ・ 中性子
		ビーム実験
長谷川 拓郎	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学 ・ 修士 (理学) ・ 中性子
		ビーム実験
高橋 慎吾	茨城大学 ・ 理工学研究科 ・ 大学院生	物理学 ・ 修士(理学) ・ 中性子ビーム
		実験, SEOP
小林 龍珠	茨城大学 ・ 理工学研究科 ・ 大学院生	物理学 ・ 学士(理学) ・ 中性子ビーム
		実験, SEOP
河村 しほり	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学 ・ 学士 (理学) ・ 中性子
		ビーム実験
後藤 優	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学 ・ 学士 (理学) ・ 中性子
		ビーム実験
奥泉 舞桜	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学 ・ 学士 (理学) ・ 中性子
		ビーム実験
南部 太郎	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学 ・ 学士 (理学) ・ 中性子
		ビーム実験
伏原 麻尋	名古屋大学 ・ 理学研究科 ・ 大学院生	素粒子物理学・学士(工学)・中性子
		ビーム実験
萩原 直紀	東京工業大学 ・ 理学研究院 ・ 大学院生	原子核物理学 ・ 学士(理学) ・ 中性子
		ビーム実験
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Study of Discrete Symmetries in Polarized Epithermal Neutron Optics (NOPTREX: Neutron Optical Parity and Time-Reversal Experiment) H. M. Shimizu on behalf of the NOPTREX Collaboration

Nagoya University, Nagoya 464-8602, Japan

(May 29, 2023)

Abstract

We propose to study the breaking of the time reversal invariance (T-violation) in the spin behavior of epithermal neutrons propagating through polarized nuclear targets to search for T-odd spin correlation terms beyond the standard model with an enhanced sensitivity. The neutron absorption process is dominated by the compound nuclear process, which is observed as well-resolved narrow resonances for incident neutrons in the energy region of eV. The small energy spacing between individual resonances causes the interference of partial amplitudes in the entrance channel of compound nuclear states, which may induce energy-dependent symmetry-violating effects in case the interfering partial amplitudes have opposite parities. The small admixture of the weak interaction in the nuclear interaction have been observed as parity-violating asymmetries with the enhancement as large as 10^6 concentrated in p-wave resonances (l = 1). The enhancement is understood as the result of the combination of the kinematical resonance enhancement of the asymmetry visibility and the statistical mechanism of the parity-violating effect in multistep processes inside the compound nuclear states. Recently we have studied the complete decomposition of partial amplitudes in the entrance channel for 139 La, which exhibits about 10^6 times parity-violation enhancement at the incident neutron energy of $E_{\rm n} = 0.74 \, {\rm eV}$, and found that this process has a kinematical enhancement of T-violation visibility at the same order of magnitude as the parity-violation. The statistical mechanism of T-violating effects has been studied theoretically and can be expected to enable a novel search for T-violation with a meaningful discovery potential compared with other types of new physics searches via T- or CP- (Charge-Parity-invariance-) violation. We will apply the optical nature of neutron propagation in nuclear polarized matters to measure the T-violating effects in the forward scattering amplitude, to which the final state interaction does not contribute. In addition, this experiment is suitable to extract the isoscalar T-violating meson-nucleon coupling, which has not been selectively measured in the search for neutron electric-dipole-moment.

This experiment requires the energy-resolved intense neutron beam in the energy range of eV, which has become available after short-pulse spallation neutron sources became operational. We have concluded that the J-PARC spallation neutron source is the best neutron source to carry out this experiment among existing and planned spallation sources. If nuclear polarized target is prepared in addition to the current situation, this experiment can be put into reality. The study of polarized lanthanum target is in progress on the basis of the feasibility study of dynamical polarization of lanthanum nuclei in lanthanum aluminate single crystal diluted with neodymium ions as paramagnetic centers.

On the basis of above situation, we propose to develop and install polarized nuclear target to the neutron facility of the J-PARC and study the neutron spin behavior in polarized nuclear target, mechanism of symmetry-violating effects in compound states, search for T-violating effects and to search for new physics beyond the standard model. Although the relation between observables and fundamental CP-violation is strongly dependent on the origin of CP-violation, we compared the sensitivity to T-violation of the proposed experiment with that of neutron electric-dipole-moment search experiments by estimating their magnitude by taking only the isoscalar coupling into account ignoring isovector and isotensor couplings. The comparison suggests that a T-violation sensitivity of the proposed experiment using feasibility-proven technologies and the J-PARC spallation source with the primary proton beam power of 1 MW can reach to 10 times better than that of the neutron electric-dipole-moment search with $10^{-26}e \cdot \text{cm}$. The sensitivity comparable to EDM with $10^{-27}e \cdot \text{cm}$ can be also achieved within 100 days by improving nuclear polarization techniques.

3. Introduction

The absence (so far) of evidence for new physics from new particle creation at the LHC beyond the Higgs discovery reinforces the necessity of employing the broadest possible strategy for "Beyond Standard Model (BSM)" searches. It seems that we may need to infer the most likely candidate answers to the open questions in our field not from any single experimental result but from the overall pattern of results from many different areas of research. In combination with parallel works in searches for BSM physics at the LHC, in neutrino physics experiments, and in many other ongoing precision Standard Model (SM) tests, T-violation searches in nucleons and nuclei can make a very important contribution to outline a global picture that we need to construct from laboratory experiments, astronomical observations and theory to make further progress on the many unanswered questions of the SM.

Another powerful motivation to search for new T, B (Baryon number), and L (Lepton number)-odd interactions comes from cosmology. A. Sakharov [1] suggested that CP violation (and therefore T violation, assuming CPT invariance) along with B violation and deviation from thermal equilibrium, is an essential requirement to produce the matter-antimatter asymmetry in the early universe. An "easy" solution to this problem of introducing the baryon asymmetry into the Big Bang by hand as an initial condition is no longer tenable if one assumes the existence of cosmic inflation to explain the spacelike angular scales of correlated fluctuations in the temperature of the microwave background. Thisis because, even if the baryon number of the universe started somehow with some nonzero value, the inflation very quickly drives the baryon to photon ratio to essentially zero, and then Sakharov's argument applies again for later times after inflation. Within this cosmological framework, the fascinating question of the microscopic origin of the observed dominance of matter over antimatter in the universe becomes a scientific question susceptible to quantitative analysis.

We notice that searches for new sources of T, B, and L violation using nucleons and nuclei are also important because they can make an essential contribution to the broader set of clues on BSM physics that we hope to get from research in other sectors. In addition, the extremely enhanced sensitivity to parity-violating effects in compound nuclear process is suggesting a new possibility to the search for T-violation with a sensitivity comparable to, or even much better than, existing other experimental methods.

The compound nuclear process is a resonant state with a narrow width which commonly appears at highly excited energy regions, which can be induced by the slow neutron absorption. While such nuclear process is dominated by the strong processes, large asymmetries of the resonant absorption cross section for different helicity of incident neutrons in the epithermal energy region were found for medium-heavy nuclei and intensively studied [3, 4].

The neutron absorption process is dominated by the resonant absorption via compound nuclear states, which is observed as well-resolved narrow resonances for incident neutrons in the energy region of eV. Most of large resonances are caused by the partial wave of incident neutrons with the orbital angular momentum of 0 (s-wave). Small resonances induced by the incident neutrons with the orbital angular momentum of 1 (p-wave) are also observed among s-wave resonances. These resonances are distributed with the energy spacing of $10 - 100 \,\mathrm{eV}$, which is much smaller than the energy scale of direct or quasi-direct processes such as the excitation of particle-hole states in nuclei. Their width is as narrow as about 0.1 eV, which correspond to the lifetime as long as about million times of the time scale of direct process. This implies that neighboring compound nuclear states have large probability to interfere with each other and may result in the enhancement of parity-violation between s-wave and p-wave resonances consistently with the experimental facts, in which large parity-violating asymmetries are found in p-wave resonances with neighboring s-wave sharing the same total spin as shown in Fig. 1. Figure 2 is a summary



Figure 1: Enhancement of parity violation is observed as the helicity dependence of the cross section of p-wave resonances which neighbors s-wave resonance.

of experimental values of large parity-violating effects, which shows that the helicity dependent asymmetry is enhanced up to 10^{-1} while that in nucleon-nucleon interaction is at the level of 10^{-7} . On the basis of the interference between s- and p-wave amplitudes in the entrance channel, the value of $A_{\rm L}$ can be written as

$$A_{\rm L} = -\frac{2xv}{|E_{\rm p} - E_{\rm s}|} \sqrt{\frac{\Gamma_{\rm p}^{\rm n}}{\Gamma_{\rm s}^{\rm n}}},\tag{1}$$

where $E_{\rm p}$ and $E_{\rm s}$ are the p-wave and s-wave resonance energies, respectively, $\Gamma_{\rm s}^{\rm n}$ and $\Gamma_{\rm p}^{\rm n}$ the p-wave and s-wave neutron widths, which can be determined from the cross section measurement. The v the average value of the Podd matrix element in the nucleon-nucleon interaction in nuclei. The x is the fraction of partial amplitudes for p-wave neutrons with the total spin of j = 1/2,



Figure 2: Large parity violating effects. Horizontal axis is the resonance energy and the vertical axis the longitudinal asymmetry $A_{\rm L}$, which is the ratio of the helicity dependent cross section to the resonance cross section [10].

which cannot be determined solely from the cross section measurement. The analysis in Ref. [10] showed that the value of v can be interpreted as the averaged weak matrix element in nuclei by applying likelihood analysis with x as a randomly distributed parameter within the domain allowed by physical constraint.

The total angular momentum of incident neutron $\mathbf{j} = \mathbf{s} + \mathbf{l}$ has the value of j = 1/2 or j = 3/2. The partial neutron width for these two cases is denoted as $\Gamma_{\mathrm{p},1/2}^{\mathrm{n}}$ and $\Gamma_{\mathrm{p},3/2}^{\mathrm{n}}$ and x is given as $x^2 = \Gamma_{\mathrm{p},1/2}^{\mathrm{n}}/\Gamma_{\mathrm{p}}^{\mathrm{n}}$. By putting $y^2 = \Gamma_{\mathrm{p},3/2}^{\mathrm{n}}/\Gamma_{\mathrm{p}}^{\mathrm{n}}$, we obtain $x^2 + y^2 = 1$ from the relation $\Gamma_{\mathrm{p}}^{\mathrm{n}} = \Gamma_{\mathrm{p},1/2}^{\mathrm{n}} + \Gamma_{\mathrm{p},3/2}^{\mathrm{n}}$, which implies that we can define a real parameter ϕ as $x = \cos \phi$ and $y = \sin \phi$.

This enhancement mechanism can be generalized to other discrete symmetry for the case that two amplitudes, having opposite polarities under the symmetry operation, are connected on the boundary of the entrance channel into compound states. Reference [6] gave a quantitative estimation of the T-violation enhancement on the basis of P-violation enhancement. Below, we briefly describe the case of T-violation.

