Research Plan Application for LTP v3

長期課題管理番号	
受理年月日	

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大強度陽子加速器施設（J-PARC）
物質・生命科学実験施設　一般課題（長期）研究計画書
Research Plan Application for General Proposal（Long Term）at MLF

J-PARC センター長殿
To Director of J-PARC center　　　　　　　　　　　　　　　　申請日 ________年____月____日

(*)マークは入力必須項目です。[(*) Mandatory]

０）研究代表者情報　[Information of principal investigator]

E-mail(*)	wsnow@indiana.edu
氏名　Name(*)	William Michael Snow
所属機関・部局　Affiliation(*)	Indiana University Department of Physics
職名　Status(*)	Professor and Center Director
電話　Tel(*)	+1-(812)-855-7914

１）基本情報　[Basic information]

ｉ）研究課題名（英語）(*)　[Title of project research (in English)]

Transmission Measurements with Polarized Epithermal Neutrons and Unpolarized (n, γ) Angular Distribution Measurements for Parity Violation and Time Reversal Violation Physics

ⅱ）研究概要（英語）(*)　[Abstract of project research (in English)]

We propose to search for new p-wave resonances in several heavy nuclei using two different techniques: parity-odd total cross section through the (n, γ) channel and parity-even (n, γ) angular distributions. If we discover evidence for large mixing of opposite parity levels in one or more of these nuclei they could become new candidates for our planned search for time reversal violation in polarized neutron/polarized nucleus transmission by the NOPTREX collaboration. This information will also help test the existing theory for parity-odd mixing in heavy nuclei. We will look for P-odd asymmetries in ~15 nuclei with 140<A<180A and nonzero spin. This proposal builds on our successful series of measurements on ANNRI of gamma angular distributions which determine the κ(J) parameter on many p-wave resonances using (n, γ) reactions, on the recent JPARC advancements in the development of neutron polarizers based on transmission through polarized ^{3}He gas, and on the optimization of the performance of the ANNRI Ge detector array count rate using element-specific upstream attenuators to maximize the signal/background ratio for p-wave resonances. We successfully used NOBORU to test the new parts of the apparatus required for the parity violation measurements on ANNRI.

iii）利用するビームライン（実験装置）複数記載可　主要ビームラインに○(*)
[Requested beamline(s), Main Instrument(s) should be marked by ○]

BL04 (NOBORU)

iv）連携利用　[Complementary Use]　☐

・If you are planning to conduct an experiment(s) or a calculation(s) relating to this proposal using other large experimental facility/facilities or a supercomputer, please indicate the name of the facility and the beamline number/the name of the instrument. (You don't need to write the MLF beamline for this proposal here.)

[1] Facility (Facilities) of complementary use (Check multiple options if applicable)
Neutron: ☐JRR-3, ☐ANSTO, ☐SNS, ☐ISIS-Neutron
Muon: ☐PSI, ☐TRIUMF, ☐ISIS-Muon
Synchrotron Radiation: ☐SPring-8, ☐Photon Factory, ☐ESRF, ☐APS
Supercomputer: ☐Fugaku
☐Facility/facilities other than those named above
(Write the name etc. of the facility:)

[2] The Beamline number and/or the name of the instrument (Write multiple items if applicable)

2）リエゾン　[Liaison(s)]

氏名 Name(*)、職位 Status(*)、所属 Affiliation(*)、E-mail(*)
Atsushi Kimura, Senior Researcher, JAEA, kimura.atsushi04@jaea.go.jp

3）共同研究者　[Collaborator(s)]

氏名 Name(*)、職位 Status(*)、所属 Affiliation(*)、E-mail(*)、役割 Role(*)

William Michael Snow, Professor, Indiana Univ., wsnow@indiana.edu, Management, Experimental Design, Measurement, Analysis

Clayton Auton, Graduate Student, Indiana University, cauton@iu.edu, Measurement, Analysis, ^{3}He R&D

Kylie Dickerson, Graduate Student, Indiana University, kyadi@iu.edu, Measurement, Analysis

Gabe Otero, Graduate Student, Indiana University, goterom@iu.edu, Measurement, Analysis

Mofan Zhang, Graduate Student, Indiana University, zhangmo@iu.edu, Measurement, Analysis

Ivan Novikov, Professor, Western Kentucky University, ivan.novikov@wku.edu, Design, Measurement, Analysis

David Bowman, Senior Scientist, Oak Ridge National Lab, bowmanjd@ornl.gov, Design, Analysis.

Seppo Penttila, Senior Staff Scientist, Oak Ridge National Lab, penttilasi@ornl.gov, Design, Measurement, Analysis

Vladimir Gudkov, Professor of Physics, University of South Carolina, vgudkov0@mailbox.sc.edu Analysis, Theoretical Support

Jason Fry, Assistant Professor, Eastern Kentucky University, jason.fry@eku.edu, Design, Measurement, Analysis

Danielle Schaper, Postdoc, Los Alamos National Lab, dcsc225@g.uky.edu, Measurement, Analysis

Paul King, Lecturer, Ohio University, kingp1@ohio.edu, Measurement, Analysis

Chris Crawford, Professor, University of Kentucky, cbcraw2@g.uky.edu, Measurement, Analysis

Libertad Barron Palos, Professor, National Autonomous University of Mexico, libertad.barron@mail.com, Measurement, Analysis

Luis Charon Garcia, Graduate Student, National Autonomous University of Mexico, lcharon1991@gmail.com, Analysis

Alberto Perez Martin, Graduate Student, National Autonomous University of Mexico, albepm89@gmail.com, Analysis

Damon Spayde, Professor, Hendrix College, Spayde@hendrix.edu, Analysis

Katsuya Hirota, Associate Professor, Nagoya Univ., hirota@phi.phys.nagoya-u.jp, Design

Masaaki Kitaguchi, Associate Professor, Nagoya Univ., kitaguchi@phi.phys.nagoya-u.jp, Design

Tamaki Yoshioka, Associate Professor, Nagoya Univ., yoshioka@phys.kyushu-u.ac.jp, Design

Tatsushi Shima, Associate Professor, Nagoya Univ., shima@rcnp.osaka-u.ac.jp, Design

Hiroyuki Fujioka, Associate Professor, Tokyo Institute of Technology, fujioka@phys.titech.ac.jp, Design

Takashi Ino, Lecturer, KEK, takashi.ino@kek.jp, Design

Hirohiko Shimizu, Professor, Nagoya Univ., shimizu@phi.phys.nagoya-u.jp, Design

Kohei Ishizaki, Graduate Student, Nagoya Univ., ishizaki@phi.phys.nagoya-u.ac.jp, Measurement

Takuhiro Fujiie, Graduate Student, Nagoya Univ., fujiie@phi.phys.nagoya-u.ac.jp, Measurement

Ikuo Ide, Graduate Student, Nagoya Univ., ide@phi.phys.nagoya-u.ac.jp, Measurement

Hiroki Tada, Graduate Student, Nagoya Univ., tada@phi.phys.nagoya-u.ac.jp, Measurement

Rintaro Nakabe, Graduate Student, Nagoya Univ., nakabe@phi.phys.nagoya-u.ac.jp, Measurement

