# **BL3:** A Next Generation Beam Neutron Lifetime Experiment



















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CIPANP 2025, Madison WI







# Neutron Lifetime Experiments Neutron Lifetime<sup>Two</sup> main methods



#### ultracold neutron (UCN) storage method











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#### Uncertainty < 10 s



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#### Improved measurements of neutron lifetime with cold neutron beam at J-PARC

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The "neutron lifetime puzzle" arises from the discrepancy between neutron lifetime measurements obtained using the beam method, which measures decay products, and the bottle method, which measures the disappearance of neutrons. To resolve this puzzle, we conducted an experiment using a pulsed cold neutron beam at J-PARC. In this experiment, the neutron lifetime is determined from the ratio of neutron decay counts to  ${}^{3}\text{He}(n,p){}^{3}\text{H}$  reactions in a gas detector. This experiment belongs to the beam method but differs from previous experiments that measured protons, as it instead detects electrons, enabling measurements with distinct systematic uncertainties. By enlarging the beam transport system and reducing systematic uncertainties, we achieved a fivefold improvement in precision. Analysis of all acquired data yielded a neutron lifetime of  $\tau_n = 877.2 \pm 1.7_{(\text{stat.})} + 4.0_{-3.6(\text{sys.})}$  s. This result is consistent with bottle method measurements but exhibits a  $2.3\sigma$  tension with the average value obtained from the proton-detection-based beam method.

Introduction- A neutron decays into three particles, a  $f_A$  of  $g_A$  [7]. proton, an electron, and an antineutrino via weak interactions. The neutron  $\beta$  decay lifetime,  $\tau_n$ , is a crucial parameter that determines the neutron-to-proton ratio at the onset of Big Bang nucleosynthesis (BBN) [1, 2]. The combination of the BBN model and the baryon-tophoton ratio derived from the cosmic microwave background observations [3, 4] provides an accurate prediction of the abundance of light elements, allowing tests of physical phenomena in the early universe. Additionally, the  $V_{\rm ud}$  term in the Cabibbo-Kobayashi-Maskawa (CKM) matrix can be determined using  $\tau_n$  and  $\lambda$ , which is the ratio of axial-vector to vector coupling constants,  $q_A/q_V$ , independently of nuclear models. Revised radiative corrections in 2018 [5] suggested the CKM unitarity violation exceeding  $2\sigma$  [6], emphasizing the importance of the measurement of the neutron lifetime. Precise data on  $\tau_n$  is also valuable for testing lattice QCD calculations

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Neutron lifetime has been measured using two primary methods. The first is the beam method [8, 9], where neutron  $\beta$  decay products, specifically protons in these references, are counted relative to the number of incident neutrons, yielding an average lifetime of  $\tau_n^{\text{beam}} =$  $888.0 \pm 2.0$  s. The second is the bottle method [10– 17], which measures the disappearance of ultra-cold neutrons (UCNs) confined in a container over time, producing an average value of  $\tau_{\rm n}^{\rm bottle} = 878.4 \pm 0.5$  s. The 9.5-s  $(4.6\sigma)$  discrepancy between the two methods is known as the "neutron lifetime puzzle" [18], raising concerns about the reliability of neutron lifetime measurements.

Possible causes for this discrepancy include unaccounted systematic uncertainties, such as protons from neutron decay undergoing charge exchange with residual gas [19], though this effect is considered negligible [20]. The 9.5-s, approximately 1% discrepancy between beam



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ties were applied as common shifts. The overall neutron lifetime result from J-PARC, combining all conditions, is  $\tau_{\rm n} = 877.2 \pm 1.7_{\rm (stat.)} \stackrel{+4.0}{-3.6}_{\rm (sys.)}$ . The combining average yielded  $\chi^2/\text{DOF} = 15.8/3$ , though the underlying cause of this deviation remains undetermined.

TABLE II. Neutron lifetime values for each gas pressure (100 kPa, 50 kPa) and SFC configuration (new, old), with averages. Units in seconds.