The total spin of the compound nucleus denoted by J comprises of the target nuclear spin I, the neutron spin s and the orbital angular momentum l. The state vector of the entrance channel is transformed as

$$P: |lsI\rangle \to (-1)^l |lsI\rangle, \qquad (2)$$

under spatial inversion, while it is transformed as

$$T: |lsI\rangle \to (-1)^{i\pi S_y} \hat{K} |lsI\rangle, \qquad (3)$$

under time reversal operation, where \hat{K} gives the complex conjugate, where S = s + I is the channel spin. This confirms that the P-violating observables arises from s-wave and p-wave amplitudes and T-violating ones from the amplitudes with different channel spins. Therefore, the kinematical enhancement of T-violation can be calculated by recombining angular momenta as

$$|((Is)S,l)J\rangle = \sum_{j} \langle (I,(sl)j)J|((Is)S,l)J\rangle | (I,(sl)j)J\rangle ,$$
(4)

and the corresponding forward scattering amplitude has been formulated as

$$f = A' + P_1 H'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) + P_2 E'\left((\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})^2 - \frac{1}{3}\right) \\ + (\boldsymbol{\sigma}_n \cdot \hat{\mathbf{I}})\left\{P_1 B' + P_2 F'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) + P_3 \frac{B'_3}{3}\left((\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})^2 - 1\right)\right\} \\ + (\boldsymbol{\sigma}_n \cdot \hat{\mathbf{k}}_n)\left\{C' + P_1 K'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) - P_2 \frac{F'}{3} + P_3 \frac{2B'_3}{3}(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})\right\} \\ + (\boldsymbol{\sigma}_n \cdot (\hat{\mathbf{k}}_n \times \hat{\mathbf{I}}))\left(P_1 D' + P_2 G'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})\right), \tag{5}$$

where P_1 , P_2 and P_3 are the vector polarization, 2ndrank tensor polarization and 3rd-rank tensor polarization of target nuclei and A', B', ... are energy dependent coefficients explicitly given in Eq. 26 in the Appendix within s-wave and p-wave interference formulated in Ref. [9]. The P-odd correlation term C' and P-odd T-odd correlation term D' in Eq. 5 can be related as

$$D' = \kappa(J)\frac{w}{v}C',\tag{6}$$

where w is the P-odd T-odd matrix element averaged in the compound nuclear state and $\kappa(J)$ is a function of ϕ given as

$$\kappa(J) = (-1)^{J+I+\frac{3}{2}} \sqrt{2(2S+1)} \\ \times \left(\left\{ \begin{array}{cc} 1 & \frac{1}{2} & \frac{1}{2} \\ I & J & S \end{array} \right\} + \sqrt{2} \left\{ \begin{array}{cc} 1 & \frac{1}{2} & \frac{3}{2} \\ I & J & S \end{array} \right\} \tan \phi \right) (7)$$

with $x = \cos \phi$ and $y = \sin \phi$ in Ref. [8]. The value of ϕ was recently studied for ¹³⁹La and the magnitude of $\kappa(J)$ is found at the order of unity [12] using the relation between the value of ϕ and the magnitude of the energy-dependent angular distribution of individual γ -rays in the vicinity of p-wave resonances [11]. Here we notice that the f contains only one unknown parameter w/v, which measures the magnitude of P-odd T-odd matrix element relative to P-odd matrix element.

The sensitivity of w/v to T-violation has been analyzed on the basis of an effective field theory as

$$\frac{w}{v} \simeq (-0.47) \left(\frac{\overline{g}_{\pi}^{(0)}}{h_{\pi}^{1}} + (0.26) \frac{\overline{g}_{\pi}^{(1)}}{h_{\pi}^{1}} \right), \tag{8}$$

at the leading order, where $\overline{g}_{\pi}^{(0)}$ and $\overline{g}_{\pi}^{(1)}$ are isoscalar and isovector T-violating meson-nucleon coupling constants, and h_{π}^1 is a P-violating meson exchange coupling constant, where the superscript denotes the isospin change for the process. This method was applied to interpret the experimental upper limits of nEDM and ¹⁹⁹Hg-EDM in terms of leading-order coupling constants $\bar{g}_{\pi}^{(0)}$ and $\bar{g}_{\pi}^{(1)}$ as

$$\overline{g}_{\pi}^{(0)} < 2.5 \times 10^{-10}, \quad \overline{g}_{\pi}^{(1)} < 0.5 \times 10^{-11}$$
 (9)

in Ref. [13]. The value of h^1_{π} was recently obtained from the measurement of the P-violation in $n + p \rightarrow d + \gamma$ reactions as

$$h_{\pi}^{1} = (3.04 \pm 1.23) \times 10^{-7},$$
 (10)

as reported in Ref. [16] Consequently, present upper limits can be interpreted as

$$\frac{w}{v} < 3.9 \times 10^{-4}.$$
 (11)

We notice that a suppression factor of $A^{-1/3} \sim 1/5$ in the case of the ¹³⁹La target, which corresponds to $w/v < 0.8 \times 10^{-4}$, is suggested in Ref. [15].

In this proposal, we adopt Eq. 11 as the minimum success to activate a new discovery potential of the Tviolation search in the forward scattering amplitude of polarized epithermal neutron optics in polarized nuclear target and propose experimental method to achieve the constraint and improve further improvement based on the progress of the proposed experiment.

In general, non-zero T-odd correlation does not always signal T-violation for scattering states, which is often referred to as the final-state-interaction. The forward scattering is the exceptional case where non-zero T-odd correlation terms directly signals T-violation. This is the remarkable advantage of the proposed experiment. However, we need to carefully design the experimental setup to suppress possible false effects carried by non-forward neutrons via single and/or multiple scatterings in the target.

4. Experimental Procedures

We employ the optical description for the behavior of the neutron spin in the polarized nuclear target. The initial and final spinors denoted by U_i and U_f are related with the density matrix \mathfrak{S} as

$$U_f = \mathfrak{S}U_i, \quad \mathfrak{S} = e^{i\frac{2\pi\rho}{k_{\rm n}}fz}$$
(12)

on transmission through the polarized target with the forward scattering amplitude f for the thickness of z, where ρ is the number density of target nuclei. Substi-



Figure 3: Measurement of D term with polarized neutrons and polarized target.

tuting Eq. 5, we obtain

$$\mathfrak{S} = A + B(\boldsymbol{\sigma}_{n} \cdot \boldsymbol{\hat{I}}) + C(\boldsymbol{\sigma}_{n} \cdot \boldsymbol{\hat{k}}_{n}) + D(\boldsymbol{\sigma}_{n} \cdot (\boldsymbol{\hat{k}}_{n} \times \boldsymbol{\hat{I}})), (13)$$

where

$$A = e^{i\alpha} \cos\beta, \quad B = ie^{i\alpha} \frac{\sin\beta}{\beta} \beta_B,$$

$$C = ie^{i\alpha} \frac{\sin\beta}{\beta} \beta_C, \quad D = ie^{i\alpha} \frac{\sin\beta}{\beta} \beta_D,$$

$$\alpha = Z \left(A' + P_1 H'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) + P_2 E'\left((\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})^2 - \frac{1}{3}\right)\right),$$

$$\beta_B = Z \left(P_1 B' + P_2 F'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) + P_3 \frac{B'_3}{3} \left((\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}})^2 - 1\right)\right),$$

$$\beta_C = Z \left(C' + P_1 K'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) - P_2 \frac{F'}{3} + P_3 \frac{2B'_3}{3}(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) \right),$$

$$\beta_D = Z \left(P_1 D' + P_2 G'(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) \right)$$

$$\beta = (\beta_B^2 + \beta_C^2 + \beta_D^2)^{1/2}, \quad Z = \frac{2\pi\rho}{k_n} z.$$
(14)

According to Eq. 5 and 26, this density matrix contains the adjustable parameters, that are the nuclear polarizations P_1 , P_2 and P_3 , and the only one unknown parameter w/v. The w/v will be determined after the nuclear polarizations are determined.

Here we list some of spin-dependent observables. Following the notation in Ref. [17], the analyzing power $\mathbf{A} = \text{Tr}(\mathfrak{S}^{\dagger} \boldsymbol{\sigma} \mathfrak{S})$ and polarization $\mathbf{P} = \text{Tr}(\boldsymbol{\sigma} \mathfrak{S}^{\dagger} \mathfrak{S})$ are given as

 $\begin{aligned} A_x &= 4(\text{Re}A^*D + \text{Im}B^*C), \quad P_x &= 4(\text{Re}A^*D - \text{Im}B^*C), \\ A_y &= 4(\text{Re}A^*B + \text{Im}C^*D), \quad P_y &= 4(\text{Re}A^*B - \text{Im}C^*D), \\ A_z &= 4(\text{Re}A^*C + \text{Im}D^*B), \quad P_z &= 4(\text{Re}A^*C - \text{Im}D^*B), \end{aligned}$ (15)

and diagonal polarization transfer coefficients defined as

$$K_{\pm i}^{\pm j} = \operatorname{Tr}\left(\frac{1 \pm \sigma_j}{2} \mathfrak{S}^{\dagger} \frac{1 \pm \sigma_i}{2} \mathfrak{S}\right)$$
(16)

are given as

$$K_{\pm x}^{\pm x} = |A|^{2} + |D|^{2} \pm 2 \operatorname{Re} A^{*} D,$$

$$K_{\mp x}^{\pm x} = |B|^{2} + |C|^{2} \pm 2 \operatorname{Im} B^{*} C,$$

$$K_{\pm y}^{\pm y} = |A|^{2} + |B|^{2} \pm 2 \operatorname{Re} A^{*} B,$$

$$K_{\mp y}^{\pm y} = |C|^{2} + |D|^{2} \pm 2 \operatorname{Im} C^{*} D,$$

$$K_{\pm z}^{\pm z} = |A|^{2} + |C|^{2} \pm 2 \operatorname{Re} A^{*} C,$$

$$K_{\pm z}^{\pm z} = |D|^{2} + |B|^{2} \pm 2 \operatorname{Im} D^{*} B.$$
(17)

Figure 4 shows examples of combination of observables proportional to D.



Figure 4: Combinations of observables proportional to D.

4.1. Measurement of Target Nuclear Polarization

We plan to employ neutron polarizer, polarized target and spin analyzer as shown in Fig. 5 and controlling the polarizer, analyzer and spin transport between them so that we can measure the each combination of $K_{\pm i}^{\pm j}$. The Epithermal neutrons are injected into the setup through a collimator and disk choppers, which define the beam cross section.

For determination of P_1 , K_{-z}^{+z} and/or K_{+z}^{-z} will be measured.

$$K_{-z}^{+z} = |B|^2 + |D|^2 + 2 \text{Im} D^* B$$

$$K_{+z}^{-z} = |B|^2 + |D|^2 - 2 \text{Im} D^* B$$
(18)



Figure 5: Concept of experimental setup (Top view).

The *D* is very small comparing to *B*. The *B* term consists with $P_1B' + P_2F'(\hat{k}_n \cdot \hat{I}) + P_3B'_3((\hat{k}_n \cdot \hat{I})^2 - 1)/3$. The value of K_{-x}^{+x} is oscillated as a function of neutron TOF because of the pseudomagnetic field. Although the pseudomagnetic field is compensated at the p-wave resonance energy, the oscillation occurs out of the pwave resonance because of the neutron-energy dependence of *B*. The frequency of the oscillation depends on P_1B' , $P_2F'(\hat{k}_n \cdot \hat{I})$, and $P_3B'_3$, however, the contribution is different due to their neutron-energy dependences. For example, in the neutron energy of 1.2 eV the contribution of F' is 10^{-4} times smaller than that of B'. We can extract P_1B' by using the frequency of the oscillation of P_1 and P_3 by using the frequency of the oscillation of the performance.