Mayu Hishida, Graduate Student, Nagoya Univ., hishida@phi.phys.nagoya-u.ac.jp, Measurement
Koki Morikawa, Graduate Student, Nagoya Univ., morikawa@phi.phys.nagoya-u.ac.jp, Measurement
Masayuki Hiromoto, Graduate Student, Osaka Univ., hiromoto@rcnp.osaka-u.ac.jp, Measurement
Hiromoto Yoshikawa, Graduate Student, Osaka Univ., yoshikaw@rcnp.osaka-u.ac.jp, Measurement
Ryota Kondo, Graduate Student, Osaka Univ., kondo24b@rcnp.osaka-u.ac.jp, Measurement
Sou Nakai, Graduate Student, Osaka Univ., nakais@rcnp.osaka-u.ac.jp, Measurement
Shusuke Takada, Graduate Student, Kyushu Univ., takada@epp.phys.kyushu-u.ac.jp, Measurement
W. Jiang, Chinese Spallation Neutron Source, jiangwei@ihep.ac.cn, Analysis
G. Luan, Chinese Institute of Atomic Energy, lgyciae@hotmail.com, Analysis
X. Ruan, Chinese Institute of Atomic Energy, xichao_ruan@126.com, Analysis
J. Tang, Chinese Spallation Neutron Source, tangjy@ihep.ac.cn, Management
X. Tong, Chinese Spallation Neutron Source, tongxin@ihep.ac.cn, Measurement
Q. Zhang, Chinese Institute of Atomic Energy, zqwvictor@126.com Analysis

合計 42 名 [Total number of collaborator(s)]

４）研究計画（5 ページ以内）(*) [Scientific case (within 5 pages)]

We propose to search for new p-wave resonances in several heavy nuclei using two different techniques: parity-odd total cross section measurements through the (n, γ) channel and parity-even (n, γ) angular distribution measurements. We explain the scientific interest to conduct this research, which comes from two different but related scientific areas: the search for time reversal violation in polarized neutron/polarized nucleus transmission and the theory for s-p wave mixing in heavy nuclei.

Search for new nuclei for time reversal violation experiments

Parity-odd (P) and Time Reversal-odd (T) effects in neutron-nucleus forward transmission provide null tests for time reversal invariance{Bowman2014}. The present theory involving the mixing of nearby s-wave and p-wave resonances that accounts for the amplification of parity-odd amplitudes also predicts a similar amplification of Time Reversal Invariance Violating (TRIV) amplitudes{Fadeev2019}. With the advent of MW-class short-pulsed spallation neutron sources such as JPARC and SNS, sensitive tests of TRIV in neutron-nucleon interactions can be realized. In the case of the 0.7 eV p-wave resonance in ^{139}La the P-odd amplitude on resonance is larger than one would expect from the bare N-N parity-odd interaction by a factor of a million, by far the largest amplification of a symmetry-violating reaction anywhere in nuclear and particle physics. Compound nuclear systems are therefore attractive candidates for T-violation searches. The international collaboration NOPTREX proposes to conduct the first search for a term in the neutron forward scattering amplitude of the form $\mathbf{s}_n \cdot \mathbf{k}_n \times \mathbf{I}$ where $\mathbf{s}_n$ is the spin of the neutron, $\mathbf{k}_n$ is the neutron momentum,

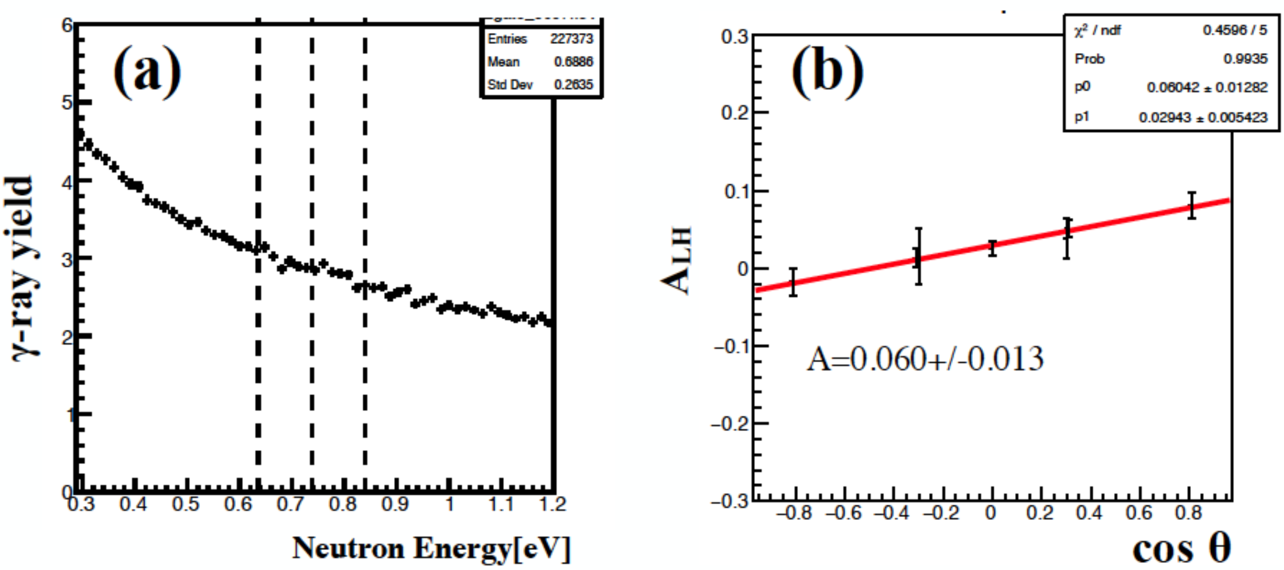
$$\Delta\sigma_{\mathrm{T}} = \kappa(J)\frac{W_{\mathrm{T}}}{W}\Delta\sigma_{\mathrm{P}},$$

and **I** is the spin of the nucleus. This search has the potential to be about 1-2 orders of magnitude more sensitive than the current limit from neutron electric dipole moment (nEDM) experiments, whose upper bound has improved by less than a factor of 2 over the last 14 years {Baker2006, Abel2020}, although the latest experiments possess improved systematic errors which imply that better neutron EDM measurements are possible. The T-violating cross section is related to the P-odd cross section in the relation above where W_T and W are fundamental T- and P-violating amplitudes of interest whose ratio we seek to measure or constrain, $\Delta\sigma_P$ is the P-odd part of the resonance cross section, $\Delta\sigma_T$ is the T-odd part of the resonance cross section, and $\kappa(J)$ is a partial width-weighted spectroscopic conversion factor from P-violation to T-violation in the compound nucleus that must be measured for the nuclei of nonzero spin of interest to NOPTREX. We will search for the T-violating effect at the p-wave resonance. The ^{139}La 0.7 eV p-wave resonance has a 10% P-odd asymmetry in the resonance cross section, and $\kappa(J)$ was measured {Okudaira2018} to be at least 1.

However, unknown p-wave resonances which interfere with s-wave resonances exist in several other isotopes, and can be additional candidates for the T-violation search experiment if the product $\Delta\sigma_P\,\kappa(J)$ is large enough. By searching for new p-wave resonances with either large P-odd transmission asymmetries from $\Delta\sigma_P$ or large asymmetries in (n, γ) angular distributions from $\kappa(J)$ we may discover new candidate nuclei for a future time reversal search. We will focus our search in regions of A not measured before and in I=1/2 nuclei which are much easier to polarize. The TRIPLE collaboration found parity violation in many p-wave resonances in nuclei with A near the peaks of the 3p and 4p p-wave strength functions. They aimed to maximize the number of p-wave and s-wave resonance overlaps per unit energy interval in the eV-keV regime to collect enough data for their statistical analysis of parity violation in heavy nuclei. The spherical optical model which TRIPLE used to estimate the positions of the 3p and 4p p-wave strength functions predicts a minimum at A=160, so TRIPLE chose not to measure nuclei near this region of A. Since the TRIPLE work was conducted, improved data{Mughabghab2018a} has revealed an additional small peak near A=160 which is split off from the 4p giant resonance due to nuclear deformation effects as predicted long ago{Buck1962}. Only later measurements of the deformation parameters of nuclei in this region provided the needed input data. The ratio S1/S0 of the p-wave and s-wave strength functions is now known to have a small local maximum centered at A=160. This local maximum of S1/S0 is not as large as in the regions 80<A<130 and 220<A<230 where TRIPLE took most of its data, but it is larger for 140<A<180 than it is for the ^{139}La nucleus, which as we now know is the best candidate known so far for the NOPTREX T violation search. ^{139}La is not predicted by the statistical analysis to be the most likely nucleus to possess a p-wave resonance with large parity violation. For the time reversal test we do not perform a statistical analysis of many resonances in many nuclei: we only want resonances with a large product of the P-odd cross section $P\sigma_p$ and the spin-weighted partial width parameter κ(J). We therefore propose a series of measurements of P in several of these unmeasured nuclei between 140<A<180 in nuclei with nonzero spin.