Conditions	Value	Stat.	Cut position	Other sys.
100 kPa/old SFQ	870.9	3.5	+1.8/-2.8	+5.5/-4.9
100 kPa/new SFC	C 868.3	4.0	+1.5/-2.9	+3.8/-3.2
50  kPa/old SFC	868.2	7.7	+2.7/-0.9	+4.8/-3.9
50 kPa/new SFC	884.8	2.4	+0.8/-1.3	+3.2/-3.0
Combined	877.2	1.7		+4.0/-3.6

### Pressure-dependent systematic?

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## Neutron Decay Parameters





 $\lambda = \frac{G_A}{G_V}$ 

$$V_{ud}^2 = \frac{4093.7 \text{ s}}{\tau_n (1 + 3G_A^2)}$$





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## Neutron Decay Parameters



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 $\lambda = \frac{G_A}{G_V}$ 

$$V_{ud}^2 = \frac{4093.7 \,\mathrm{s}}{\tau_n (1 + 3G_A^2)}$$





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## **Neutron Life**



Neutron Research (shown), physicists will monitor a beam of neutrons to determine the neutron's lifetime RONALD CAPPELLETTI/NIST









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#### APS News, July 2019

#### **APRIL MEETING**

#### Sorting Out the Neutron Lifetime

BY SOPHIA CHEN

 or over a decade, physicists have puzzled over the neutron lifetime: how long, on average, it takes the isolated particle to decay into a proton, electron, and antineutrino. Counting the number of neutrons in a container over time, they measure the half-life to be about 14 minutes and 39 seconds. Using a different experimental method where they count one of the neutron's decay products, they measure the lifetime to be about 8 seconds longer.

"It's an exciting time to work in the field," says Shannon Hoogerheide of the National Institute of Standards and Technology (NIST). In 2018, three independent teams of physicists have published new measurements of the neutron lifetime, which have improved precision but preserve the discrepancy.

During a mini-symposium at this year's APS April meeting in Denver, experts gathered to develop strategies for resolving the discrepancy, including a tantalizing theory involving dark matter decay.

But the discrepancy could still be the result of systematic uncertainties, so some groups are working to make better measurements.

"We've taken more lifetime data this year, and we're analyzing it right now," says Kevin Hickerson of the Ultracold Neutron Tau (UCNT) experiment at Los Alamos National Laboratory.

Hickerson's method, a socalled bottle experiment, involves counting neutrons over time and results in the shorter measured of about a millikelvin inside a one-



NIST proton trap for measuring neutron lifetime. A free neutron entering the trap as part of a beam will decay into a proton, an electron, and an antineutrino. The number of protons detected can be used to calculate the neutron lifetime, IMAGE E WEBBER/NIST

meter diameter container—"the bathtub," they call it.

"We fill it with neutrons, and then we count," he says. "And we fill it again, wait longer, and count again. Then we fit an exponential to that decay." The three 2018 measurements, one made by Hickerson's group, were all bottle experiments, albeit with slightly different setups [Science 360, 627 (2018)].

The other method, known as a beam experiment, involves counting the protons that the neutrons decay into. At NIST, researchers send a beam of neutrons through an electromagnetic field, which traps and then deflects any proton decay products, explained Hoogerheide. NIST's experiment yielded the most recent beam result in 2005. Using the same data, they updated those results with better calilifetime. He and his colleagues trap bration in 2013, and her team is ultracold neutrons at a temperature currently working to improve that measurement

Researchers were particularly excited to discuss whether the discrepancy arose from an unknown dark matter decay product. This theory, proposed by Bartosz Fornal and Benjamin Grinstein of the University of California, San Diego, has the neutron decaying into a dark matter particle 1 percent of the time. This particle would have a mass of about 1 GeV, about 100 times lighter than the weakly interacting massive particles usually predicted by supersymmetry. If neutrons occasionally became dark particles, that would explain why neutrons disappear more quickly in the bottle experiment than proton decay products appear in the beam experiment. "If this turns out to be how nature works, this would turn out to be a very inexpensive way of trying to probe dark matter," says Fornal.