When we set the additional magnetic field of the compensation field at p-wave resonance region, the oscillation occurs even at p-wave resonance peak. The frequency of the oscillation include the effect from F' and B'_3 contribution, which has the magnitude of 10^{-1} of B'. We can extract $P_2(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) + P_3$ from the frequency difference between near and far from p-wave resonance.

Actually P_1 and P_2 have the order of magnitude of 10^{-1} and neutron polarization is 0.7. The contrast of the oscillation may be about 0.1. The neutron counts of 10^8 is required to measure the frequency with the accuracy of 10^{-3} with the contrast of 10%. The incident neutron flux of $1.8 \times 10^7/\text{s}$ in the energy width of 0.1 eV is planned, therefore, the measurement with 10 s is enough to determine P_1 . The order of $P_2(\hat{\mathbf{k}}_n \cdot \hat{\mathbf{I}}) + P_3$ should be less than 10^{-2} , therefore, it requires 10^5 s to determine that.

In order to estimate P_3 and/or $(\hat{k}_n \cdot \hat{I})$, the incident beam direction is changed by scanning of the slit in front of the target. The slit with 1 cm × 1 cm is installed and scanned vertically. The value of $(\hat{k}_n \cdot \hat{I})$ can be changed in the order of ± 0.002 . When we make a plot of $P_2(\hat{k}_n \cdot \hat{I}) + P_3 vs (\hat{k}_n \cdot \hat{I})$, the minimum value represents the P_3 and the value of $P_2(\hat{k}_n \cdot \hat{I})$ can be limited.

By using K_{+z}^{+z} and K_{-z}^{-z} , we can extract P_2 directly.

$$K_{+z}^{+z} = |A|^2 + |C|^2 + 2\text{Re}A^*C$$

$$K_{-z}^{-z} = |A|^2 + |C|^2 - 2\text{Re}A^*C$$
(19)



Figure 6: Spin transfer coefficients K_{-i}^{+i} and K_{-i}^{+i} as functions of neutron TOF.

The asymmetry of K_{+z}^{+z} and K_{-z}^{-z}

$$\frac{K_{+z}^{+z} - K_{-z}^{-z}}{K_{+z}^{+z} + K_{-z}^{-z}} \sim \frac{4 \text{Re} A^* C}{|A|^2}$$
(20)

leads the C, which contains C' and $P_2F'/3$, not K'and B'_3 (K' and B'_3 are canceled). The P_2 value can be extracted by calculation of C' and F'. The magnitude of F' is about 10^{-1} of that of C', and C' is 10^{-2} of the total cross section A'. For P_2 , the asymmetry with the accuracy of 10^{-4} is required. It requires about 100 s.

Finally, we can estimate the limit of $(\hat{k}_n \cdot \hat{I})$ by informations discussed above.

4.2. Interference between A and D

After determination of polarizations, the D term will be extracted by measuring the analyzing power along x-axis A_x and polarization along x-axis P_x and combine them to extract D from the relation

$$A_x + P_x = 8(\operatorname{Re}A^*D). \tag{21}$$



Figure 7: Real part and imaginary part of coefficients in Eq. 5 as functions of neutron energy.

The *D* will be redundantly determined by combining the polarization transfer coefficients K_{+x}^{+x} and K_{-x}^{-x} as

$$\frac{K_{+x}^{+x} - K_{-x}^{-x}}{K_{+x}^{+x} + K_{-x}^{-x}} \sim \frac{4 \text{Re}A^* D}{|A|^2}$$
(22)

The systematic uncertainty from the spin control may shift the central value of the asymmetry, which will be cause the center value of the asymmetry change, however, the difference of energy dependence between A and D remains. At the p-wave resonance region $\operatorname{Re}A^*D|/|A|$ has the peak if D exists. We fit the asymmetry plot by Breit-Wigner function around p-wave resonance region to search T-violating effect.

4.3. Apparatus for the experiment

Required apparatus for this experiment is discussed below.

4.3.1. Moderator and Neutron beamline

Pulsed spallation neutron sources have the very important advantage of neutron time of flight measurement for the neutron energy. The time width of the proton pulse and the moderator time and emission time distributions in the eV neutron energy range from the water moderators typically used in these spallation sources are narrow enough to enable one to resolve the typical

widths of the p-wave resonances using neutron time of flight measurements. Furthermore one gets neutrons separated by time of flight for energies both above and especially below the resonance energy. These neutrons, which are more intense than the neutrons within the p-wave resonance width which are useful for the T violation data by more than a factor of 1000, are a very important resource for the characterization and suppression of potential systematic errors.

4.3.2. Neutron Beam Monitor

A low efficiency neutron beam monitor that is insensitive to gamma rays is needed for neutron flux normalization. We already have in hand an ion chamber using ³He gas followed by ⁴He gas of the same pressure and length. The difference signal is very insensitive to gamma rays in the beam.

4.3.3. Neutron Polarizer

We propose the use of polarized ³He using spinexchange optical pumping (SEOP). Polarized ³He can be used to polarize neutrons throughout the full dynamic range of neutron energies needed for this experiment. Already the technology in use at existing neutron sources (85% ³He polarization) is very close to the regime needed to perform this experiment. The laser power at the relevant wavelength for Rb and Rb/K optical pumping increases in ongoing R&D work for polarized ³He use in neutron scattering, polarized targets for nuclear/particle physics experiments, and medical imaging. The neutron polarization is very uniform over the phase space of the neutron beam: this is very important for the suppression of potential sources of systematic errors. The spins of the polarized ³He nuclei can be reversed adiabatically with nearly zero losses in polarization: this is very important for the reversal of all fields and polarizations. The on-line optical pumping is known by experience to reliably deliver a constant neutron polarization over periods of several months.

4.3.4. Polarized Neutron Spin Transport

The neutron polarization must be guided into and out of the region of the polarized nuclear target with a defined neutron polarization direction. The fields can be small on the order of 10G. This can be done with electromagnets which possess no ferromagnetic components for field generation. To check for systematics one can use bipolar power supplies with precisely reversible currents for the external field seen by the ³He polarizer, and the spin transport into and out of the polarized target region.

The transition of the neutron spin into the polarized target region must be handled with special care. The neutron spin must be introduced into the target region using a sharp nonadiabatic transition over a short distance. The best choice for this purpose is to pass the polarized neutrons through a superconducting magnetic shield. In addition the exact angle of the neutron spin that enters the target must be controllable in all directions. Both of these technologies has been implemented successfully already for polarized epithermal neutron scattering at the ILL in an instrument called Cryopad [ref] which performs 3D neutron polarization analysis and therefore requires the instrument to not only introduce the neutron polarization into the sample region nonadiabatically but also to be able to reorient the neutron polarization direction both before and after the target using nutation of the neutron polarization with coils.

4.3.5. Polarized ¹³⁹La Nuclear Target

We propose to use ${}^{139}La$ nuclei in the form of lanthanum aluminate crystals polarized using dynamic nuclear polarization. In this case the aluminum nuclei will also be polarized. This process will also generate tensor polarization as well. Using the NMR data from the experimentally achieved value of ^{139}La polarization of 47.5%, one can estimate [5, 6, 7, 8] that the total nuclear pseudomagnetic field includint the effect of the polarized aluminum is opposite to the applied magnetic field and is smaller than it would be if only from the ¹³⁹La. This reduces one of the most important systematic errors in the measurement from nuclear pseudomagnetic precession. We estimate that the external magnetic field needed to cancel the nuclear pseudomagnetic field inside the crystal only needs to be 0.27 T on the resonance for 100% ¹³⁹La polarization. This relatively small field allows us to use niobium with $T_{\rm c}$ of 8K as a superconducting shield material.

4.3.6. Forward Neutron Detector

Detectors with unit efficiency and sufficient time resolution to resolve the eV resonances well enough to see the thermal Doppler broadening of the resonance widths exist and were used at LANSCE years ago by the TRIPLE collaboration for nuclear parity violation studies. One needs a high neutron efficiency and a fast timing resolution for this detector in order to be able to resolve with the highest possible neutron time-of-flight resolution the very important p-wave resonance region as the transmission and scattering properties of the polarized target are rapidly varying in this energy region. Two of the detector technologies, one based on ¹⁰B liquid scintillator and another based on the detection of gamma rays from neutron capture in a ${}^{10}B_4C$ target followed by detection of the gamma in a NaI(Tl) scintillator array operated in current mode are both under development and will be available for this experiment.

4.3.7. Scattered Neutron Detector

The finite size of the beam for the T violation transmission experiment means that there will be some contamination of nonforward scattered neutrons which stay inside the beam envelope. These neutrons are not exactly forward scattering and therefore can cause systematic errors. At a pulsed neutron source there is a pretty way to measure these small angle scattered neutrons: almost all excitations in the target medium which scatter at small angles for incident neutrons at eV energies will scatter also at larger angles for the much more abundant neutrons at lower energies which appear later in the neutron time of flight spectrum. Therefore with a 2D neutron detector one can measure this scattered beam component which appears at later TOF and get info on the eV small angle scattering. We have in hand a 2D position sensirtive neutron detector of the type usually used in small angle neutron scattering instruments.

4.3.8. Gamma Ray Detectors

Some of the polarized neutrons which enter the target will capture and make gamma rays. The asymmetries and angular distributions of these gamma rays carry useful information on the neutron polarization direction upon capture. In particular the A_{10} term in the formalism of Flambaum carries information on the entrance channel dynamics and can be useful to measure. We therefore plan to surround the polarized target with some gamma detectors.

4.4. Potential sources of systematic error

The systematic errors from NOPTREX are all dominated by the dynamcis and interactions of the polarized neutrons in the polarized and aligned nuclear target. The dominat effect here is the spin dependence of the neutron-nucleus strong interaction which causes nuclear pseudomagnetici precession. This has already been measured for the ¹³⁹La and ²⁷ Al nuclei and therefore one can estimate its effects in LaAlO₃. In addition the parity violation on the resonance can also generate some systematic effects as well. Here we consider many types of potential sources of systematic errors along with an estimate of the precision with which some aspects of the apparatus need to possess for their control.

(1) Incident Neutron Polarization Alignment. The relative precision of the alignment of the neutron polarization direction as it enters the LaAlO₃ target should be defined at the level of about 10^{-4} . This polarization angle can be adjusted using neutron spin nutators of the same type as used in the CRYOPAD polarized neutron scattering instrument at ILL. For the measurement of this angle we can use the intense flux of slower neutrons in the beam which will spend more time in the magnetic field region and therefore get a larger rotation angle to be detected with a downstream polarization analyzer.

(2) Uniformity of Nuclear Target Polarization. We consider two types of target non-uniformity: large-scale polarization magnitude gradients and local small-scale

variations in the polarization magnitude. The uniformity of the nuclear polarization of the target on large scales is important because, if it is nonuniform along the neutron beam direction, the parity-odd asymmetry on the ¹³⁹La resonance combined with the attenuation of the neutron intensity in the target can generate a neutron spin rotation that ruins the cancellation of the pseudomagnetic precession and therefore makes a systematic error. To avoid this we need a nuclear polarization uniformity. This has implications for the manner in which the microwave power is introduced into the LaAlO₃ crystal.