Theory of s-p resonance mixing in heavy nuclei:

To test the theory of s-p mixing and look for NOPTREX candidates one wants to identify p-wave resonances. Although this can be done using polarized neutron-polarized nucleus transmission, it is very difficult in general to polarize nuclei. As the p-wave resonances in heavy nuclei are in the middle of a dense sea of s-wave resonances parity violation can mix them with s-wave resonances, and many new p-wave resonances were discovered by TRIPLE as parity violation in heavy nuclei is most greatly amplified on p-waves of the same J as a nearly s-wave. We propose a third method. The angular distribution of gammas in (n, γ) reactions on resonance have an asymmetry in the shape of the p-wave resonance as a function of neutron energy {Flambaum1985}. This angular distribution in unpolarized (n, γ) reactions comes from a $\mathbf{k}_n \cdot \mathbf{k}_\gamma$ angular correlation where $\mathbf{k}_n$ is the neutron momentum and $\mathbf{k}_\gamma$ is the gamma momentum and has been observed on ANNRI in ^{139}La, ^{117}Sn, ^{81}Br, and other nuclei {Okudaira2018, Koga2019, Endo2019}. Since the small p-wave amplitude can be enhanced by the interference with the s-wave amplitude, a large asymmetry can be observed. Consider the neutron spectrum of ^{139}La (n, γ) reaction gated with 5097 keV gamma-ray peak as shown in Figure 1. Note carefully that the p-wave resonance at 0.74eV, which is well-known to exist, is not observed in this transition in the gated gamma ray yield (Fig (a)), however, the asymmetry A in the gamma angular distribution reveals the p-wave resonance clearly (Fig (b)). {Okudaira2020}. Therefore, the angular distribution measurement can be a sensitive probe for unknown p-wave resonances which have not yet been observed and may have been missed in the P violation work. Furthermore as shown in {Flambaun1985} there is a complicated but direct relation between A, $\kappa(J)$, and $\Delta\sigma_P$. This asymmetry measurement can therefore determine the product $\Delta\sigma_P\,\kappa(J)$ of direct interest for NOPTREX. This data can also be used to quantify the accuracy of the Flambaum two-resonance mixing approximation formulae in the case where $\Delta\sigma_P$ is already known from TRIPLE measurements and check the p-wave assignments of various nuclei, some of which are only a guess. This data can also give a more accurate measurement of the p-wave strength function to use in general nuclear physics applications, especially the statistical theory of parity violation in heavy nuclei.



(a) The neutron spectrum from unpolarized (n, γ) on the 0.7 eV resonance gated on the 5079keV gamma-ray peak for all ANNRI detector angles. (b) The angular distribution of the asymmetry of the shape of 0.74eV p-wave resonance as a function of neutron energy. This data from ANNRI shows that a p-wave resonance can be visible in a properly-gated angular distribution but invisible in the (n, γ) cross section.

A new paper by Flambaum {Flambaum2022} speculates that nuclei with octupole deformations in the resonance states might produce non-statistical parity violation effects on p-wave resonances. Many of the nuclei that Flambaum lists as possible candidates fall within the range of nuclei of our search.

Related previous research

Compound neutron-nucleus resonance reactions have proven to be an excellent laboratory in which to study parity violation {Mitchell1999}. The complex, many-body nature of this nuclear system with its very high level density was predicted theoretically {Sushkov1980, Sushkov1982} and confirmed by experiment {Alfimenkov1983, Alfimenkov1984} to greatly amplify parity violating (PV) neutron-nucleus interactions. This amplification is large enough on p-wave resonances that a broad experimental survey of several nuclei conducted by the TRIPLE collaboration{Roberson1993} measured PV effects in the total cross section for about 80 different resonances{Mitchell2001}. By measuring the transmission asymmetry of longitudinally polarized neutrons through an unpolarized target, one can determine the parity-odd helicity dependence of the total cross section. The transmission asymmetry is defined as $A=[Y^{+}-Y^{-}]/[Y^{+}+Y^{-}]=\tanh(f_n\sigma_p ntP)$ where $Y^{+/-}$ is the neutron transmission yield for the two neutron helicities, f_n is the polarization of the neutron beam, σ_p is the p-wave cross section for unpolarized neutrons, n is the number density of the target nuclei, t is the target thickness, and P is the parity-odd longitudinal analyzing power, defined by its relationship to the helicity-dependent cross section, $\sigma^{+/-}=\sigma_p[1 +/- f_nP]$. Tomsovic and others {Tomsovic2000} applied this statistical theory to the TRIPLE data to successfully analyze the widths of the distributions of observed parity-odd asymmetries P in several heavy nuclei in the isolated resonance regime and showed that the width of this distribution was consistent with the size expected based on the Standard Model weak interaction between nucleons. Ongoing experimental and theoretical progress on the determination of the parity-odd NN interactions will soon be used to test this statistical theory in more quantitative detail.

Due to the proportionality between potential TRIV amplitudes and PV amplitudes, TRIV tests need more complete and precise information on the properties of the resonances which exhibit large s-p mixing. Our NOPTREX group has already conducted many measurements of (n, γ) angular distributions in nuclei where large P-odd asymmetries in the eV neutron energy range have already been discovered to determine the details of the quantum numbers of the resonances. These experiments used unpolarized neutrons and the large germanium gamma detector array on the ANNRI instrument at the JPARC MLF {ANNRI2015}. The large value of κ(J) discovered in ^{139}La {Okudaira2018} has shown that the 0.7 eV p-wave resonance in ^{139}La is an excellent candidate for a time reversal search in polarized neutron transmission. The NOPTREX collaboration has recently submitted a proposal to conduct a time reversal experiment in polarized ^{139}La at JPARC based in part on this discovery on ANNRI. Additional measurements of κ(J) in several other nuclei are under analysis, and a measurement of κ(J) in ^{131}Xe has been completed and is under analysis. NOPTREX recently performed polarized (n, γ) angular distribution measurements on ANNRI in ^{139}La{Yamamoto2020} to check the Flambaum and Sushkov formalism {Flambaum1985} used to analyze these measurements. The neutrons were polarized using laser-polarized ^{3}He gas, which was successfully implemented on ANNRI and made a large enough neutron polarization for the angular distribution measurements. Therefore the ANNRI measurements by NOPTREX have already been scientifically productive, with more scientific results to come in the future. The ANNRI measurement results have shown that the proposed T violation search in ^{139}La can be sensitive to new physics.

Measurement design and required instrumentation

The great majority of the measurement time needed for this program is requested from the ANNRI instrument in year 3. In year 2 we conducted successful tests of new apparatus components on the NOBORU beam. ANNRI has a large neutron flux in the eV neutron energy range of interest and has the Ge detector array needed for the proposed measurements.

We propose to measure P using the (n, γ) channel of the cross section. The size of the P-odd asymmetry in neutron transmission measurements is diluted by the nonresonant n-A potential scattering, whereas the P-odd asymmetry in the (n, γ) channel which dominates the resonance cross section is insensitive to potential scattering, which does not produce gammas. Therefore the amount of material thickness needed in the neutron beam is of order millimeters if a gamma detector is used. If we discover an element with a large parity violation we can later use the ANNRI Ge detector array combined with the extensive measurements on ANNRI and other facilities on many separated isotopes in the rare earth region to identify which isotope corresponds to a particular neutron resonance energy.