**NEUTRON CONTINUED ON PAGE 5** 

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#### Dark Matter Interpretation of the Neutron Decay Anomaly

Department of Physics, Universi

Editors' Suggestion Featured in Physics

(Received 19 Januar)

There is a long-standir experiments. We propose to more dark sector particles i We construct representativ

DOI: 10.1103/PhysRevLett.12

Introduction.-The neutron is one building blocks of matter. Along v electron, it makes up most of th Without it, complex atomic nuclei have formed. Although the neutron eighty years ago [1] and has beer thereafter, its precise lifetime is still [2,3]. The dominant neutron decay  $n \rightarrow p + e^- + \bar{\nu}_e$ , described by t  $\mathcal{M} = (G_F/\sqrt{2})V_{ud}g_V[\bar{p}\gamma_u n - \lambda \bar{p}\gamma_5\gamma_u)$ theoretical estimate for the neutro 4908.7(1.9) s/[ $|V_{ud}|^2(1+3\lambda^2)$ ] [4–7 Group (PDG) world average for the coupling ratio is  $\lambda = -1.2723 \pm 0.00$ PDG average  $|V_{ud}| = 0.97417 \pm 0.00$ 875.3 s and 891.2 s within  $3\sigma$ .

There are two qualitatively different lifetime measurements: bottle and bea

In the first method, ultracold neu container for a time comparable to the remaining neutrons that did not decay a decaying exponential,  $\exp(-t/\tau_n)$ . five bottle experiments included in average is  $\tau_n^{\text{bottle}} = 879.6 \pm 0.6 \text{ s}$  [9– ments using trapping techniques [14 lifetime within 2.0 $\sigma$  of this average.

In the beam method, both the number beam and the protons resulting from and the lifetime is obtained from the  $-N/\tau_n$ . This yields a considerably low the average from the two beam experi PDG average [16,17] is  $\tau_n^{\text{beam}} = 888$ 

0031-9007/18/120(19)/191801(6)

#### PHYSICAL REVIEW LETTERS **121**, 061802 (2018)

#### **Neutron Stars Exclude Light Dark Baryons**

David McKeen,<sup>1,2,\*</sup> Ann E. Nelson,<sup>3,†</sup> Sanjay Reddy,<sup>4,‡</sup> and Dake Zhc <sup>1</sup>Pittsburgh Particle Physics, Astrophysics, and Cosmology Center, Department of Physics and Astron Pittsburgh, Pennsylvania 15260, USA

<sup>2</sup>TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia V6T 2A3, Ca <sup>3</sup>Department of Physics, University of Washington, Seattle, Washington 9819.<sup>4</sup> <sup>4</sup>Institute for Nuclear Theory, University of Washington, Seattle, Washington 98.

(Received 26 February 2018; revised manuscript received 1 June 2018; published

Exotic particles carrying baryon number and with a mass of the order of the nucleon proposed for various reasons including baryogenesis, dark matter, mirror worlds, and the puzzle. We show that the existence of neutron stars with a mass greater than 0.7 M constraints on such particles, requiring them to be heavier than 1.2 GeV or to have st self-interactions.

#### DOI: 10.1103/PhysRevLett.121.061802

Introduction.—Exotic states that carry baryon number and have masses below a few GeV have been theorized in a number of contexts, such as asymmetric dark matter [1,2], mirror worlds [3], neutron-antineutron oscillations [4], or nucleon decays [5]. In general, such states are highly constrained, because they can drastically alter the properties of normal baryonic matter—in particular, if too light, they can potentially render normal matter unstable. We currently understand that matter is observationally stable, because the standard model (accidentally) conserves baryon number. This ensures that the proton, the lightest baryon, does not decay (up to effects caused by higherdimensional operators that violate baryon number).

Now, consider the simple case of an electrically neutral single new fermion  $\chi$  that carries a unit baryon number and carries no other conserved charge. Assuming that its couplings to ordinary matter are not highly suppressed, because of the conservation of baryon number and electric charge, it must have a mass larger than the difference between the proton and electron masses,  $m_{\gamma} > m_p - m_p$  $m_e = 937.76$  MeV, in order to not destabilize the proton. In fact, a slightly stronger lower bound on  $m_{\gamma}$  comes from the stability of the weakly bound <sup>9</sup>Be nucleus:  $m_{\gamma} >$ 937.90 MeV. If  $m_{\chi} > m_n = 939.57$  MeV, a new neutron decay channel can open up,  $n \rightarrow \chi + \cdots$ , where the ellipsis includes other particles that allow the reaction to conserve (linear and angular) momentum.

