Neutrinos from pion production at the Spallation Neutron Source

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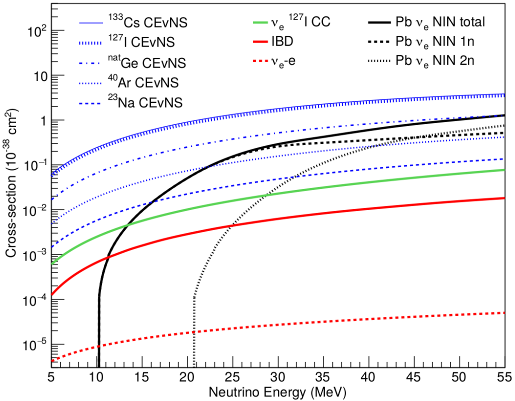
Carnegie Mellon University

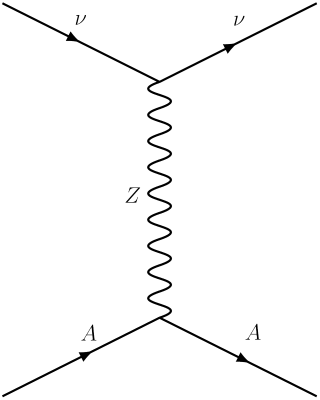
Tuesday, June 4
MENU 2019

Overview

Coherent elastic neutrino-nucleus scattering (CEvNS)

- Coherence $\implies qR < 1$
- Flavor-blind weak interaction
- High cross section (for neutrinos)[1]





[1] D. Akimov et al., "COHERENT 2018 at the Spallation Neutron Source", arXiv:1803.09183v2, 2018.

CEvNS Physics

- Sterile Searches
  - Disappearance of all active ν flavors
- ν Properties
  - Magnetic moment
  - Effective charge radius

Supernova Physics

- ◇ CEvNS research informs supernova core-collapse models
- ◇ CEvNS can be used as a tool to *observe* supernovae
  - ▷ Lots of detectable neutrinos released in core collapse in the tens-of-MeV energy range
  - ▷ Timescale $\sim$10's of seconds after collapse

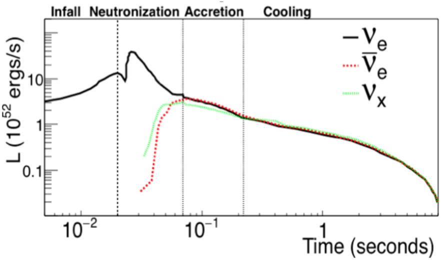
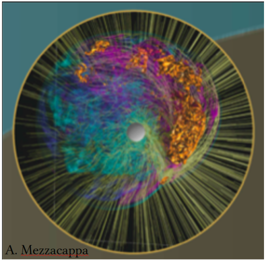
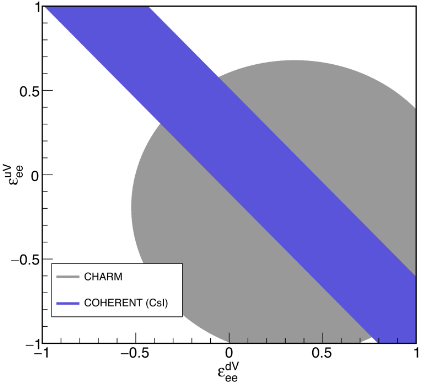


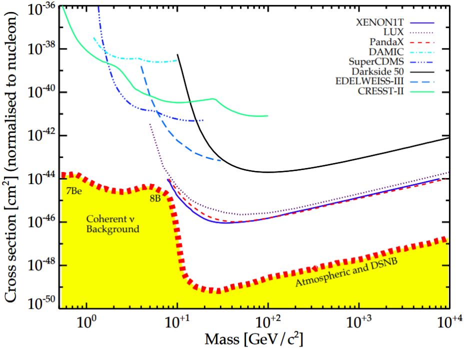
Figure from Kate Scholberg, Duke – NuInt 2018



COHERENT SNS

New Interactions & Dark Matter





Non-standard interactions between neutrinos and quarks [2]

Constraint from data!

Irreducible background for next-gen WIMP searches [3]

[2] D. Akimov et al., "Observation of coherent elastic neutrino-nucleus scattering", Science **357** (2017).

[3] J. Billard et al., "Implication of neutrino backgrounds on each of the next generation dark matter detection experiments", Phys. Rev. **D89**, 023524 (2014).