References

{Baker2006} C. Baker et al, Phys. Rev. Lett. **97**, 131801 (2006).
{Abel2020} C. Abel et al, accepted in Phys. Rev. Lett. (2020). arXiv:2001.11966
{Alfimenkov1983} V. P. Alfimenkov, S. B. Borzakov, V. Van Tkhuan, Yu. D. Mareev, L. B. Pikelner, A. S. Khrykin, and E. I. Sharapov, Nucl. Phys. A 398, 93 (1983).
{Alfimenkov1984} V. P. Alfimenkov, S. B. Borzakov, V. Van Tkhuan, Yu. D. Mareev, L. B. Pikel'ner, I. M. Frank, A. S. Khrykin, and E. I. Sharapov, JETP Lett. 39, 416 (1984).
{Shimizu1993} H.M. Shimizu, T. Adachi, L. Ishimoto, A. Masaike, Y. Masuda, and K. Morimoto, Nucl. Phys. A 552, 293 (1993).
{Mitchell1999} G. E. Mitchell, J. D. Bowman, and H. A. Weidenmuller, Rev. Mod. Phys. **71**, 445 (1999).
{Mitchell2001} G. E. Mitchell, J. D. Bowman, S. I. Penttila, E. I. Sharapov, Phys. Rep. **354**, 157 (2001).
{Sushkov1980} O. P. Sushkov and V. V. Flambaum, JETP Lett. **32**, 352 (1980).
{Sushkov1982} O. P. Sushkov and V. V. Flambaum, Sov. Phys. Usp. **25**, 1 (1982).
{Tomsovic2000} S. Tomsovic, M. B. Johnson, A. Hayes, J. D. Bowman, Phys. Rev. C **62**, 054607 (2000).
{Fadeev2019} P. Fadeev and V. V. Flambaum, Phys. Rev. C **100**, 015504 (2019).
{Bowman2014} J. D. Bowman and V. Gudkov, Phys. Rev. C **90**, 065503 (2014).
{ANNRI2015} Proceedings of the 2014 Symposium on Nuclear Data November 27-28, 2014, Hokkaido University, Sapporo, Japan, (Eds.) M. Aikawa, O. Iwamoto, S. Ebata, S. Kuneida, S. Nakamura, and H. Koura, JAEA-Conf 2015-003 INDC(JPN)-201 DOI:10.11484/jaea-conf-2015-003
{Okudaira2018} T. Okudaira, S. Takada, K. Hirota, A. Kimura, M. Kitaguchi, J. Koga, K. Nagamoto, T. Nakao, A. Okada, K. Sakai, H. M. Shimizu, T. Yamamoto, T. Yoshioka, Phys. Rev. C **97**, 034622 (2018).
{Szymanski1996} J.J. Szymanski, W. M. Snow, J. D. Bowman, B. Cain, B. E. Crawford, P. P. J. Delheij, R. D. Hartman, T. Haseyama, C. D. Keith, J. N. Knudson, A. Komives, M. Leuschner, L. Y. Lowie, A. Masaike, Y. Matsuda, G. E. Mitchell, S. I. Penttila, H. Postma, D. Rich, N. R. Roberson, S. J. Seestrom, E. I. Sharapov,

S. L. Stephenson, Y. F. Yen, V. W. Yuan, Phys. Rev. C **53**, R2576 (1996).
{Skoy1996} V. R. Skoy et al., Phys. Rev. C **53**, R2573 (1996).
{Roberson1993} N.R. Roberson et al., Nucl. Inst. Meth. A **326**, 549 (1993).
{Coulter1990} K. P. Coulter et al., Nucl. Instrum. Meth. A **288**, 463 (1990).
{Gentile2017} T. R. Gentile, P. J. Nacher, B. Saam, T. G. Walker, Rev. Mod. Phys. **89**, 045004 (2017).
{Seestrom1999} S. J. Seestrom, C. M. Frankle, J. D. Bowman, B. C. Crawford, T. Haseyama, A. Masaike, A. Matsuda, S. I. Penttila, R. N. Roberson, E. I. Sharapov, S. L. Stephenson, Nucl. Inst. Meth.A**433**,603 (1999).
{Mughabghab2018a} S. F. Mughabghab, *Atlas of Neutron Resonances: Resonance Properties and Thermal Cross Sections Z=1-60,* 6th edition, Volume 1, Elsevier, Amsterdam (2018).
{Buck1962} B. Buck and F. Perey, Phys. Rev. Lett. **8**, 444 (1962).
{CDBowman1989} C. D. Bowman, J. D. Bowman, and V. W. Yuan, Phys. Rev. C **39**, 1721 (1989).
{Yuan91} V. W. Yuan et al., Phys. Rev. C **44**, 5 (1991).
{Tippens1995} J. D. Bowman, S. I. Penttila, and W. B. Tippens, Nucl. Inst. Meth. A **369**, 195 (1995).
{Bowman1990} J.D. Bowman, J.J. Szymanski, V.W. Yuan, C.D. Bowman, A. Silverman, and C. Zhu et al., Nucl. Inst. Meth. A **297**, 183 (1990).
{Williams1988} W. G. Williams, *Polarized Neutrons*, Oxford University Press (1988).
{Flambaum1985} V.V. Flambaum, O.P. Sushkov, Nucl. Phys. A 435, 352–380 (1985).
{Koga2019} J. Koga et al., EPJ Web of Conf. **219**, 09004 (2019).
{Endo2019} S. Endo et al., EPJ Web of Conf. **219**, 09003 (2019).
{Okudaira2020} T.Okudaira, private communication (2020).
{Flambaum2021} V. V. Flambaum and A. J. Mansour, Phys. Rev. C **105**, 015501(2022).
{Blyth2018} D. Blyth et al. (The NPDGamma Collaboration), Phys. Rev. Lett. **121**, 242002 (2018).
{Gericke2005} M. T. Gericke et al., Nucl. Inst. Meth. **A540**, 328 (2005).
{Wilburn2005}W.S. Wilburn, J.D. Bowman, S.I. Penttila, M.T. Gericke, Nucl. Inst. Meth. A**540**, 180 (2005).
{Yamamoto2020} T. Yamamoto et al., Phys. Rev. C**101**, 064624 (2020). arXiv:2002.08655

ｉ）研究背景（研究計画に関連する国内外の研究動向及び申請課題の位置づけ）[Background of your research project for the proposed experiment (research trend and status of your research)]

The hot trend in this area is the search for new sources of time reversal violation beyond the Standard Model of particle physics. Many studies in neutrino physics, high energy colliders, particle decay experiments, and precision measurements in neutron, atomic, and molecular physics. The NOPTREX experiment, which has never been tried before, can be an important contribution to this overall scientific effort. Although a few nuclei including ^{139}La are now known to be suitable for the NOPTREX experiment, not all interesting nuclei have been investigated. The completion of the experimental search for the interesting nuclei for NOPTREX is the unsolved problem we address with this proposal.

The scientific significance of the work is the possibility of a new discovery which can make the NOPTREX experiment more sensitive to a search for new sources of T violation, which if discovered can be important for understanding the baryon asymmetry of the universe. In addition, the new information on P violation in unmeasured heavy nuclei can be used to confront the theory of statistical parity violation in heavy nuclei. We can also test the recent speculation of Flambaum that nuclei with octupole deformations might possess nonstatistical trends in parity-odd asymmetries.

The applications of the work are the development of a new operation mode for the ANNRI instrument involving polarized eV neutron beams with fast-enough NMR spin flipping for parity violation measurements. After completion of the project one could perform various additional types of polarized (n, γ) spectroscopy on ANNRI. The educational merits are in the education of young scientific researchers in neutron physics and gamma spectroscopy techniques.