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061802-1 Published by the American Physical Society

## **Exotic Physics Solution?**

Eur. Phys. I. C (2019) 79.484

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Letter

#### Neutron lifetime puzzle and neutron-mirror

#### Zurab Berezhiani<sup>1,2,a</sup>

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Received: 13 November 2018 / Accepted: 22 May 2019 / Published online: 10 June 2019 © The Author(s) 2019

Abstract Standard Model, with its present precision, predicts the neutron  $\beta$ -decay time  $\tau_{SM} = 878.7 \pm 0.6$  s which is perfectly compatible with the neutron lifetime measured in the trap experiments  $\tau_{\rm trap} = 879.4 \pm 0.6$  s. However, the lifetime measured in the beam experiments via counting the protons produced by  $\beta$ -decay  $n \rightarrow p e \bar{\nu}_e$ ,  $\tau_{\text{beam}} = 888 \pm 2.0$ s, is deviated from  $\tau_{SM}$  by 9 seconds (4.4 $\sigma$ ). This discrepancy can be explained via the neutron *n* conversion into mirror neutron n', its dark partner from parallel mirror sector. Provided that *n* and *n'* have a tiny mass splitting  $\sim 10^{-7}$  eV, in mag-

netic fields of few Tesla used in beam experiments, n - n'transition is resonantly enhanced converting a 1% fraction of neutrons into mirror neutrons which decay in invisible mode  $n' \rightarrow p'e'\bar{\nu}'_e$ . Thus less protons are produced and the measured value  $\tau_{\text{beam}}$  appears larger than the true decay time  $\tau_{\rm SM} = \tau_{\rm trap}$ .

1. Exact determination of the neutron lifetime remains a problem. It is measured in two types of experiments. The trap experiments measure the disappearance rate of the ultra-cold neutrons (UCN) counting the survived UCN after storing them for different times in material or magnetic traps, and determine the neutron decay width  $\Gamma_n = \tau_n^{-1}$ . The beam experiments are the appearance experiments, measuring the width of  $\beta$ -decay  $n \to pe\bar{\nu}_e, \Gamma_\beta = \tau_\beta^{-1}$ , by counting the protons produced in the monitored beam of cold neutrons. As far as in the Standard Model (SM) the neutron decay always produces a proton, both methods should measure the same value  $\Gamma_n = \Gamma_\beta$ .

However, the tension is mounting between the results obtained by two methods [1,2]. Presently available experimental results using the trap [3-11] and the beam [12,13]methods, summarized in Fig. 1, yield separately

<sup>a</sup>e-mail: zurab.berezhiani@lngs.infn.it

$E_{\rm trap} = (879.4 \pm 0.6)  {\rm s}$	(1)	by rec
$_{\text{beam}} = (888.0 \pm 2.0) \text{ s}$	(2)	wi

It is interesting to note

938.78 MeV,  $\chi$  is itself kept

of baryon number and electric (

a potential candidate for dark n

electrically neutral and stable. It

situation the stability of normal

ensured by the *same* symmetry

A potential new decay ch

recently received attention as a

ancy between values of the neut

two different techniques, the "t

[3,6,7]. The bottle method, w

neutrons that remain in a trap

and is therefore sensitive to the

 $\tau_n^{\text{bottle}} = 879.6 \pm 0.6 \text{ s}$  [8]. The

rate of protons emitted in a fi

neutrons, thus measuring onl

neutron, and results in  $\tau_n^{\text{beam}}$ 

two measurements can be reco

decay mode for the neutron, s

However, a recent reevaluation

neutron lifetime from post-200

tron  $q_A$  concludes that any nor

neutron is limited to less than 2

In this Letter, we note that a 1

number and has a mass cl

drastically affect the propertie

sities seen in the interiors of ne

the neutron chemical potential

than  $m_n$ , reaching values of  $\simeq 2 \odot c_n$  in the neuroscience of  $\sim 2$ 