The spatial distribution of the ¹³⁹La polarization in the polarized nuclear target can also possess local nonuniformities from the different distances of the nuclei from the Nd doping centers. These centers should be reasonably uniform but this depends on the quality of crystal growth. The positive evidence for approximate spin temperature equilibrium in the previous DNP work is consistent with the spatial nonuniformities beign small but this information is not direct. For direct information one can use polarized neutron imaging to perform 3D imaging of internal magnetic fields and nuclear polarization with enough spatial resolution to diagnose possible sources of systematic error from polarized target nonuniformities. These nonuniformities if present will also lead to small angle neutron scattering which can be seen in the neutron scattering detector.

(3) Spatial Precision of Pseudomagnetic Precession *Cancellation*. The nuclear pseudomagnatic field is only present where the matter is, whereas an unshielded magnetic field spreads. To prevent this from happening we need to contain the polarized target crystal tightly inside a superconducting magnetic shield to minimize the distance along the neutron beam direction where these fields are not matched. Neutron spin rotation angle for a 0.7 eV neutron in 1 cm is 66 radians/Tesla. The magnetic field penetration depth into niobium is below 100 nm. If we assume that the magnetic field is negligible after one micron penetration length into the niobium, for a 5 cm long target this gives a fractional accuracy of the cancellation of the pseudomagnetic field polarization rotation along the neutron trajectory of a few parts in 10^{-5} . The critical field for niobium superconductor is rather high: already at 4K H_{c1} is about 1.5T.

(4) Nonforward Neutron Scattering Effects. There are some systematic effects which can come from nonforward neutron scattering in the target. For a deviation from the exact forward scattering limit the total cross section differences are no longer exactly related to the forward scattering amplitude differences and the condition for the absence of final state effects is no longer met.

It is not possible to derive the size of these effects from first principles as they depend on the specific physics of LaAlO₃. However we can detect the presence of processes that can lead to these systematics by using the broad distribution of neutron energies in the beam. There are about 10^4 more neutrons outside of the pwave resonance than inside the resonance which are available to search for such scattering effects. If the inelastic neutron scattering comes from an elementary excitation of the medium (magnons for example) which is present at the resonance energy and gives a small angle scattering angle, the same excitation at the same momentum transfer Q will give a larger scattering angle for a lower incident neutron energy and therefore will be clearly visible in a downstream neutron detector outside the beam.

For elastic scattering the dominant systematic effect is from neutron diffraction in the crystal. If a neutron is diffracted into some direction then it also satisfies the diffraction condition to be scattered into the same inital direction. One can therefore get multiple scattering from two events in the crystal which sends the twicediffracted neutron first sideways and then back into the forward direction. However these events will be delayed in neutron time of flight due to the extra distance traveled by the neutron and will appear outside the main peak in the resonance transmission data where it can be eliminated from the asymmetry analysis.

(5) Neutron Kinetic Energy Change Upon Spin Reversal. If the neutron changes its kinetic energy upon spin reversal it will encounter the P-wave resonance at a different neutrion time of flight and therefore a false asymmetry will be generated in the transmission detector signal. The defense against this effect is to change the spin without a change in the neutron kinetic energy. There are various different ways to do this which have worked well in the past for meV and eV neutron energies. Also as long as the neutron spin reversal is applied in the low magnetic field region the change in the neutron kinetic energy is of order neV or below, which is much smaller than the 0.7 eV p-wave resonance width.

(6) Precision of the Alignment of the Crystal. The faces of the LaAlO₃ crystal must be parallel and oriented normal to the average neutron beam momentum. Otherwise the finite beam divergence coupled to the misalignment of the pseudomagnetic field integral along the neutron trajectory can reduce the cancellation of the pseudomagnetic field and the magnetic field.

(7) Neutron Spin Orbit Scattering. Electromagnetic spin-orbit scattering of the component of the neutron polarization normal to the neutron momnetum will generate a left-right asymmetry which can couple to otherasymmetries to generate a systematic effect.

(8) Polarization and Intensity Gradients in the Neutron Beam. If the windows of the poalrized ³He neutron spin filter are not parallel then there are polarization and intensity gradients in the neutron beam. These can generate systematic errors in combination with the target pseudomagnetic precession as the beam moves through the target. If this is a problem it can be suppressed by slowly rotating the cylindrical polarized 3 He cell inside the SEOP ovel about the neutron beam direction. This procedure will average out any such nonuniformities due to 3 He cell nonuniform properties.

(9) Time Dependence of the Neutron or Nuclear Polarization or Target Magnetic Field. If either neutron or nuclear polarization of the target magnetic field changes in time one can get a neutron transmission asymmetry upon spin reversal. As long as any of these timedependent changes are slow they can be greatly suppressed by choosing a pettern of neutron spin reversal like +--++- which cancels linear and quadratic compnents of the time dependence.

(10) Asymmetry of Polarized Neutron Interactions in the Transmission Detector. As the neutrons are still polarized when they are absorbed in the detector, any neutron spin-dependent interactions in the detector could cause a systematic error. The detector will be made of nonmagnetic materials and also will possess no nuclear polarization. In addition the nuclei in the detector which will be chosen to basorb the neutrons, ¹⁰B, is already known to possess an extremely small parity-odd gamma asymmetry. The detector materials should also be chosen so that the circular polarization of the gammas form this process cannot scatter from the polarized electrons in a magnetized material and lead to a neutron spin-dependent detector response.

(11) Background From Gammas in the 0.7 eV Resonance. The total neutron width in the 0.7 eV p-wave resonance is dominated by gamma emission. If these gammas make a background in the neutron transmission detector there can be a systematic error generated. This can be reduced by shielding the detector from external gammas or by using a detector method which is insensitive to gammas, or both.

(12) Neutron Polarization Component Along Target Polarization In this case upon spin flips parallel and antiparallel to the target polarization, there is a transmission asymmetry from parity violation proportional to $\sigma_{n} \cdot \hat{I}$.

There is also a noticeable change of the kinetic energy of the neutrons as they enter the pseudomagnetic field of the polarized target. This energy change is of order 1 μ eV. This leads to a 2×10^{-6} shift of the neutron energy in the polarized nuclear target upon spin flip if uncompensated by any external magnetic field. The width of the 0.7 eV p-wave resonance is about 40 meV. This shift is therefore 5×10^{-5} of the p-wave resonance width.

(13) Neutron Polarization Component Along Neutron Momentum. In this case there is a transmission asymmetry from parity violation proportional to $\sigma_{n} \cdot \hat{k}_{n}$.

(14) Violations of the Adiabatic Neutron Spin Motion Upion Spin Reversal. In this case the spin reversal is not complete and there can be unwanted components of the neutron spin passing through the polarized target which generate systematic errors. These unwanted spin components cna be greatly suppressed with proper design of the neutron spin transport system.

4.5. Research plan

4.5.1. Measurement of $\operatorname{Re}A^*D$

The actual design of experiment is described in this section.

The epithermal neutrons from the poisoned moderator are injected into the setup through a collimator and disk choppers, which define the beam cross section and TOF structure. Assuming that the target area is $4 \text{ cm} \times 4 \text{ cm}$ and a neutron beam of $0.74 \text{ eV} \pm 0.05 \text{ eV}$ is used, the intensity of the neutron beam at the target position with a beam power of 1 MW is estimated using the Monte-Carlo simulation as $1.8 \times 10^7 \text{ n/s}$.

The ³He spin filters as a neutron polarizer and an analyzer are installed before and after the polarized nuclear target of ¹³⁹La. The polarization direction of the neutron polarizer and analyzer based on ³He spin filter is switched periodically. We consider the period as J-PARC MR injection timing (about every 6 s). We repeat K_{+z}^{+z} , K_{-z}^{+z} , K_{-z}^{-z} , K_{+z}^{-z} , and K_{+x}^{+x} , K_{-x}^{-x} to monitor P_1 , P_2 , P_3 and measure the D term.

There are some options to polarize the target, now we consider that the 139 La target is always polarized by using the dynamical nuclear polarization (DNP) technique. The target is kept in the magnetic field of 0.1 T and the temperature of 0.1 K. The microwave with the frequency of 3 GHz and the power of 1 mW is irradiated onto the target while measurements. The polarization is kept to about 50% to cancel the pseudomagnetic field of the target with the external field of 0.1 T.

The magnetic field around the target must be separated between the target and beam paths just before and after the target. Neutrons with the spin of the direction of x-axis are injected adiabatically into the target through the magnetic shield. The magnetic shield is considered as a superconducting shield made with Nb. The critical magnetic field is about 0.15 T.

The development of polarized target is most important and most difficult issue of this proposal. The details of the polarized target is described in next chapter.

Transmitted neutrons are detected by using a neutron detector with the counting rate of 1 GHz in maximum. We are now considering the detector as a current mode detector, which consists of ¹⁰B target and surrounding NaI γ -ray detectors.

The γ -ray detectors are placed surrounding the polarized target. The γ -rays can be used to monitor the target polarization by using quantity-change or asymmetry of the (n, γ) reactions.

Scattered neutrons from the target are detected by (conventional) neutron detectors surrounding the polarized target. This enables us to study the nuclear resonance reaction precisely through the scattering amplitude. Required measurement time is estimated. We assume the polarized target of the single crystal of LaAlO₃, with the cross section of 4 cm \times 4 cm and the thickness of 2.8 cm. The value of Re A^*D is 6.7×10^{-6} , which is equivalent to the limit of T-violation by neutron EDM experiments. The polarization of incident neutrons is 0.87 and the polarization of the target La is 0.4, which are achievable with today's technique. This requires the measurement time of 7.4 days.

This estimation is based on the enhancement of T-violation is the same as that of P-violation. Fadeev claimed that the enhancement of T-violation in compound nuclei should be suppressed to 1/5 of that of P-violation. If so, the required time should be extended to 185 days, which is realizable.



Figure 8: 3D view of the beamline

4.5.2. Studies of Compound Nuclei and resonance reactions

In order to establish and to confirm the formalism of compound nuclei, the detailed study of the resonance reaction in compound nuclei will be performed before and while the T-violation measurement.

First, the resonance parameters, the peak energies and the widths are measured by using (n, γ) reaction. The *A* term can be measured with unpolarized neutrons and unpolarized target. For the precision measurement, the pulse-shape of the incident neutrons are carefully studied. The temperature of the nuclear target is controlled to estimate the doppler broadening of the peak. We have already planned the measurement of the pulse shape by using diffraction technique with perfect silicon crystal.

Although the polarization is not so high, the neutron polarizer based on ³He is now available for epithermal neutrons. We study the *C* term, which is correlated to $\boldsymbol{\sigma}_{n} \cdot \hat{\boldsymbol{k}}_{n}$ precisely, especially its energy-dependence.

Once the polarized target is available, even though the polarization is not so high, we can start the studies of some other correlation terms, for example B term. The neutron-energy dependence is also interesting subject, which is not studied previously. We can also find F', K', and B'_3 terms experimentally. The details how to study each correlation term is described in Appendix. For all studies, new dedicated beamline with epithermal neutrons is strongly recommended.

4.6. R&D items

4.6.1. Epithermal neutron beamline

We propose to construct a new beamline at the port BL07 which views the poisoned moderator as a compromise to accommodate this experiment.