ⅱ）本申請の目的（本申請で何をどこまで明らかにするか、及び課題の新奇性、独創性を記述）[Purpose(s) of this proposed experiment (State clearly what you intend to clarify in this experiment and what are novelty and originality of your research plan)]

For the NOPTREX scientific goals one needs p-wave resonances in nuclei with nonzero spin that can be polarized, and nuclei with I=1/2 are especially interesting as they suffer from fewer depolarizing effects from external perturbing fields in solids. In the 140<A<180 range the following I>0 cases exist (natural abundances in parentheses): ^{141}Pr, I=5/2 (100%), ^{143}Nd, I=7/2 (12.2%), ^{145}Nd, I=7/2 (8.5%), ^{147}Sm, I=7/2 (15%), ^{149}Sm, I=7/2 (13.8%), ^{151}Eu, I=5/2 (47.8%), ^{153}Eu, I=5/2 (52.2%), ^{155}Gd, I=3/2 (14.8%), ^{157}Gd, I=5/2 (15.7%), ^{159}Tb, I=3/2 (100%), ^{161}Dy, I=5/2 (18.9%), ^{163}Dy, I=5/2 (24.9%), ^{165}Ho, I=7/2 (100%), ^{167}Er, I=7/2 (22.9%), ^{169}Tm, I=1/2 (100%), ^{171}Yb, I=1/2 (14.1%), ^{173}Yb, I=5/2 (16.3%), ^{175}Lu, I=7/2 (97.4%), ^{179}Hf, I=9/2 (13.8%). One interesting nucleus is ^{169}Tm, both 100% abundant and with spin I=1/2. Dynamic nuclear polarization should be possible in a diamagnetic salt with this material. ^{171}Yb, I=1/2 (14.1%) is also interesting: it has been hyperpolarized and is known to the NMR community. Other nuclei considered long ago by G. Williams and collaborators for neutron spin filter applications polarizable using internal hyperfine fields of various compounds include ^{149}Sm, ^{151}Eu, ^{167}Er, and ^{165}Ho. We will search for large P-odd effects and p-even angular distributions in these nuclei. Our proposed experiment is novel because no experimental search for neutron-nucleus parity violation has been conducted in any of the nuclei listed above.

A discovery can be very important to uncover a new nucleus to use in the NOPTREX T violation experiment, and also the information will be useful for the global statistical analysis of parity violation in heavy nuclei. This plan will complement the already-existing extensive database of parity violation measurements in heavy nuclei by the TRIPLE collaboration. It would complete the survey for P-odd effects in polarized neutron transmission in almost all nuclei with spin of potential interest to NOPTREX, and it would help to learn more about p-wave resonances in heavy nuclei. The proposed experiments need a Ge gamma detector array, an intense source of polarized eV neutrons, and a current-mode neutron transmission detector. The ANNRI instrument at JPARC MLF is the unique apparatus in the world with the greatest flux and the required instrumentation for this work, and it already has the Ge array whose high gamma energy resolution is essential for the identification of the different gammas from n-A resonance capture. We propose to add the neutron polarizer, spin transport and ^{3}He SEOP-based NMR spin flipper, and the high efficiency ^{6}Li-scintillator current mode detector to ANNRI to enable the parity violation measurements.

The measurement of P-odd asymmetries in n-A interactions through the (n, γ) needs the addition of a polarized ^{3}He neutron spin filter {Coulter1990} based on spin-exchange optical pumping {Gentile2017}. Such a ^{3}He neutron spin filter has already been operated successfully on ANNRI for (n, γ) angular distribution measurements in ^{139}La. A JAEA/JPARC collaboration has developed the polarized ^{3}He neutron spin filter for many applications at JPARC MLF and can field the polarizer for this eV neutron spin flipper test. We also note that such a test of a polarizer/eV spin flipper/analyzer/current mode detector combination is a very useful additional technical step towards the proposed apparatus for the T violation search in ^{139}La. We will choose nuclei of potential use for NOPTREX {Williams1988}.

The purpose of experiments in cycle 2023B is to use the apparatus components tested in 2023A to search for parity violation in selected 140<A<180 nuclei with nonzero spin and reasonable isotopic abundances which could be used in the NOPTREX experiment if a p-wave resonance with a large P-odd asymmetry is discovered. The first two nuclei to be measured will be ^{169}Tm and ^{171}Yb, both I=1/2. The next priorities are ^{149}Sm, ^{151}Eu, ^{167}Er, and ^{165}Ho. In addition this experiment can at the same time search for asymmetries in unpolarized parity even (n, γ) angular distributions by properly averaging the data from the two spin states. Both of these measurements can be performed using the ANNRI Ge detector and a thin target.

The purpose experiments in cycle 2024A is to continue the search for parity violation in selected 140<A<180 nuclei with nonzero spin and reasonable isotopic abundances which could be used in the NOPTREX experiment if a p-wave resonance with a large P-odd asymmetry is discovered. The nuclei to be measured will be chosen from the list: ^{141}Pr, ^{143}Nd, ^{145}Nd, ^{153}Eu, ^{155}Gd, ^{157}Gd, ^{159}Tb, ^{161}Dy, ^{163}Dy, ^{173}Yb, ^{175}Lu, and ^{179}Hf. In addition this experiment can at the same time search for asymmetries in unpolarized (n, γ) angular distributions by averaging as mentioned above. This second measurement can also be performed using the ANNRI Ge detector and a thin target.

This plan is slightly modified based on results from the 2023A beam cycle. The instrumentation for parity violation measurements on ANNRI was successfully tested in cycle 2023A on the NOBORU beamline, and we verified that our apparatus can measure the well-known parity-odd asymmetry on the 0.7 eV p-wave resonance in ^{139}La. In addition, we also verified that we can achieve the scientific goals of the original long-term proposal in a technically simpler way by using the polarized ^{3}He neutron spin filter and the ANNRI germanium array, which will be much easier to implement. This conclusion is based on 5 days of data taken on BL10 on ^{113}Cd and ^{127}I nuclei, which both have known p-waves in our neutron energy range of interest. By optimization of the upstream attenuator made of the same material as the target, we showed that we can increase the count rate in the germanium detectors enough to see P-odd effects in the size range of interest. After deciding to use the Ge array for the P-violation measurements, we have also decided not to pursue the original plan to search for p-wave resonances in nuclei with I=1/2 and 80<A<130 as we cannot implement the required CsI(Tl) downstream detector to enable this part of the original plan.

iii）これまでに MLF で採択された課題と本申請との関連　[Relationship(s) between this proposal and your previously approved proposal(s) by MLF]

2016B0021 Characterization of High-counting-rate Epithermal Neutron Detectors. Developed CsI(Tl) detector with current-mode electronics. D. Schaper et al., **A modular apparatus for use in high-precision measurements of parity violation in polarized eV neutron transmission**, Nucl. Inst. Meth. A **969**, 163961

(2020). arXiv:2001.03432
2019A0113 Measurement of s-p Mixing Parameter κ(J) on the 3.2 eV P-odd resonance in ^{131}Xe. Nucleus of interest to NOPTREX. Experiment completed.
2019B0071 Measurement of s-p Mixing Parameter κ(J) on the 3.2 eV P-odd resonance in ^{131}Xe. Nucleus of interest to NOPTREX. Experiment completed. T. Okudaira, et al., **Angular distribution of γ-rays from neutron induced p-wave resonance of ^{132}Xe,** Phys. Rev. C **107**, 054602 (2023). arXiv:2212.10889

All of these proposals are devoted to measurements on p-wave resonances in nuclei that are already known to have a large parity violation. This long-term proposal will search for parity violation in nuclei where no measurements have been conducted and is therefore completely different.