 $\operatorname{Br}_{n \to \chi} = 1 - \frac{\tau_n^{\text{bottle}}}{\tau_{\text{beam}}} = 1$ 

branching fraction









Exciting hint toward the so

<sup>2</sup>Instituto de Física, Pontificia Universi

We revisit the neutron lifetime puzzle, a disc

neutron decay. Since both types of measurement

of free neutrons, we argue that the existence of

We elaborate on the required properties of such

states have not been experimentally identified

DOI: 10.1103/PhysRevD.110.073004

I. INTRODUCTION

A. The neutron in the quark model

The neutron is one of the main constituents of nuc

matter. It is a composite state, whose properties are ruled

the strong and the electroweak interactions between

lightest quarks of the Standard Model of particle physics.

of pivotal importance in many phenomena ranging from

bang nucleosynthesis to experimental particle physics [

properties of this particle in terms of fundamental deg

of freedom is an open field of research, it is possible

understand several properties in terms of much sim

models. In our discussion we will make use of the langu

and notation of the quark model. In this model, protons

neutrons are composite particles made up of qua

Protons consist of a particular combination of two "

(u) quarks and one "down" (d) quark, while neuti

consist of combinations of one up quark and two de

quarks. While quarks carry a fractional electric charge,

combination of quarks in protons and neutrons result

Isospin describes the similarity between protons

neutrons. It was introduced by Heisenberg [2] and 1

developed further by Wigner [3]. Algebraically, the iso:

operator I can be represented analogously to the

operator of spin one-half particles  $\vec{S}$  in terms of the P

matrices  $\vec{\sigma}$ , which are a representation of the group SU

particles with integer electric charges.

Even though a detailed understanding of the low ene

(Received 11 March 2024; acc

PHYSICAL REV

Benjamin Koch

<sup>1</sup>Institut für Theoretische

Wiedner Hauptstras

The discrep:  $\tau_{\rm tran} = (8.6)$ trolled syster physics mus how the theo imentally me the discrepai Some time the neutron l twin n' and s to a mass ga the beam me as it is predic would measu  $\Gamma_n = \tau_n^{-1}$ , i. this solution theoretical a

 $\tau_{\rm trap} = \tau_n <$ 

and  $\tau_{\text{beam}} - \tau_{\text{t}}$ ratio Γ<sub>new</sub>/ I However. tion is incons rate. In fact, i coupling cor

 $\tau_{\beta}(1+3g_A^2)$ 

This relation essentially fi radiative cor The  $\beta$ -asy the exper cently by vith each of precision:

 $g_A = 1.2762$ 

Published by the American Physical Society under the tern the Creative Commons Attribution 4.0 International lice Further distribution of this work must maintain attributio the author(s) and the published article's title, journal cita and DOI. Funded by  $SCOAP^3$ .

<sup>°</sup>Contact author: benjamin.koch@tuwien.ac.at

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journal homepage: www.elsevier.com/locate/newast	Para di tempo de servico de servi

#### New results on the two-body decay of neutrons shed new light on neutron stars

#### Eugene Oks

**ELSEVIER** 

Physics Department, 380 Duncan Drive, Auburn University, Auburn, AL, 36849, USA

ARTICLE INFO

Key words: Neutron stars Dark matter Neutron lifetime puzzle Two-body decay of neutrons Second flavor of hydrogen atoms Multi-messenger astro