- 1. Intensity of epithermal neutrons almost independent of the kind of moderators (ref. Fig. 9) J-PARC/MLF spallation neutron source has three kinds of moderators: coupled, decoupled and poisoned moderators. The time-integrated intensity $\partial \Phi / \partial E$ [cm⁻² s⁻¹ sr⁻¹ eV⁻¹ @ 1 MW] on the moderator surface is shown in Fig. 9, which visualizes that it does not depend on the kind of moderators in epithermal region.
- 2. Spin control can be monitored precisely if thermal and cold neutrons are monitored simultaneousely. Better time resolution is preferred.



Figure 9: Time-integrated intensity on the moderator surface $\partial \Phi / \partial E \ [\text{cm}^{-2} \ \text{s}^{-1} \ \text{sr}^{-1} \ \text{eV}^{-1} \ @ 1 \ \text{MW}]_{\circ}$

4.6.2. Neutron Polarizer

In order to polarize epithermal neutrons, the candidates of the neutron polarization device are ³He spin filter and proton spin filter. Both utilizes a spin dependent cross section for neutrons to polarize neutrons. Since the ³He spin filter is suitable for low energy neutrons less than several eV, the ³He spin filter to polarize 0.74 eV neutrons, which is resonance energy of p-wave resonance of ¹³⁹La, is mainly discussed in this section. ³He has a very large absorption cross section (10666 barn at thermal energy) for neutrons with spin antiparallel to the ³He spin, while the absorption cross section



Figure 10: Full-width at half maximum of the neutron pulse as a function of neutron energy $t_{\rm FWHM}$.

for parallel neutrons is approximately zero. The neutron beam is polarized passing through a glass cell into which polarized ³He is encapsulated. A figure of merit (FOM) used to describe the polarization efficiency of the ³He spin filter is defined as

$$FOM = P^2T, (23)$$

where P and T are neutron polarization and neutron transmission, respectively. As shown in Fig. 11, P, T



Figure 11: The variation of the neutron polarization, transmission, and FOM as a function of the amount of 3He for 0.74 eV neutrons, evaluated for a ³He polarization of 70%.

and thus the FOM depends on the thickness of the ${}^{3}\text{He}$, given by the product of the pressure of ${}^{3}\text{He}$ gas and the length of the ${}^{3}\text{He}$ spin filter. For a ${}^{3}\text{He}$ polarization of 70% and 0.74 eV neutrons, the FOM has a maxi-

mum at 79 tm·cm, for which P = 87% and T = 30%. Therefore, we need to develop a ³He spin filter of 79 atm·cm with 70% ³He polarization. Since the maximum pressure of ³He is 3.1 atm, the length of the glass cell would be 25 cm. Additionally, the radius of the glass cell should be 7 cm at least as the size of a neutron beam is 4×4 cm² (a diagonal is 6.9 cm).

³He is polarized with the Spin Optical Pumping (SEOP) method with alkali metal. Pure rubidium is enclosed with ³He gas in the glass cell, and peripheral electrons of the Rb atoms are polarized by the circularly polarized laser. The polarization of the electrons moves to the ³He nuclei with the hyper fine interaction, and the ³He nuclei are polarized. Today a new technique called as 'Hybrid-SEOP' is developed to build the polarization up quickly by using spin exchange with K atoms and Rb atoms. The SEOP technique requires a high power laser with narrow bandwidth to polarize Rb.

A well-uniform magnetic field is applied to the ³He spin filter using a solenoid and a compensation coil with a magnetic shield to maintain the ³He polarization. The ³He polarization relaxes by the inhomogeneity of the magnetic field, impurities inside the glass cell, collisions with other ³He nucleus, and other effects. Especially, a clean vacuum system to encapsulate ³He and alkali metal to the glass cell is important to fabricate ³He which have long relaxation time.

A high power laser is also important to polarize large volume of ³He gas. In order to polarize the large ³He spin filter, we should irradiate the high intensity laser light (around 200 W) from both sides of the ³He spin filter to avoid attenuation of the laser light in the ³He spin filter. Also the laser system is needed to be installed the neutron beam line to maintain high ³He polarization in the T-violation experiment.

4.6.3. Neutron Detector

The detector used in this study is sensitive in the assumed resonance energy region, and an epithermal neutron detector that can be used in the region of approximately 1 eV is required. Assuming a full neutron beam of MLF beamline, it is desirable that the instantaneous count rate in the 1 eV region is about 100 Mcps/cm² ~ 1 Gcps/cm². In addition, if estimate from statistics, in order to count about 10^{10} event in 30 days, an instantaneous count rate of 1 Mcps is required. Therefore, the performance required for the detector is at least 1 Mcps, and if possible, a neutron detector that satisfies 1 Gcps is required.

There are no fast neutron detector satisfying such an instantaneous count rate has been realized, so the following two types of detector candidates are planned and developed.

1. Current mode operation of PMT output by detecting γ rays with using ¹⁰B neutron converter.

2. Development of a new high count rate neutron detector using scintillators with a short decay time constant

Currently, Kentuchy University is proceeding with the design and production of 1. as the candidate detector for this research project, and the Japanese side is proceeding with the study of 2. as the backup detector.

Current mode detector

It is desirable that the detection efficiency is as high as possible since the measurement requires many statistics. On the other hand, the maximum instantaneous counting rate of the neutron is about 2×10^8 n/s/cm² in the $E_n = 1$ eV region. In such a high count rate measurement, the output signal may be continuous even when a detection element and an amplifier with a fast time constant are used. The first candidate of our transmission neutron detector is the Current Mode Detector, which is a method of reading the current of PMT output signal. Figure 21 shows the schematic view of the our Current Mode Detector, which is developed at Kentucky University. Incident neutron beam is stoped at 10 B converter plate and converted to 0.388 MeV γ rays. The γ rays are detected with a nearby NaI detector. The detector test is progressing at J-PARC MLF BL10 and Los Alamos Neutron Science Center.

Scintillation detector

In order to achieve high counting rate by photon counting the epithermal neutrons with a scintillation detector, it is required to have a fast decay time, a solid that can be segmented, and a time characteristic that allows n/γ discrimination. Liquid scintillator containing the ¹⁰B has been commonly used to detect neutrons in eV region and the candidate. The decay time of this liquid scintillator is about 4 ns, very high counting rates can be achieved using this scintillator. Moreover, since γ -rays can be background for the measurement, neutron and γ -ray discrimination is also important. The discrimination can be performed by using the pulse shape difference between the neutron and the γ -ray detection. On the other hand, since the material is liquid, it is difficult to segment and it is difficult to increase the counting rate of the whole detector.

Another candidate is the ¹⁰B containing plastic scintillator, and CsI(pure) scintillator with B layer. Both scintillator has the decay time of about 10 ns. Both are solid and can be segmented. The plastic scintillator is not available the n/γ separation but there is a possibility that detection efficiency can be increased. The CsI(pure) scintillator with B layer detector may be available n/γ separation. The evaluation of these scintillators are proceeding.

A scintillator with a large light yields causes a voltage drop in the PMT in high count measurement, so it is better to use a scintillator with a small light yield.

Scintillator	decay time (ns)	Neutron absorption probability at 0.75 eV 1cm thickness	n/ γ separation
B-Loaded liquid	3.2	82%	yes
CsI(pure)	10,36	0.8%	(yes)
with Boron layer		for ¹⁰ B $1\mu m^t$	
Li-glass	16,49,78	93%	no
B-Loaded plastic	1.5	88%	no

Table 1: Scintillator candidates

5. Polarized target

5.1. Past achievements in the research project 2018-2021

We are planning to use a single crystal of LaAlO₃ doped with Neodymium ions(Nd) as target material of the polarized La target because about 50% polarization of La in 0.03mol% Nd-doped crystal has already been obtained in the magnetic field of 2.3 T and at the temperature of 0.3 K by using the dynamic nuclear polarization method(DNP)[31]. Toward developing the polarized target with the LaAlO₃ crystals, the RCNP research project "Development of polarized target for new physics search via T-violation" has started since FY2018 and is ongoing even now[33]. At present, the preparation of the DNP apparatus for tests in high magnetic field (about 5 T) is in progress. Although the DNP has not been carried out at RCNP, we have achieved important results in the research project as follows.

- \bullet Measurements of relaxation times (T_1s) at various conditions
- Establishment of crystal growth method at IMR, Tohoku University
- Confirmation of the DNP with the crystals grown by ourselves at Yamagata University

In the T-violation experiments, the pseudomagnetic spin rotation of a neutron, which is caused by the nuclear interaction between a neutron spin and a nuclear spin of La, reduces the sensitivity to the T-violating effects. For making the systematic effect as small as possible, the external magnetic field for holding the nuclear polarization is applied to cancel out the pseudomagnetic rotation. In the LaAlO₃ crystals, the pseudomagnetic field is calculated to be about 0.2 T for 100 % polarization of La[7]. For about 50 % polarization, the external magnetic field of about 0.1 T allows us to almost cancel out the systematic rotation of the neutron spins. This requires us to investigate T_1 of La in about 0.1 T because its length strongly involves a feasibility as the polarized target or a strategy on preparation process of the polarized target. Hence, we have measured T_1s at various conditions and estimated the T_1 in 0.1 T at temperature of 0.1 K, which is generally achievable with a standard cryogenic system, because the magnetic field of 0.1 T is too small to obtain sufficient signal-to-noise ratio(S/N) in an ordinary NMR apparatus[34].

The T₁ measurements were carried out under magnetic fields of 0.5-2.5 T at temperatures of 0.1-1.5 K by using two kinds of cryogenic systems at RCNP. We used the crystal with Nd concentration of 0.03 mol% and dimension of 15mm cubic and measured the time dependence of the NMR signals in behavior of decay or buildup to various thermal equilibriums. Assuming the dominant relaxation is the process via electric spin-spin reservoir (SSR), which contribution has been already confirmed according to the DNP studies on the La polarization[35] and the equivalence of T₁s between La and Al[34], the nuclear relaxation can be described as,

$$\frac{1}{T_1} \propto C^2 \frac{1}{T_{1ss}} \left(\frac{1}{B_0}\right)^2 \left(1 - P_0^2\right), \qquad (24)$$

where the C is the Nd concentration, the T_{1ss} is the relaxation time of the SSR, the B_0 is a strength of the magnetic field, and the P_0 is the thermal polarization of electrons in Nd ions[39]. The extrapolation with Eq. (24) can provide the estimation of the T₁ in 0.1 T and at 0.1 K,

$$T_1 \ge 1h. \tag{25}$$

The result suggests to reduce the C and decrease the temperature lower than 0.1 K for improving the T_1 . Since the T_1 is inversely proportional to C^2 and the buildup time of the polarization in the DNP is proportional to C, the optimization of the Nd concentration for making the T_1 longer is fairly beneficial because a saturated polarization in the DNP is determined by the balance between the buildup and the relaxation times.

On the crystal growth, we have established the fundamental method for growing LaAlO₃ crystals based on the floating zone(FZ) method at IMR, Tohoku University[36, 34]. The size of crystals is small, where the typical dimension is a diameter of 5 mm and a length of 20 mm, but a procedure for removing twin domain structures has almost established, which are effectively responsible for reducing the number of polarized La nuclei. Normal LaAlO₃ crystals contain the twin domain structures because of structural phase transition in cooling process just after the crystal growth [37]. In addition to the improvement of crystalline nature, we have become able to provide crystals with various Nd concentration around 0.01 mol%. This technological achievement is quite essential because the optimization of the Nd concentration becomes possible in the vicinity of 0.01 mol%. For this purpose, it is necessary to confirm the enhancement of both NMR signals of La and Al in the DNP tests with the crystals grown by ourselves.