ⅳ）当該研究グループによる本申請に関連した成果リスト［List of relevant publications by this experiment group members］

D. Bowman and V. Gudkov, **On the Search for Time Reversal Invariance Violation in Neutron Transmission,** Phys. Rev. C **90**, 065503 (2014).
V. Gudkov and H. M. Shimizu, **Pseudomagnetic effects for resonance neutrons in the search for time reversal invariance violation**, Phys. Rev. C **95**, 045501 (2017).
V. Gudkov and H. M. Shimizu, **Nuclear spin dependence of time reversal invariance violating effects in neutron scattering**, Phys. Rev. C **97**, 065502 (2018).
*T. Okudaira, S. Takada, K. Hirota, A. Kimura, M. Kitaguchi, J. Koga, K. Nagamoto, T. Nakano, A. Okada, K. Sakai, H. M. Shimizu, T. Yamamoto, and T. Yoshioka, **Angular Distribution of γ-rays from Neutron-Induced Compound States of ^{140}La,** Phys. Rev. C **97**, 034622 (2018).
W. M. Snow, K. Dickerson, J. Devaney, and C. Haddock, **Calculations of the Theoretical Performance of Neutron Mirrors Based on Reflections from Neutron Resonances in Heavy Nuclei**, Phys. Rev. A **100**, 023612 (2019).
V. Gudkov and H. M. Shimizu, **Neutron spin dynamics in polarized targets,** Phys. Rev. **C102**, 015503 (2020). arXiv: 1910.08598
* D. Schaper C. Auton, L. Barron-Palos, M. Borrego, A. Chavez, L. Cole, C. B. Crawford, J. Curole, H. Dhahri, J. Doskow, W. Fox, M.H. Gervais, B. M. Goodson, K. Knickerbocker, P. Jiang, P. M. King, H. Lu, M. Mocko, D. Olivera-Velarde, S.I. Penttila, A. Perez-Martin, B. Short, W. M. Snow, K. Steffen, J. Vanderwerp, and G. Visser, **A modular apparatus for use in high-precision measurements of parity violation in polarized eV neutron transmission**, Nucl. Inst. Meth. A **969**, 163961 (2020). arXiv:2001.03432
* T. Yamamoto, T. Okudaira, S. Endo, H. Fujioka, K. Hirota, T. Ino, K. Ishizaki, A. Kimura, M. Kitaguchi, J. Koga, S. Makise, Y. Niinomi, T. Oku, K. Sakai, T. Shima, H. M. Shimizu, S. Takada, Y. Tani, H. Yoshikawa, T. Yoshioka, **Transverse asymmetry of rays from neutron-induced compound states of ^{140}La**, Phys. Rev. C**101**, 064624 (2020). arXiv:2002.08655
* T. Okudaira, T. Oku, T. Ino, H. Hayashida, H. Kira, K. Sakai, K. Hiroi, S. Takahashi, K. Aizawa, H. Endo, S. Endo, M. Hino, K. Hirota, T. Honda, K. Ikeda, K. Kakurai, W. Kambara, M. Kitaguchi, T. Oda, H. Ohshita, T. Otomo, H. M. Shimizu, T. Shinohara, J. Suzuki, T. Yamamoto, **Development and application of a ^{3}He Neutron Spin Filter at J-PARC**, Nucl. Inst. Meth.　A **977,** 164301 (2020), arXiv: 2005.14399
* T. Okudaira, S. Endo, H. Fujioka, K. Hirota, K. Ishizaki, A. Kimura, M. Kitaguchi, J. Koga, Y. Ninomi, K.

Sakai, T. Shima, H. M. Shimizu, S. Takada, Y. Tani, T. Yamamoto, H. Yoshikawa, and T. Yoshioka, **Energy dependent angular distribution of individual γ-rays in the 139La(*n*, γ)140La* reaction**, Phys. Rev. C **104**, 014601 (2021). arXiv: 2101.00262

K. Ishizaki, H. Hotta, I. Ide, M. Iinuma, T. Iwata, M. Kitaguchi, H. Kohri, D. Miura, Y. Miyachi, T. Ohta, H. M. Shimizu, H. Yoshikawa, and M. Yosoi, **Measurement of nuclear spin relaxation time in lanthanum aluminate for the development of polarized lanthanum target**, Nucl. Inst. Meth. A**1020**, 165845 (2021). arXiv:2105.06299

M. J. Molway, L. Bales-Shaffer, K. Ranta, D. Basler, M. Murphy, B. E. Kidd, A. T. Gafar, J. Porter, K. Albin, B. M. Goodson, E. Y. Chekmenev, M. S. Rosen, W. M. Snow, J. Ball, E. Sparling, M. Prince, D. Cocking, and M. J. Barlow, **Two-Orders-of-Magnitude Improvement in the Total Spin Angular Momentum of ^{131}Xe Nuclei Using Spin Exchange Optical Pumping**, submitted to Journal of Magnetic Resonance (2023). arXiv:2105.03076

W. M. Snow, C. Haddock, and B. Heacock, **Searches for Exotic Interaction Using Neutrons**, invited paper, Special Issue: The Neutron Physics - Dark Matter Connection: Bridge Through the Baryon Symmetry Violation, **Symmetry 14**, 10 (2021).

* J. Koga, S. Takada, S. Endo, H. Fujioka, K. Hirota, K. Ishizaki, A. Kimura, M. Kitaguchi, Y. Niinomi, T. Okudaira, K. Sakai, T. Shima, H. M. Shimizu, Y. Tani, T. Yamamoto, H. Yoshikawa, and T. Yoshioka, **Angular Distribution of γ-rays from the p-wave Resonance of ^{118}Sn on ANNRI,** Phys. Rev. C 105, 054615 (2022). arXiv:2022.06222.

* S. Endo, T. Okudaira, R. Abe, H. Fujioka, K. Hirota, A. Kimura, M. Kitaguchi, T. Oku, K. Sakai, T. Shima, H. M. Shimizu, S. Takada, S. Takahashi, T. Yamamoto, H. Yoshikawa, and T. Yoshioka, **Measurement of the transverse asymmetry of γ-rays in the ^{117}Sn(n, γ)^{118}Sn reaction**, Phys. Rev. C **106**, 064601 (2022). arXiv:2210.15807.

* T. Okudaira et al, **Angular distribution of individual γ-rays from neutron induced p-wave resonance in the 131Xe(n, γ)132Xe* reaction,** Phys. Rev. C **107**, 054602 (2023). arXiv:2212.10889

H. Lu, W. M. Snow, D. Basler, B. M. Goodson, M. Barlow, and G. M. Schrank, Z. Salhi, O. Holderer, S. Passini, A. Ioffe, P. Gutfrunde, and E. Babcock, **The Nuclear Polarization Induced Neutron Birefringence of ^{129}Xe and ^{131}Xe Nuclei,** submitted to Phys. Rev. Lett. (2022). arXiv: 2301.00460

H. Lu, W. M. Snow, D. Basler, B. M. Goodson, Z. Salhi, O. Holderer, S. Passini, A. Ioffe, and E. Babcock, **Method for accurate determination of the ^{3}He neutron incoherent scattering length b_i,** submitted to Phys. Rev. C (2023).

L. Charon-Garcia, J. Curole, V. P. Gudkov, W. M. Snow, and L. Barron-Palos **P-even and -odd asymmetries in n+ ^{117}Sn at the vicinity of the p resonance E_p=1.33 eV,** submitted to Phys. Rev. C (2023).

v）長期課題でこれまで実施した研究内容［Past results in the Long Term project］

The instrumentation for parity violation measurements on ANNRI was successfully tested in cycle 2023A on the NOBORU beamline, and we verified that our apparatus can measure the well-known parity-odd asymmetry on the 0.7 eV p-wave resonance in ^{139}La. The first figure below shows the 0.7 eV p-wave resonance and the 3.0 eV s-wave resonance in ^{139}La as seen in our test run in the ^{6}Li current mode neutron detector, a CsI(Tl) current mode gamma detector, and a NaI(Tl) current mode gamma detector.