ABSTRACT

In attempts to resolve the neutron lifetime puzzle, there was suggested a hypothetical decay of neutrons into some unspecified dark matter (DM) particles. Later there were performed studies on how the hypothetical decay of neutrons would affect neutron stars. Recently it was shown that with the allowance for the second solution of Dirac equation for hydrogen atoms, the theoretical branching ratio (BR) for the two-body decay of neutrons (compared to their three-body decay) is amplified by a factor of 3300 from 0.000004. So, the BR becomes about 1.3% in the excellent agreement with the "experimental" BR =  $(1.15 \pm 0.27)$ % required for reconciling the two distinct experimental values of the neutron lifetime: one from the beam experiments, another from the trap experiments. This meant that the two-body decay of neutrons in the beam experiments (that count only the protons) plays a much more sizable part in the overestimation of the lifetime of neutrons in these experiments than previously thought. Hydrogen atoms corresponding to the second solution of Dirac equations are called the second flavor of hydrogen atoms (SFHA) by the analogy with the flavors of quarks. The existence of the SFHA is evidenced by four different types of atomic/molecular experiments. The primary feature of the SFHA is that due to having only the s-states, they do not emit or absorb the electromagnetic radiation (except for the 21 cm line): they are practically dark. The SFHA became a candidate for a part of DM for the first time after the SFHA-based successful qualitative and quantitative explanation of the perplexing observation by Bowman et al. of the anomalous absorption in the redshifted 21 cm line from the early Universe. In the present paper we analyzed how this neutron decay into the SFHA affects neutron stars. We showed that old neutron stars could very slowly generate the new specific, described in detail baryonic DM in the form of the SFHA. Some old neutron stars would release it into their tiny atmospheres, while some other old neutron stars would release it into the interstellar medium. Besides, mergers of a neutron star with another neutron star or with a black hole, accompanied by the ejection of neutron-rich material, can also lead to the formation of SFHA as the ejecta cools down. This is another interesting aspect of the multi-messenger astronomy focused on studying these mergers through the gravitational waves they generate. These mechanisms of generating new baryonic DM in the universe should have the fundamental importance. We point out the indirect observational evidence of the continuing generation of new baryonic DM. We hope that our results will stimulate a further research in this direction.

#### 1. Introduction

The average measured lifetime (AML) of neutrons is puzzling – see, e. g., works (Broussard, 2022; Gonzalez, 2021; Serebrov et al., 2021; Particle Data Group, 2020; Berezhiani, 2019; Tan, 2019; Czarnecki et al., 2018; Sun, 2018; Tang, 2018; Pattie, 2018): e.g., according to Gonzalez et al. paper (2021), the AML of trapped ultracold neutrons  $\tau_{trap} = (877.75 \pm 0.28_{stat} + 0.22/\text{-}0.16_{syst}) \text{ s}$  – in contrast to the beam AML of neutrons  $\tau_{beam} = 888.0 \pm 2.0$  s. For solving this puzzle, Fornal and Grinstein (2018) suggested that neutron might decay into an

unspecified dark matter (DM) particle. Later Grinstein et al. (2019) and then Husain et al. (2022) explored how this decay channel would affect *neutron stars*. The problem still was that the resulting hypothetical DM particle was not identified. Moreover, Dubbers et al. (2019) showed that the Branching Ratio (BR) for this process is at least several times smaller than the BR required for reconciling the experimental values of  $\tau_{trap}$  and

Check for updates

Green and Thomson (1990) brought up the two-body decay of neutrons (the decay into a hydrogen atom and antineutrino) into consideration. However, the BR for this process, known at that time, was

E-mail address: oksevgu@auburn.edu.

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#### CIPANP 2025, Madison WI

#### F. E. Wietfeldt



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$$\tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_0 v_{\text{th}}}$$







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$$\tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_0 v_{\text{th}}}$$







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$$\tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_0 v_{\text{th}}}$$







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$$\tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_0 v_{\text{th}}}$$

$$L_{det} = nl + l$$









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$$\tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_0 v_{\text{th}}}$$

$$L_{det} = nl +$$

number of trap electrodes









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$$\tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_0 v_{\text{th}}}$$

$$L_{det} = nl + l$$

number of trap electrodes







length of electrode + spacer



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$$\tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_0 v_{\text{th}}}$$

length of

$$L_{det} = nl + l$$

number of trap electrodes









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$$\tau = \frac{R_n \varepsilon_p L_{\text{det}}}{R_p \varepsilon_0 v_{\text{th}}}$$

length of electrode + spacer

$$L_{det} = nl + l$$

number of trap electrodes











CIPANP 2025, Madison WI











Institut Laue-Langevin, 6 March 2025





J. S. NICO et al.

### 2005 result : $\tau_n = 886.3 \pm 1.2[\text{stat}] \pm 3.2[\text{sys}]$

Source of correction

<sup>6</sup>LiF deposit areal density <sup>6</sup>Li cross section Neutron detector solid angle Absorption of neutrons by <sup>6</sup>Li Neutron beam profile and detector soli Neutron beam profile and <sup>6</sup>Li deposit Neutron beam halo Absorption of neutrons by Si substrate Scattering of neutrons by Si substrate Trap nonlinearity Proton backscatter calculation Neutron counting dead time