CEvNS Cross Section

$$\frac{d\sigma}{dT}_{\text{coh}} = \frac{G_F^2 M}{2\pi}\left[(G_V+G_A)^2 + (G_V-G_A)^2\left(1-\frac{T}{E_\nu}\right)^2 - (G_V^2-G_A^2)\frac{MT}{E_\nu^2}\right]$$

$$G_A = \left(g_A^p(Z_+ - Z_-) + g_A^n(N_+ - N_-)\right)F_{\text{nucl}}^A(Q^2)$$

$$G_V = (g_V^p Z + g_V^n N)F_{\text{nucl}}^V(Q^2)$$

- ◇ Predicted using SM in 1974[4]
- ◇ $g_V^p \sim 1 - 4\sin^2(\theta_W)$ suppresses Z^2
  $\implies \frac{d\sigma}{dT} \propto N^2$ (N = # neutrons)
- ◇ $T_{\max} = \frac{2E_\nu^2}{M+2E_\nu}$
  $\implies T \lesssim$ keV (nucleus-dependent)

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790
(Received 15 October 1973; revised manuscript received 19 November 1973)

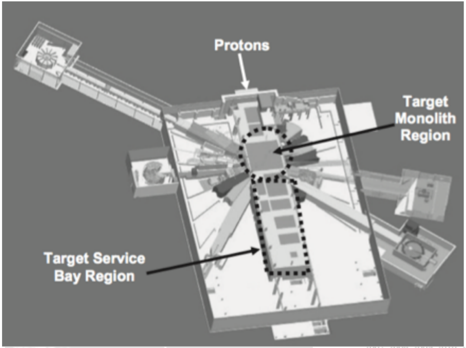
Our suggestion may be an act of hubris, because the inevitable constraints of interaction rate, resolution, and background pose grave experimental difficulties for elastic neutrino-nucleus scattering. We will discuss these problems at the end of this note, but first we wish to present the theoretical ideas relevant to the experiments.

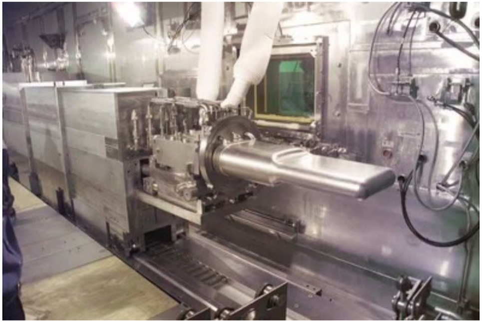
[4] D. Z. Freedman, "Coherent effects of a weak neutral current", Phys. Rev. **D9**, 1389 (1974).

The Spallation Neutron Source – Overview

- User facility at Oak Ridge National Lab (Knoxville, Tennessee, USA)
- Neutron production from protons on Hg target
- 1.4 MW $\Longrightarrow$ most intense neutron source in the world!

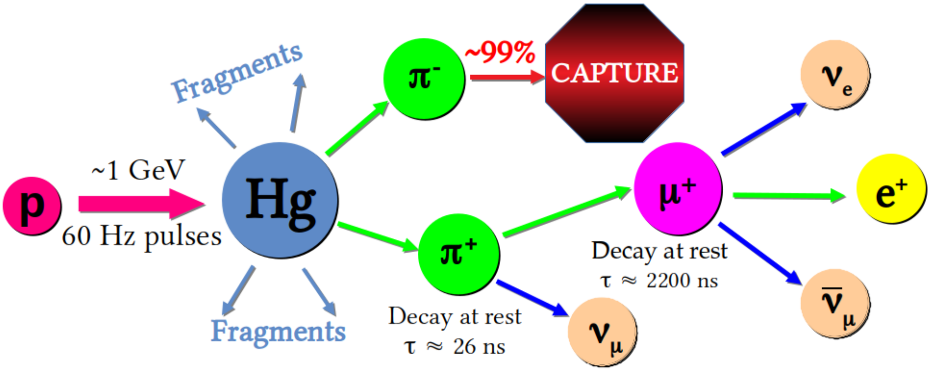
The Spallation Neutron Source – Target





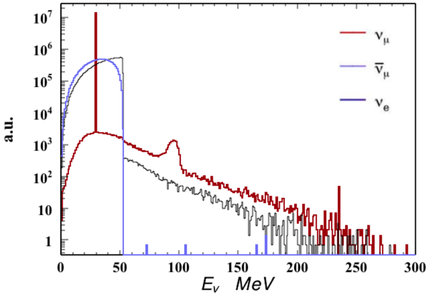
- ◇ 1 GeV protons in 60 Hz, ∼700 ns wide pulses incident on liquid Hg
- ◇ Pulsing improves background rejection and blinding