In the DNP experiments at Yamagata University, we have made the first observation of the enhancement in La and Al polarization with the 0.05 mol% crystals at 1.3 K in 2.3 T. Although each enhancement of 2.68 ± 0.20 for La and 2.45 ± 0.03 for Al is small, this is a great step toward further DNP studies. The DNP via the SSR leads to the almost equal enhancement between La and Al. In the use of 0.01 mol% crystal, we have observed the enhancement of Al larger than 14 at the same condition, where the La enhancement is likely to be the same as Al. Combining the present results with the past ones reported in reference [38, 35], the dependence on the Nd concentration is summarized as the table2.

The above summary shows interesting region of the Nd concentration is from 0.005 mol% to 0.01 mol% in terms of the Nd optimization.

At present, the following issues are in progress.

- Preparation of the DNP apparatus for performing the DNP tests at RCNP
- Further optimization of the Nd concentration at Yamagata University
- Studies on a method for growing a large crystal at IMR, Tohoku University
- Exploration of a method for adsorbing aromatic molecules into the LaAlO₃ crystals for active control of the T_1

For continuing the R&D of the polarized La target based on the DNP, it is essential to establish the DNP technique at RCNP. Then, the DNP tests with the crystals of 0.005-0.01 mol% Nd concentrations are necessary for making it possible to select the best crystal. After the selection, it is also significant to perform the similar studies with the best crystal for estimating the T_1 in 0.1 T. Since the T-violation experiment requires the crystal which dimension is $40 \text{ mm} \times 40 \text{ mm} \times 30 \text{ mm}$, a method of growing such large crystals is also necessary. We have already started the studies based on the Czochralski (CZ) or the Kyropulos method[40, 41]. Additionally, as an alternative instead of the DNP, we are thinking of applying the brute-force method to pure crystals of LaAlO₃. The T₁ of the pure LaAlO₃ crystals is extremely long because of no paramagnetic ions[39], but such long T_1 makes it difficult to reach high polarization at thermal equilibrium. The active control of the T_1 is a possible solution to overcome such difficulty. One of specific ways is to use aromatic molecules, where the excited triplet state accelerates the nuclear relaxation and the ground state gives no influence to the

original relaxation. We are planning to use benzophenone molecules as "relaxation switch" [42] and exploring an effective method for adsorbing them into the LaAlO₃ crystals. These issues will be also continued in the continuous project(category I) " Development of various polarized nuclear targets with dynamic and static nuclear polarizations", where the spokes person is changed from H. Shimizu and M. Iinuma to H. Kohri[43]

5.2. Low-field DNP

Taking into account of the estimation given by Eq. (25), the T₁ of the best crystal in 0.1 T might be insufficient for the T-violation experiment. A possible way to completely overcome the relaxation problem is to constantly perform the DNP in 0.1 T during the measurement of T-violation. Moreover, the DNP in such low field brings an efficient use of the beam time because the additional time for preparing the polarization is unnecessary. The conceptual setup around the polarized target is shown in Fig. 12.



Figure 12: Concept of setup around the polarized target

The polarized target, which dimension is a square of 40 mm × 40 mm and a length of 30 mm, is prepared under the magnetic field of 0.1 T at the temperature of 0.1 K for the cancellation of the pseudomagnetic field. The initial goal of the La polarization is 50%. The lowfield DNP is always performed during the measurement of the T-violations to keep the constant polarization of 50%, where the frequency of the RF pulses for irradiating the target materials is 2.8GHz. To make the magnetic field uniform in both of direction and strength, the field generated by a coil is forcibly confined in the target space and uniformly formed with four superconducting magnetic shields made of Niobium, which are located at both of front and back faces to the injection of a neutron beam and at both sides of the target.

The efficiency of the polarization transfer from electron to La nuclear spins is required to be about 85 % because the thermal polarization of the electrons provided by the Nd ions is 58%. Although our experiences

Nd concentration	condition	La enhancement	Al enhancement	relaxation time
0.05 mol%	2.3 T, 1.3 K	2.7	2.5	15 min.
0.03 mol% [35]	2.3 T, 1.5 K	~ 100	~ 100	80 min.
0.01 mol%	2.3 T, 1.3 K		> 14	> 80 min.
0.005 mol% [38]	2.3 T, 1.5 K	1	1	

Table 2: Nd concentration

on the low-field DNP are not so much, the polarization transfer in the low-field is basically possible by using the Integrated Solid Effect (ISE), which is used as a general technique in the triplet DNP[44]. In order to perform the ISE, the frequency should be swept over about 20MHz, which corresponds to the ESR linewidth of 6G. This linewidth is confirmed by ourselves and the previous measurements [45]. The RF power is inputted via a RF cavity based on the loop-gap resonator because the ISE is essentially a coherent polarization transfer. Since the resonant frequency is 2.8GHz, the corresponding Q value is about 150, which is practically achievable even if the crystal is placed inside of the cavity. The RF cavity also has a role of preventing a large loss of the RF input power to keep the temperature of 0.1K constant. It is cooled down via a cold-head thermally contacted to Liquid helium at 4K, whereas the target crystal in the housing is cooled down via He4 by the mixing chamber at 0.1K. The crystal is dominantly heated up by the absorption of the RF power and its heat load depends on the Nd concentration of the crystal. Its value in the 0.01 mol% crystal, for example, is estimated to be 2mW, which is achievable by using present cryogenic technology. Since the LaAlO₃ is generally used as a ferroelectric substrate for the RF, the dominant RF power loss is not attributed to the absorption in the target crystal itself, but to the absorption in the RF cavity. By thermally separating the crystal from the RF cavity, the cooling efficiency of whole cryogenics become balanced. A little more detail of structure around the target is illustrated in Fig. 13, which shows rough image of the 0.1K dilution, the target housing, the RF cavity, the Helmholtz magnet for generating the magnetic field of 0.1 T, and four superconducting shields.

However, there have been no experiments with the low-field DNP so far because the conventional DNP is typically carried out in higher magnetic field than 2T. Therefore, it is necessary to study its feasibility. For the purpose, we will try to perform the ISE with the RF cavity at 4 K or 1.5 K. An example of rough designs of the RF cavity is shown in Fig. (14). To avoid unwanted troubles, we will use the Nd-optimized crystals which are selected in the DNP tests in a high field. After confirming the feasibility, we will move to the design and the construction around the polarized target. The feasibility studies will be also expanded in the continuous project[43]. If the low-field DNP is not feasible,



Figure 13: Structure of the Helmholtz magnet and the 0.1K dilution. The RF cavity is cooled down via the cold-head by Li He4.

it is necessary to consider all potentialities for realizing the polarized target based on the DNP in a high field.

5.3. Brute-force with the active control of T_1

If the crystal is left under the condition of 17T and 0.01K, the La thermal polarization of 50% is achievable. In RCNP, such cryogenics system is still working. The polarization is growing up to 50 % by just putting the crystal in the above cryogenics. The active control allows us to obtain such polarization within a realistic time. After getting enough polarization, the switch-off of the active control returns to the original T_1 , which is extremely long. This method is the second option in the case of not realizing the polarized target on the DNP.

The crystal with the sufficient polarization is carried to J-PARC by using the existing portable 1.5 K cryostat and slowly installed in the target cryostat, where the magnetic field of 0.1 T and the superconducting shields are prepared. Thus, the structure of the 0.1K dilution as shown in Fig. 15 is similar to the low-field DNP except for the RF cavity. The crystal is mounted to thermally contact to the mixing chamber through the cold-head. In the brute force method, although the T_1 in the pure crystal is expected to be extremely long, it is too long and has not been measured yet at low temperature.



loop-gap resonator

Figure 14: Example of the cavity design. The loopgap resonator is useful, because an oscillating magnetic field is very homogeneous over the target region[46]. It is made of copper and its Q value is 150.

Since the 0.1 K dilution for the target cryostat, two 1.5K cryostats for transferring the crystal from the target station in RCNP to the portable cryostat and from the portable cryostat to the target cryostat placed in the beamline are commercially available, the feasibility is in the realization of the active control of the T_1 . The feasibility is investigated along the following procedure.

- 1. Establishment of the method for adsorbing benzophenon molecules into the pure crystals of LaAlO $_3$
- 2. Tests of active control of the T_1 at 4 K or 1.5 K
- 3. Further tests of active control at 0.1 K with the dilution at RCNP

The above studies will be also expanded in the continuous project [43].



Figure 15: Structure of the Helmholtz magnet and the 0.1K dilution in the polarized target obtained by the brute force. The rod supporting the crystal housing can be inserted in and removed from the 0.1K dilution

5.4. Present Status

The current status of R&D items without polarized target are described below.

5.4.1. Studies of Nuclear Reactions

This experiment is based on the framework of compound nuclei with the mixing of s- and p-wave components. Before all, and at the same time, the details of nuclear reaction must be studied.

In order to estimate the possibility of the candidates as the target, we have measured the κ value of ¹³⁹La by observing of (n, γ) reaction. According to the s-p mixing formalism, the angular distribution of emitted γ -ray from a resonance state can be explained by using the relative amplitude of each partial wave component. At the p-wave resonance neighboring the large s-wave peak, only the ratio between j = 1/2 and j = 3/2 in the p-wave component is an unknown parameter. The angular distribution of γ -ray appears even when both of the neutron and the target are not polarized.

We have successfully measured the angular distribution from ¹³⁹La(n, γ) reaction at BL04 ANNRI beamline in MLF at J-PARC. The germanium γ -ray detectors with high resolution of γ -ray energy and the timeof-flight measurement of pulsed neutrons to resolve the neutron energy enabled us to determine the final state of the reaction and to extract the γ -ray distribution. The observed distribution was explained by using the s-p mixing formalism. Finally we get the finite region of the κ parameter, which have the magnitude of the order of 1. This showed that ¹³⁹La is the promising candidate for the T-violation search experiment because the enhancement of T-violating process is about 10⁶.

By using polarized neutron beam, we can study more details of the nuclear reaction, for example, the validity of the s-p mixing formalism. We have already tried to install the neutron polarizer based on ³He spin filter into the ANNRI beamline. Although the polarization was about 20%, we measured some correlation terms of the γ -ray. The longitudinal asymmetry, which represents P-violation and connects to C term, was observed. It was consistent with the literature values of previous measurements. We have also measured the transversal asymmetry (a correlation term with $(\boldsymbol{\sigma}_n \cdot (\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{k}}_{\gamma}))$). The results are ready to publish.

In order to search the other candidates of the target nuclei, we are continuing the measurement of (n, γ) reactions at ANNRI beamline. For example, ¹¹⁷Sn is one of the candidates because it has the nuclear spin of 1/2, which the description of the forward scattering amplitude can be written very simply. Even though ¹³¹Xe is a gas in room temperature, there is a possibility to polarize the Xe nuclei by using optical pumping method.