Proton counting statistics Neutron counting statistics

Total





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#### PHYSICAL REVIEW C 71, 055502 (2005)

#### Error Budget

	Correction (s)	Uncertainty (s)	Section	
	+5.2	2.2 1.2 1.0 0.8	IV A II D II D 1 IV A 2	neutron counter efficiency $\varepsilon_0$
id angle	+1.3	0.1	IVA2	neutron
shape	-1.7 -1.0	0.1	IVA2 IVB2	counting
e	+1.2	0.1	IVA2	
	-0.2 -5.3	0.5	IV A 3 IV C	proton
	+0.1	0.4 0.1	IVD3 IID	counting
		1.2 0.1	IV D 2 II D	
	-0.4	3.4		



#### J. S. NICO et al.

#### Error Budget

#### Source of correction

<sup>6</sup>LiF deposit areal density <sup>6</sup>Li cross section Neutron detector solid angle Absorption of neutrons by <sup>6</sup>Li Neutron beam profile and detector soli Neutron beam profile and <sup>6</sup>Li deposit Neutron beam halo Absorption of neutrons by Si substrate Scattering of neutrons by Si substrate Trap nonlinearity Proton backscatter calculation Neutron counting dead time

Proton counting statistics Neutron counting statistics

Total





PHYSICAL REVIEW C 71, 055502 (2005)

	Correction (s)	Uncertainty (s	s) Section	
"Alp ca	ha Gamma" alibration ( +5.2	2.2 1.2 1.0 0.8	IV A II D II D 1 IV A 2	neutron counter efficiency $\varepsilon_0$
id angle	+1.3	0.1	IVA2	neutron
snape	-1.7 -1.0	1.0	IV A 2 IV B 2	counting
2	+1.2	0.1	IVA2	
	-0.2 -53	0.5	IVA3 IVC	proton
	±0.1	0.4	IVD3	counting
	+0.1	1.2		
		0.1	IVD2 IID	
	-0.4 2	2.2 3.4		

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J. S. NICO et al.

### 2013 update : $\tau_n = 887.7 \pm 1.2[\text{stat}] \pm 1.9[\text{sys}]$

#### Source of correction

<sup>6</sup>LiF deposit areal density <sup>6</sup>Li cross section Neutron detector solid angle Absorption of neutrons by <sup>6</sup>Li Neutron beam profile and detector soli Neutron beam profile and <sup>6</sup>Li deposit Neutron beam halo Absorption of neutrons by Si substrate Scattering of neutrons by Si substrate Trap nonlinearity Proton backscatter calculation Neutron counting dead time

Proton counting statistics Neutron counting statistics

Total





#### PHYSICAL REVIEW C 71, 055502 (2005)

#### Error Budget

	Correction (s)	Unce	rtainty (s)	Section	
"Alp ca	ha Gamma" alibration ( +5.2	).9	2.2 1.2 1.0 0.8	IV A II D II D 1 IV A 2	neutron counter efficiency $\varepsilon_0$
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snape	-1.7 -1.0		1.0	IVA2 IVB2	counting
e	+1.2		0.1	IVA2	
	-0.2 -5.3		0.8	IV A S IV C	proton counting
	+0.1		0.4 0.1	IV D 3 II D	counting
			1.2 0.1	IV D 2 II D	
	-0.4	2.2	3.4		

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Based on the Sussex-ILL-NIST beam neutron lifetime program using a quasi-Penning proton trap.











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Based on the Sussex-ILL-NIST beam neutron lifetime program using a quasi-Penning proton trap.

Scientific Goals:

1. Further explore, cross check, and reduce all systematic uncertainties to the 10<sup>-4</sup> level.











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F. E. Wietfeldt

Based on the Sussex-ILL-NIST beam neutron lifetime program using a quasi-Penning proton trap.