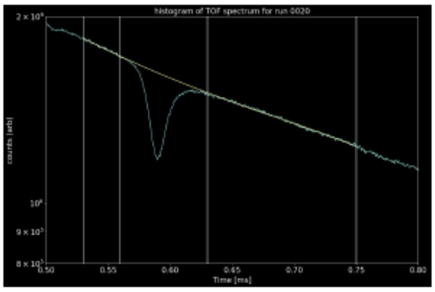


Figure 10: Li6 s-wave resonance

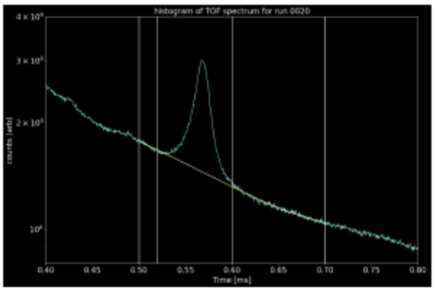


Figure 11: NaI s-wave resonance

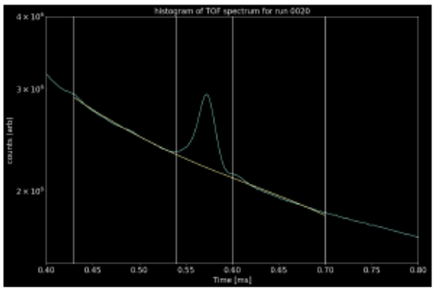


Figure 12: CsI s-wave resonance

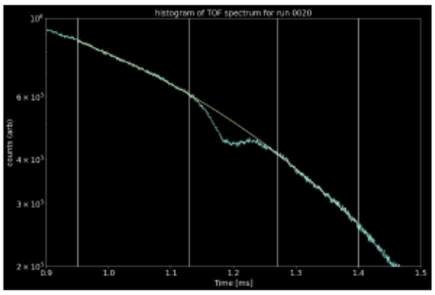


Figure 13: Li6 p-wave resonance

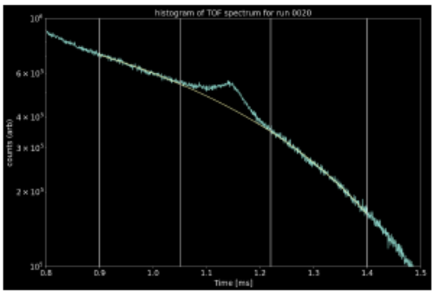


Figure 14: NaI p-wave resonance

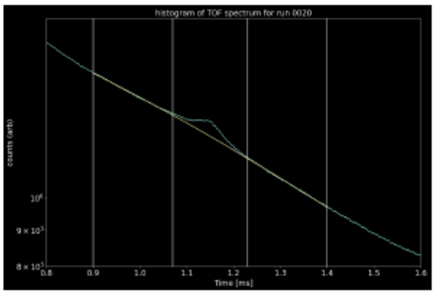
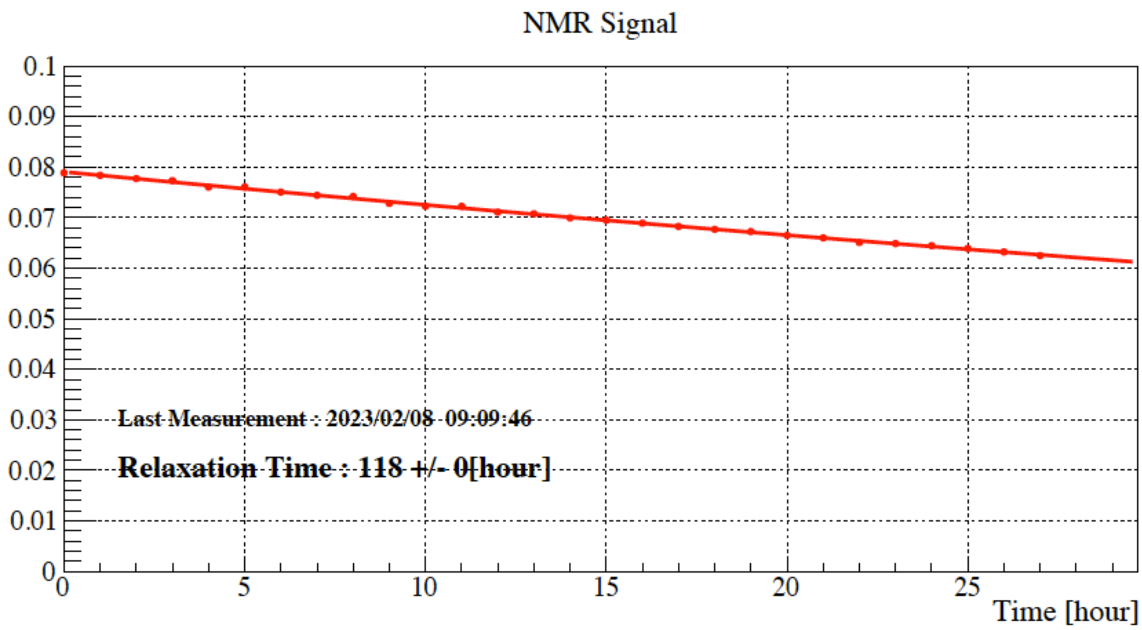
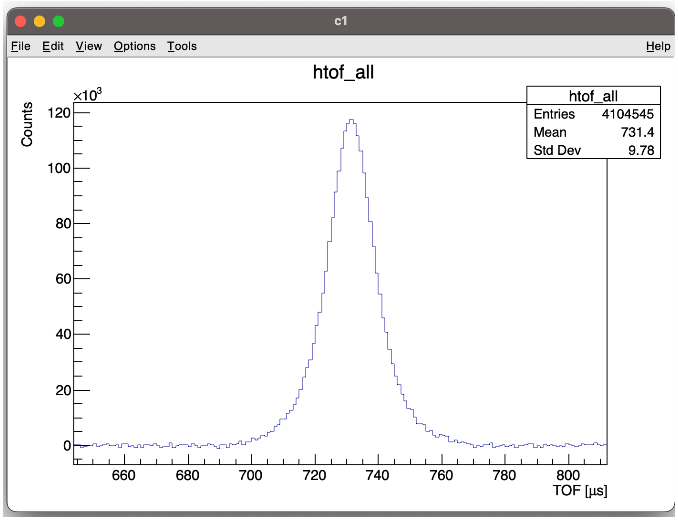