Figure 16: Resonance peak fit of La



Figure 17: Gamma-ray asymmetry of La

5.4.2. ³He Spin Filter

The development of the ³He spin filter is mainly conducted at J-PARC and KEK. A gas filling station for ³He spin filters are constructed at J-PARC in last year. We fabricated several ³He spin filters using pure Rb and Rb and K, and a long relaxation time of the ³He polarization with around 200 h is achieved for four ³He spin filters by improvement of a rinse process of the glass cell. A ³He spin filter with ³He thickness of 29.3 atm·cm and radius of 6.5 cm is now available (Fig. 19). Therefore, the ³He spin filter with 79 atm·cm can be achieved by using series of the two or three ³He spin filters.

Currently, we are developing a fiber laser system with 110 W which can irradiate the laser light from both sides of a ³He spin filter and can be installed neutron beam lines (Fig 20). The ³He polarization of over 70% has been achieved by using this laser system with the



Figure 18: κ value of La

hybrid cell of 21 atm·cm (ϕ 4.5 cm × 7.5 cm).As an SEOP system using 200 W laser has been reported in Oak Ridge National Laboratory, it seems possible to develop the above laser system.

The development of the proton spin filter to polarize epi-thermal neturons are also ongoing at RIKEN. The proton is polarized by the triplet DNP. They made a large crystal of $\phi 15 \times 4$ mm, and 28 % of the proton polarization was achieved at 90 K. They conducted an experiment to polarize neutron beam with RANS (Accelerator-driven compact neutron source at RIKEN) and obtained 8.5% polarization for 1-10 eV neutrons. As 80% proton polarization has been reported at PSI, the proton polarization will be improved by using cryostat with liquid He.

5.4.3. Neutron Detector

1. Required detector performance

The detector used in this study is sensitive in the assumed resonance energy region, and an epithermal neutron detector that can be used in the region of approximately 1 eV is required. Assuming a full neutron beam of MLF beamline, it is desirable that the instantaneous count rate in the 1 eV region is about 100Mcps/cm² ~ 1Gcps/cm². In addition, if estimate from statistics, in order to count about 10^{10} event in 30 days, an instantaneous count rate of 1 Mcps is required. Therefore, the performance required for the detector is at least 1 Mcps, and if possible, a neutron detector that satisfies 1 Gcps is required.

There are no fast neutron detector satisfying such an instantaneous count rate has been realized, so the following two types of detector candidates are planned and developed.

(a) Current mode operation of PMT output by detecting γ rays with using ¹⁰B neutron converter.



Figure 19: A $^3\mathrm{He}$ spin filter with a dimension of $\phi6.5~\mathrm{cm}$ and 11.5 cm.

(b) Development of a new high count rate neutron detector using scintillators with a short decay time constant

Currently, Kentuchy University is proceeding with the design and production of 1. as the candidate detector for this research project, and the Japanese side is proceeding with the study of 2. as the backup detector.

2. Current mode detector

It is desirable that the detection efficiency is as high as possible since the measurement requires many statistics. On the other hand, the maximum instantaneous counting rate of the neutron is about $2 \times 10^8 \text{n/s/cm}^2$ in the $E_n = 1 \text{eV}$ region. In such a high count rate measurement, the output signal may be continuous even when a detection element and an amplifier with a fast time constant are used. The first candidate of our transmission neutron detector is the Current Mode Detector, which is a method of reading the current of PMT output signal. Figure 21 shows the schematic view of the our Current Mode Detector, which is developed at Kentucky University. Incident neutron beam is stoped at ¹⁰B converter plate and converted to 0.388 MeV γ rays. The γ rays are detected with a nearby NaI detector. The detector test is progressing at J-PARC MLF BL10 and Los Alamos Neutron Science Center.

3. Scintillation detector

In order to achieve high counting rate by photon



Figure 20: Laser system which can be install to a neutron beam line to polarize a 3 He spin filter during a neutron experiment.



Figure 21: Current mode neutron detector

counting the epithermal neutrons with a scintillation detector, it is required to have a fast decay time, a solid that can be segmented, and a time characteristic that allows n/γ discrimination. Liquid scintillator containing the ¹⁰B has been commonly used to detect neutrons in eV region and the candidate. The decay time of this liquid scintillator is about 4ns, very high counting rates can be achieved using this scintillator. Moreover, since γ -rays can be background for the measurement, neutron and γ -ray discrimination is also important. The discrimination can be performed by using the pulse shape difference between the neutron and the γ -ray detection. On the other hand, since the material is liquid, it is difficult to segment and it is difficult to increase the counting rate of the whole detector.

The other candidate is the ¹⁰B containing plastic scintillator, and CsI(pure) scintillator with B layer. Both scintillator has the decay time of about 10 ns. Both are solid and can be segmented. The plastic scintillator is not available the n/γ separation but there is a possibility that detection efficiency can be increased. The CsI(pure) scintillator with B layer detector may be available n/γ separation. The evaluation of these scintillators are proceeding.

A scintillator with a large light yields causes a voltage drop in the PMT in high count measurement, so it is better to use a scintillator with a small light yield.

References

- [1] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967).
- [2] G. E. Mitchell, J. D. Bowman, and H. A. Weidenmuller, Rev. Mod. Phys. **71**, 445 (1999).
- [3] G. E. Mitchell, J. D. Bowman, S. I. Penttila, and E. I. Sharapov, Phys. Rep. 354, 157 (2001).
- [4] "Whitepaper for the 2023 NSAC Long Range Plan", arXiv:2304.03451.
- [5] V. G. Baryshevsky and M. I. Podgoretsky, Zh. Eksp. Teor. Fiz. 47, 1050 (1964).
- [6] V. P. Gudkov, Phys. Rev. C46, 357 (1992).
- [7] V. Gudkov and H. Shimizu, Phys. Rev. C 95, 045501 (2017).
- [8] V. Gudkov and H. Shimizu, Phys. Rev. C 97, 065502 (2018).
- [9] V. Gudkov and H. Shimizu, Phys. Rev. C 102, 015503 (2020).
- [10] G.E. Mitchell, J.D. Bowman, S.I. Penttilä and E.I. Sharapov, Physics Reports, 354 157 (2001).
- [11] V. V. Flambaum and O. P. Sushkov, Nucl. Phys. A 435, 352 (1985).
- [12] T. Okudaira et al., Phys, Rev. C 97, 034622 (2018).
- [13] Y.H.Song, R. Lazauskas, and V. Gudkov. Phys. Rev. C 83 065503 (2011).
- [14] S. F. Mughabghab. Atlas of Neutron Resonances 5th ed. Elsevier, Amsterdam, 2006.
- [15] Pavel Fadeev and Victor V. Flambaum, Phys. Rev. C 100, 015504 (2019).
- [16] D. Blyth et al., Phys. Rev. Lett. **121**, 242002 (2018).
- [17] P. K. Kabir, Phys. Rev. D 37, 1856 (1988).
- [18] J.D.Bowman and V.Gudkov, Phys. Rev. C90 (2014) 065503.
- [19] V.P.Gudkov, Phys. Rep. 212 (1992) 77.
- [20] G.E.Mitchell et al., Phys. Rep. **354** (2001) 157.
- [21] T.Okudaira et al., Phys. Rev. C97 (2018) 034622.
- [22] T.Yamamoto et al., Phys. Rev. C101 (2020) 064624.
- [23] J.Koga, et al., JPS Conf. Proc. 22 (2018) 011035.
- [24] V.V.Flambaum and O.P.Sushkov, Nucl. Phys. A435 (1985) 352.
- [25] L.Stodolsky, Phys. Lett. B172 (1986) 5.
- [26] V.Gudkov and H.M.Shimizu, Phys. Rev. C95 (2017) 045501.
- [27] V.Gudkov and H.M.Shimizu, Phys. Rev. C97 (2018) 065502.
 [20] D.D. L. L. V.V.Fl. L. D. D. C102 (2010)
- [28] P.Fadeev and V.V.Flambaum, Phys. Rev. C100 (2019) 015504.
- [29] T.Okudaira, 2019 "Experimental study of discrete symmetry in a compound nucleus", PhD Thesis, Nagoya University, Nagoya, Japan.
- [30] Y.-H.Song et al., Phys. Rev. C83 (2011) 065503.
- [31] P.Hautle and M.Iinuma, Nucl. Instrum. Methods Phys. Res. A440 (2000) 638.
- [32] V.Gudkov and H.M.Shimizu, Phys. Rev. C 102 (2020) 015503.
- [33] H. M. Shimizu and M. Iinuma et al., RCNP proposal " Development of polarized target for new physics search via T-violation", (2018).
- [34] K. Ishizaki et al., Nucl. Instr. Meth. A 1020, 165845 (2021).
- [35] T. Maekawa, et al., Nucl. Instr. Meth. Phys. Res. A 36 115 (1995).
- [36] K. Ishizaki, et al., PoS(PSTP2019) 061 (2020).
- [37] S. Hayward, et al., Phys. Rev. B 72 054110 (2005).
- [38] T. Maekawa, Master thesis in Kyoto University (1992).

- [39] A. Abragam and M. Goldman, Nuclear Magnetism: order and disorder (Oxford Clarendon Press, 1982).
- [40] G. Berkstresser, A. Valentino and C. Brandle, Journal of Crystal Growth 109 467 (1991).
- [41] R.E. Fahey, A.J. Strauss and A.C. Anderson, Journal of Crystal Growth 128 672 (1993).
- [42] E.J.J. Groenen and W.N. Koelman, J. of Chem. Soc., Farady Trans.2 75 58-68 (1979).
- [43] H. Kohri, et al., Proposal for project (Category I) at RCNP "Development of various polarized nuclear targets with dynamic and static nuclear polarizations", (2021)
- [44] M. Iinuma, et al., Phys. Rev. Lett. 84 171 (2000).
- [45] Y. Takahashi, et al., Nucl. Instr. Meth. Phys. Res. A 336 583 (1993).
- [46] W.N. Hardy and L.A. Whitehead, Rev. Sci. Insrum. 52 213 (1981).

BUDGET PLAN

The Spokesperson is applying for KAKENHI Grant-in-Aid for Scientific Research (S) starting from FY2024.

Item	Detail	Amount (kJPY)	Source
Experimental expenses			
	Beamline construction	420,000	TBD
	Neutron polarizer	25,000	KAKENHI
	Polarized target	160,000	KAKENHI
	Gamma-ray detector	232,000	TBD
	Neutron detector	230,000	TBD (US-team)
Travel expenses			
	to J-PARC	5,000	KAKENHI
	to RCNP	1,000	KAKENHI
Total		1,252,000	

The detail of the budget and its source is summarized as follows:

6. Resources and Requests

Human resources

	(FTE)
Beamline design	1
Neutron polarizer	1
Polarized target	3
Neutron detector	1

Technical or facility resources

- Liquid He supplying facility for development of polarized target (KEK)
- Dedicated epithermal neutron beamline (J-PARC MLF)

Budget

	Amount (kJPY)
Beamline construction	420,000
Neutron polarizer	10,000
Polarized target	160,000
Gamma-ray detector	232,000
Neutron detector	230,000

6.1. Epithermal neutron beamline

In order to study the compound nuclear reactions by using transmitted neutrons and/or (n, γ) reactions, new neutron beamline which can deriver epithermal neutrons must be constructed. Currently we are carrying out the basic research at BL04 ANNRI beamline in J-PARC, however, the the advanced studies of compound nuclei requires much longer beamtime, which can not be supported at the general-use beamtime. The existing beamline does not have sufficient space to install the in-situ neutron polarizer, analyzer, and polarized target system. Especially the polarized target system requires long-term occupation of beamline for in-beam developments.