Scientific Goals:

- 1. Further explore, cross check, and reduce all systematic uncertainties to the 10<sup>-4</sup> level.
- 2. Reduce the neutron lifetime uncertainty from the beam method to <0.3 s.









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Beam Method Systematics to Explore/Reduce

- proton backscatter extrapolation
- absolute neutron counting
- magnetic field homogeneity
- neutron absorption, scattering in Li foil
- dependence on neutron collimation
- dependence on residual gas pressure
- dependence on trapping time

• …









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Beam Method Systematics to Explore/Reduce

- proton backscatter extrapolation
- absolute neutron counting
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- dependence on residual gas pressure
- dependence on trapping time

• …









### Need more statistical power to fully investigate these at the 1 s level

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Beam Method Systematics to Explore/Reduce

- proton backscatter extrapolation
- absolute neutron counting
- magnetic field homogeneity
- neutron absorption, scattering in Li foil
- dependence on neutron collimation
- dependence on residual gas pressure
- dependence on trapping time









Need more statistical power to fully investigate these at the 1 s level

BL3 can make a 1 s (statistical) neutron lifetime measurement in <1 day.

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- Higher flux (NIST NG-C) and larger diameter neutron beam (7 mm  $\rightarrow$  40 mm)
- Longer proton trapping region (35 cm  $\rightarrow$  50 cm)
- Larger and more uniform magnetic field (<0.2%) in trapping region)
- Large (10 cm active diameter) segmented silicon proton detector (similar to KATRIN, Nab)







BL3 key features



- High efficiency for detecting backscattered protons (smaller extrapolation to zero backscatter)
- A new, larger <sup>10</sup>B Alpha-Gamma spectrometer to calibrate the neutron counter to relative precision <  $3x10^{-4}$
- In situ neutron time-of-flight system to measure the neutron wavelength spectrum to 0.03 Å precision



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- Longer proton trapping region (35 cm  $\rightarrow$  50 cm)
- Larger and more uniform magnetic field (<0.2%) in trapping region)
- Large (10 cm active diameter) segmented silicon proton detector (similar to KATRIN, Nab)

Proton trapping rate >100× higher than in the BL1/BL2 experiment







BL3 key features



- High efficiency for detecting backscattered protons (smaller extrapolation to zero backscatter)
- A new, larger <sup>10</sup>B Alpha-Gamma spectrometer to calibrate the neutron counter to relative precision <  $3x10^{-4}$
- In situ neutron time-of-flight system to measure the neutron wavelength spectrum to 0.03 Å precision













NEUTRO FETINE

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F. E. Wietfeldt











# **BL3 Magnet**





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### **BL3 Proton Trap**

spring washers provide compression

precision straight edge ensures alignment

precision silica balls ensure parallelism







9999





- electrodes are gold co fused silica
- structural parts are titanium for low magnetism



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## **BL3** Proton Detector











**GEANT** simulations of neutron decay proton initial and backscattered hits

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#### CIPANP 2025, Madison WI



## **BL3 Proton Detector**















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## **BL3 Neutron Counters and Alpha-Gamma 2.0**













neutron counter calibration on the Alpha-Gamma 2.0 instrument (5Å monochromatic beam)





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## **BL3 Neutron Counters and Alpha-Gamma 2.0**















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# **BL3 Neutron Time-of-Flight System**



- single disc chopper
- max speed = 70 Hz
- wavelength resolution <0.03Å up to 20 Å













chopper out of beam

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F. E. Wietfeldt



## **BL3 Schedule**

- Cryogenic magnet contract signed: August 2020
- Full NSF funding (\$8.2M) awarded: August 2022
- Magnet delivery expected summer 2025
- System integration and offline commissioning: 2025-2026
- Ship BL3 to NIST Center for Neutron Research and online commissioning: 2027
- Production data collection: 2027-2029









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We gratefully acknowledge major support from the U.S. National Science Foundation **Division of Physics** 

With additional support from the National Institute of Standards and Technology and the U.S. Dept. of Energy Office of Science











**U.S. DEPARTMENT OF** ENERGY

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THANK YOU!