Figure 15: CsI p-wave resonance

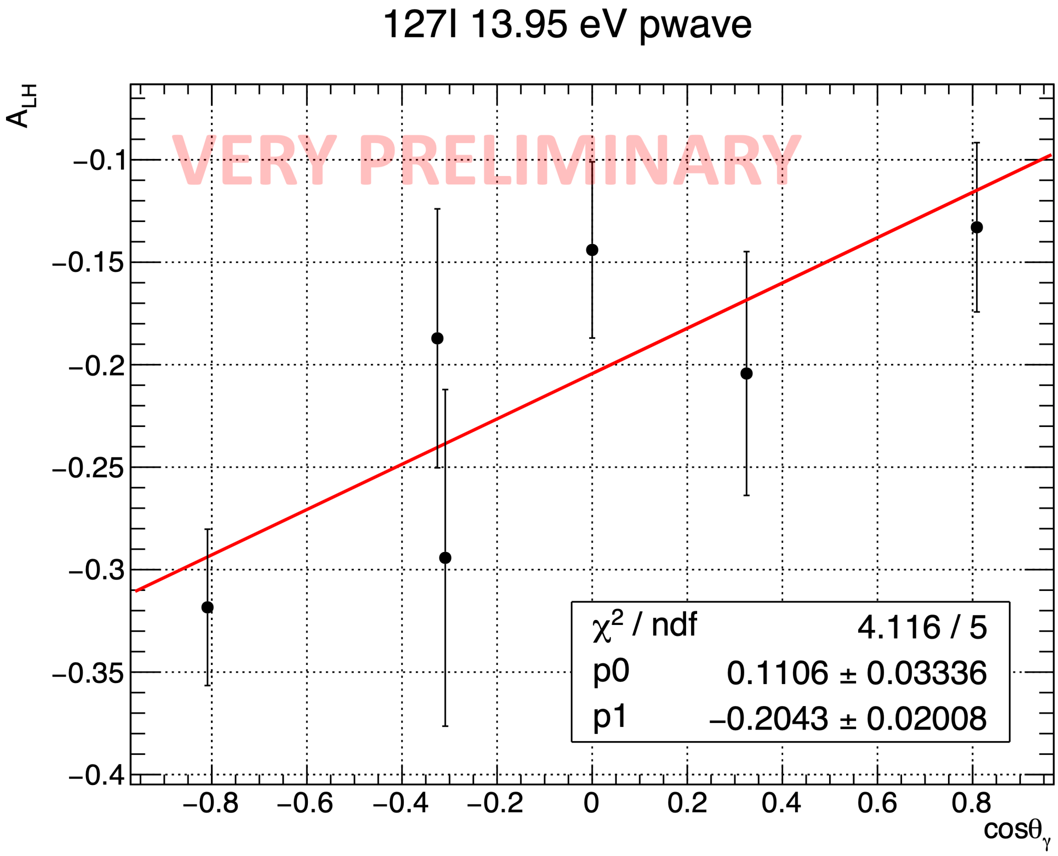


The plot above shows the polarized ^{3}He spin relaxation time on NOBORU. It is long enough to enable our proposed measurements on ANNRI.

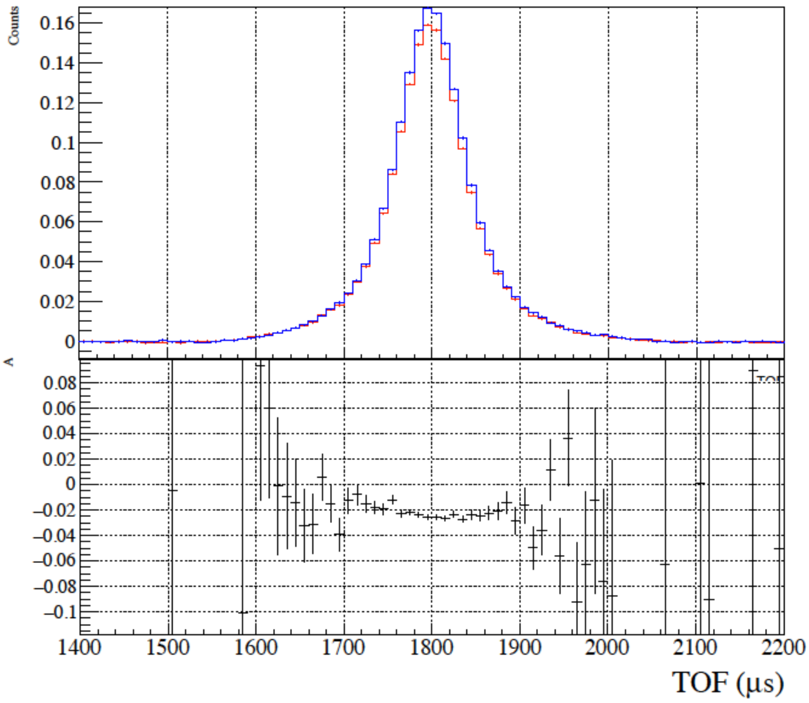
In addition, we also verified that we can achieve the scientific goals of the original long-term proposal in a technically simpler way by using the polarized ^{3}He neutron spin filter and the ANNRI germanium array, which will be much easier to implement. This conclusion is based on 5 days of data taken on BL10 on ^{113}Cd and ^{127}I nuclei, which both have known p-waves in our neutron energy range of interest. By optimization of the upstream attenuator made of the same material as the target, we showed that we can increase the count rate in the germanium detectors enough to see P-odd effects in the size range of interest.



The plot above shows 2.4 x 10^6 integrated counts in the ANNRI Ge array on the ^{113}Cd 4.53 eV p-wave resonance in Cd after background subtraction measured in April/May 2023, which is a good proxy for the "average" p-wave resonance we wish to search for in our experiments. Combined with the demonstrated neutron polarization and spin flip efficiency at this energy from the NOBORU test run, this statistical power is enough to reach the accuracies quoted above.



We have also shown that this statistical accuracy is high enough to see nonzero P-even angular asymmetries on p-wave resonances. The plot above shows an example in the 14 eV p-wave resonance in ^{127}I measured on ANNRI in April/May 2023 using an upstream ^{127}I absorber to improve the signal/background.



Finally, on May 19 2023 on the NOBORU beam we proved we can see the P-odd asymmetry on the 0.7 eV resonance in ^{139}La. The plot below shows the (unnormalized) P-odd asymmetry in one of the Ge detectors. This is exactly the same type of measurement and setup we propose to apply to the unmeasured nuclei in this proposal.

vi）長期課題の今後の研究計画［Future research plan］

It is not clear to us which "future" is being asked here. If the "future" means the plan after the past results in long-term project, then as the long-term project has not yet started it is the same as the plan presented in the section above: **[Purpose(s) of this proposed experiment (State clearly what you intend to clarify in this experiment and what are novelty and originality of your research plan)］**

If by "future" is meant after the completion of the long-term project plan: it is too early to tell. If we discover a new large P-odd asymmetry in a nucleus that can be polarized, we will proceed to measure kappa for this nucleus and see if it can be used for a sensitive T violation search. And in any case we will analyze the data for its impact on the statistical theory for P violation in heavy nuclei in this case even null results give important information.

vii）本申請に関連する個別テーマ課題リスト（課題名）と相互の関連性　［List of the proposal title(s) for Individual Experiment(s) application involved in this Long Term Proposal and the mutual relationship］

(2) **Test of Compact High Efficiency Neutron Spin Flipper Between 0.1-100 eV for the ANNRI Instrument and Measurement of Parity Violation in ^{139}La Using Helicity Dependence of Polarized (n, γ) Cross Section: NOBORU**

(3) **Search for P-Wave Resonances in Selected Nuclei Using Parity-odd (n, γ) Cross Section and Parity-Even Gamma Angular Distributions：ANNRI**

(4) **Search for P-Wave Resonances in Selected Nuclei Using Parity-odd (n, γ) Cross Section and**

Parity-Even Gamma Angular Distributions : ANNRI

The first experiment done on the NOBORU test beamline in 2022B cycle was a test measurement using the known parity violation in ^{139}La to confirm that all of the components of the apparatus (^{3}He polarizer, spin transport, neutron spin flipper, detectors, data acquisition system) work correctly. The last two ANNRI experiments will search for the new p-wave resonances.

ⅷ) 本申請に関連する研究費獲得・申請状況 [Status for Budget (Grant) which the proposer has obtained or applied for this research plan]

The major hardware components for the proposed parity violation measurements on ANNRI in addition to those already in the apparatus are: (1) in-situ ^{3}He polarizer with NMR neutron spin flipper, (2) in-beam current mode neutron detector with high efficiency between 1-10 eV, (3) data acquisition system with spin flipper information, and (4) samples and upstream beam attenuators. (1) already exists at JPARC. The ^{3}He polarization achieved in the NOBORU test experiment is sufficient. (2) and (3) exist and are tested, and (4) will be purchased and shipped to Japan by July 2023. Funds also exist for the student researcher participation from US, Japan, and China sides of the collaboration. US graduate student C. Auton won a JSPS fellowship to spend time between February 2023 and February 2024 in Japan to work on this effort. Clayton is in Japan and has worked on all experiments. He has learned the ANNRI data analysis and can prepare the samples and their associated upstream attenuators.

以上(That's all)