It contains a neutron collimator and a disk chopper system to optimize the beam cross section and energy spectrum at the target position. Radiation shields for neutrons and γ -rays are required to allow scattering in epithermal region and consequently they will be the similar scale of structure of BL10 (NOBORU). We estimate two full-time equivalent researchers for the detailed design and construction of the beamline in the first year of this project.

Table 3: Epithermal neutron beamli	ne
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Item	Amount (kJPY)
Radiation shield	300,000
Neutron beam guide	100,000
Disk chopper	10,000
Electricity facility	10,000

6.2. Neutron polarization system

As a first candidate of a neutron polarizer, ³He spin filter is now developed for epithermal neutrons. For p-wave resonance of ¹³⁹La, neutrons with the energy of 0.75 eV must be polarized. It requires 60 atm cm ³He gas with a large cell. High power laser with narrow bandwidth to polarize Rb atom for SEOP pumping. In-situ spin filter system will be install into the neutron beamline for stable operation. Monitoring NMR signals of ³He is used.

One full-time equivalents researchers make effort for development of the neutron polarizer in the first year of this project, and he will support the stable operation of the polarizer in the experiments.

Item	Description	Unit	Amount (kJPY)
³ He gas cell		10	2,000
³ He gas	10 litter	1	3,000
Gas filling system		1	2,000
Laser system	laser, optics	2	12,000
NMR+EPR system		2	6,000

Table 4:	Neutron	polarization	system
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6.3. Polarized target system

Polarized nuclear target is necessary in the beamline. Present top-priority candidate for T-violation search is 139 La.

The actual target material is LaAlO₃ single crystal with the size of 40 mm \times 40 mm \times 30 mm. Although such large crystals eventually need to be prepared, crystals with smaller size than above can be also used at the beginning stage of the experiments.

We are planning to apply the DNP technique in low magnetic field of 0.1 T to the polarized target as the first priority. The successful demonstration of DNP for La nuclei with 2.3 T magnetic field needs to be extended into the environment of a low magnetic field by performing the ISE and developing a refrigerator around 0.1 K with sufficient cooling power.

The distribution of the magnetic field for holding the polarization needs to be uniform at the level of 10^{-4} or better for DNP. Additionally, non-adiabatic boundary condition of the magnetic field is preferred to accept divergent beam making statistics better, which is formed by setting four superconducting magnetic shields adequately.

For the development of the polarized target, we estimate that three full-time researchers are necessary.

Table 5: Polarized target system

Item	Description	Amount
		(kJPY)
Dilution refrigerator	Vacuum pump, ³ He	100,000
Microwave source	$2.8~\mathrm{GHz}$	40,000
NMR system		5,000
Sample preparation	target crystal	15,000

6.4. Gamma-ray and neutron detector system

Both neutron and gamma rays detecting system are must be set on the beamline. The neutron detector is mainly used as the transmission detector, which need high counting rate. The gamma-ray detector are using for the (n, γ) reaction measurement. The Ge detector are also using for the identify the final state(F) of the compound nucleus. The neutron transmission detector, which is incident neutron beam monitor, and scattering neutron detector also must be set at beamline.

Table 6: Gamma-ray detector system

Item	Unit	Amount
		(kJPY)
Ge detector	20	200,000
BGO detector	2	4,000
Detector mount system	1	4,000
Gamma-ray collimator	1	4,000
Gamma-ray shield	1	4,000
DAQ system (20 channels)	1	20,000

Table 7: Neutron detector system

Item	Unit	Amount
		(kJPY)
High counting rate Neutron detector	20	50,000
Transmission detector (beam monitor)	1	10,000
scattering neutron detector	1	30,000
Detector mount system	1	4,000
collimator	1	4,000
Gamma-ray and neutron shield	1	4,000
DAQ system (20 channels)	1	20,000

6.5. Schedule

5		Å										
4	Experiment	+ +	zed target					Install to	new beamline	Upgrade		k
c	Commissioning	•	B term with polari	∢	Install			Install to	existing beamline		Upgrade to 1GHz	
7	Construction		s, A, C term	beamline	In-situ system		quality studies	studies	ing cryostat	Dedicated cryostat		•
1	Design		Resonance parameter	at existing	Large cell	Å	Crystal growth and	Relaxation	↓ ↓ ↓ DNP tests with exist		R&D	
FY	Beamline		Study of	compound nuclei	neutron nolarizer				polarized target		neutron detector	

Figure 22: Schedule

Appendix A. Coefficients in the Forward Scattering Amplitude

The explicit expressions of the coefficients in Eq. 5 for the case of 139 La (I=7/2) are described below [9].

$$\begin{aligned} A' &= \frac{1}{16} (7a_{s0} + 9a_{s1}) + \frac{9}{32} \frac{i}{k_{n}} \left(\mathcal{W}_{s0} + \mathcal{W}_{p} + \frac{7}{9} \mathcal{W}_{s1} \right) \\ B' &= \frac{\sqrt{21}}{16} (a_{s0} - a_{s1}) + \frac{\sqrt{21}}{32} \frac{i}{k_{n}} \left(\mathcal{W}_{s0} - \mathcal{W}_{s1} \right. \\ &\quad + \mathcal{W}_{p} \left(-\frac{39}{28} x_{s}^{2} + \frac{9}{2\sqrt{35}} x_{s} y_{s} + \frac{9}{20} y_{s}^{2} \right) \right) \\ C' &= \frac{9}{16} x \frac{v}{\sqrt{\Gamma_{s0}^{n}} \sqrt{\Gamma_{p}^{n}}} \frac{1}{k_{n}} \mathcal{W}_{s0} \mathcal{W}_{p} \\ D' &= -\frac{2}{3} \frac{w}{v} \frac{x_{s}}{x} C' \\ H' &= -\sqrt{3} \frac{1}{x} \left(\frac{1}{6} x_{s} + \frac{\sqrt{35}}{6} y_{s} \right) C' \\ K' &= \frac{3}{128} \sqrt{\frac{3}{7}} \left(3x_{s}^{2} + 18 \sqrt{\frac{7}{5}} x_{s} y_{s} + \frac{77}{5} y_{s}^{2} \right) \frac{i}{k_{n}} \mathcal{W}_{p} \\ E' &= -\frac{9}{256} \sqrt{\frac{3}{7}} \left(5x_{s}^{2} + 6 \sqrt{\frac{7}{5}} x_{s} y_{s} + \frac{77}{5} y_{s}^{2} \right) \frac{i}{k_{p}} \mathcal{W}_{p} \end{aligned}$$

$$F' = \sqrt{\frac{3}{5}} \frac{y}{x} C'$$

$$G' = -\frac{9}{32} \sqrt{\frac{3}{5}} (x_{\rm S} y'_{\rm S} - x'_{\rm S} y_{\rm S}) \frac{i}{k_{\rm n}} \frac{v_{\rm T}^{\rm pp'}}{\sqrt{\Gamma_{\rm p}^{\rm n}} \sqrt{\Gamma_{\rm p'}^{\rm n}}}$$

$$B'_{3} = -\frac{81\sqrt{33}}{2240} y^{2} \frac{i}{k_{\rm n}} W_{\rm p},$$
(A.1)

where k_n is neutron momentum, a_0 and a_1 are the scattering length of ¹³⁹La for J = 4 and J = 3 respectively, x and y are j = 1/2 and j = 3/2 contribution in the p-wave resonance respectively, x_S and y_S are channel spin S = I - 1/2 and S = I + 1/2 respectively. And \mathcal{W}_{s0} , \mathcal{W}_{s1} , \mathcal{W}_p are Breit-Wigner amplitude formula for the negative, p-wave at 0.75 eV, and s-wave at 72eV resonances respectively, Γ_{s0}^n , Γ_p^n , Γ_{s1}^n are neutron width of the Brite-Wigner parametrization:

$$-i\mathcal{W}_{\rm r} = \frac{\Gamma_{\rm r}^{\rm n}}{E - E_{\rm r} + i\Gamma_{\rm r}},\tag{A.2}$$

where E is neutron energy, $E_{\rm r}$ is resonance energy, and $\Gamma_{\rm r}$ is total width of the resonance r.

Here we summarize the method to determine each coefficients.

A'

The A' term can be measured by using unpolarized neutrons and unpolarized target. The precision of the resonance parameter, including the negative resonance, is quite important for all studied. We should perform the A' measurement even if we use the conventional beamline in J-PARC. It can be done at BL04 ANNRI for the early time, and we will shift the activities to the our own newer beamline.

B'

The B' term is related to pseudomagnetic field by polarized target. Once the polarized target is available, we start to study the B' and related terms. Especially the energy dependence of the B' term is important issue, which was not demonstrated in previous experiments. We can measure that by using TOF mentioned in the section about measurement principle.

C'

The C' term is parity violating amplitude between neutron spin of +z and -z. The C' term is independent from the nuclear polarization I. The study of C' term can be started even if the polarized target is not available. The C' term makes the largest false asymmetry in $\operatorname{Re} A^*D$ measurement. The accuracy can be same as the D' term because the same order of magnitude of the measurement time can be used while $\operatorname{Re} A^*D$ measurement.

H' and E'

The H' and E' term is the effects from $(k_n \cdot I)$. The H' is related to target vector polarization P_1 and the E' is related to target tensor polarization P_2 . Because theses are not related to neutron spin, the effects are eliminated in the asymmetry calculation in principle.

K'

The K' is the effects from $P_1(\sigma_n \cdot k_n)(k_n \cdot I)$. After the polarized target is available, the measurement of K' can start. The magnitude of K' is the same as the order of C', however, the neutron-energy dependence is different from that of C'. The K' effect appears only near around p-wave resonance peak. We can extract the K' effect by fitting of the TOF data with K' effect (only the p-wave resonance shape) and the other terms effects which have the shape of the interference between s- and p-wave resonances. The neutron momentum direction can be controlled in order to suppress and estimate the K' effect. The $(\sigma_n \cdot k_n)$ can be change by controlling beam direction k_n . The neutron slits just before the target can be scanned to control the beam direction, for example.

F'

The F' is the effects from $P_2(\sigma_n \cdot I)(k_n \cdot I)$ and $P_2(\sigma_n \cdot k_n)/3$. The energy dependence is the same as C' and D', therefore this effect can not be separated by using TOF measurements. And the magnitude of F' is the same as the order of C'. The F' can be extracted by comparing the P-violation between the polarized and unpolarized target.

G'

The G' is the effects from the interference between the p-wave resonance, which we are focusing at 0.75 eV, and the other p-wave resonance. In this paper, we neglect this effect because there is no p-wave resonance peak with sufficient amplitude near around the 0.75 eV peak.

 B'_3

The B'_3 is the effects from $P_3(\sigma_n \cdot I)((k_n \cdot I)^2 - 1)$ and $P_3(\sigma_n \cdot k_n)(k_n \cdot I) \times (2/3)$.

The magnitude of B'_3 is the same as the order of C', however, the neutron-energy dependence is different from that of C'. The B'_3 effect appears only near around p-wave resonance peak. We can extract the B'_3

effect by fitting of the TOF data with the same procedure of K' extraction (or we extract the information of the integration of K' and B'_3).

As discussed above, the contaminations from all coefficients can be extracted and/or estimated with the accuracy same as D' term. The neutron polarization σ_n and the target polarization are monitored by using NMR technique while measurement.