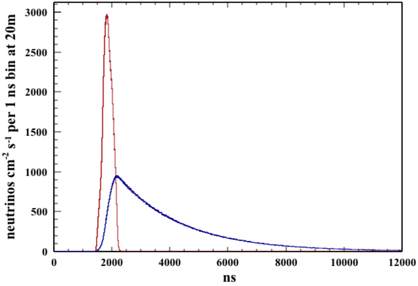
The Spallation ~~Neutron~~ NEUTRINO Source



- The SNS is an intense, pulsed neutrino source!
- π^+ stop inside the target and decay at rest
- π^- are primarily captured by Hg nuclei

Neutrino spectra – more on this later!





- ◇ Pions mostly decay at rest
- ◇ Some decay-in-flight contribution
- ◇ SNS ν's mostly $0 < E_\nu < 50$ MeV
- ◇ Two time windows:
  - ▷ Prompt: ν_μ
  - ▷ Delayed: $\bar{\nu}_\mu$ and ν_e
- ◇ Advantages of using SNS ν:
  - ▷ Higher E_ν than reactor ν
    $\Longrightarrow$ Higher cross section
  - ▷ Steady-state rejection!
  - ▷ Background: Beam neutrons

COHERENT: **unambiguous** CEvNS observation

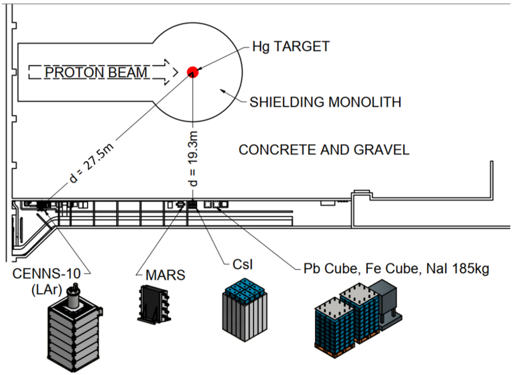
Carnegie Mellon University
THE UNIVERSITY OF CHICAGO
Duke UNIVERSITY
UF UNIVERSITY of FLORIDA
KAIST
Laurentian University Université Laurentienne
Los Alamos NATIONAL LABORATORY EST. 1943
MEPhI
NORTH CAROLINA CENTRAL UNIVERSITY FOUNDED 1910
NC STATE UNIVERSITY
NM STATE UNIVERSITY
OAK RIDGE National Laboratory
Sandia National Laboratories
THE UNIVERSITY of TENNESSEE KNOXVILLE
TUNL
UNIVERSITY of WASHINGTON
Tufts UNIVERSITY
UNIVERSITY OF SOUTH DAKOTA
VIRGINIA TECH

CNEC
U.S. DEPARTMENT OF ENERGY Office of Science
KICP
NNSA National Nuclear Security Administration
NSF

COHERENT SNS

Neutrino Alley: neutron-quiet basement hallway (8 m.w.e)

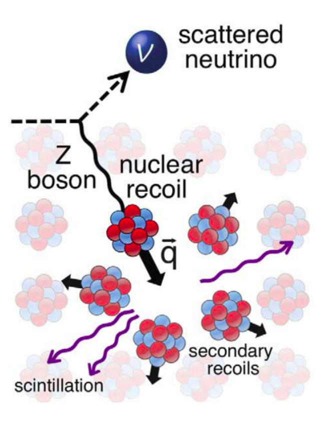
Current configuration



- ◇ MARS: monitor neutron flux
- ◇ Pb/Fe cubes: neutrino-induced-neutrons
- ◇ NaI, CENNS-10, and CsI: CEvNS

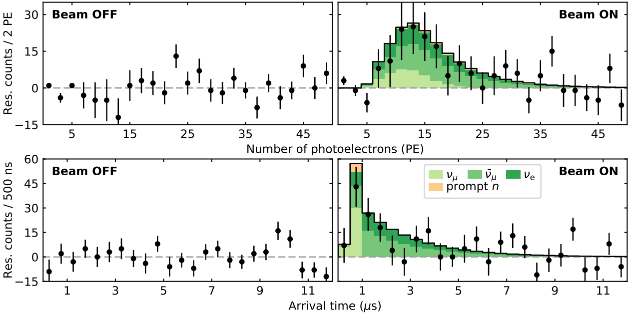
Detecting CEvNS: CsI[Na]

- Experimental Signature: Low energy nuclear recoil
- 14.6-kg scintillating crystal
- Single PMT triggered on SNS timing signal



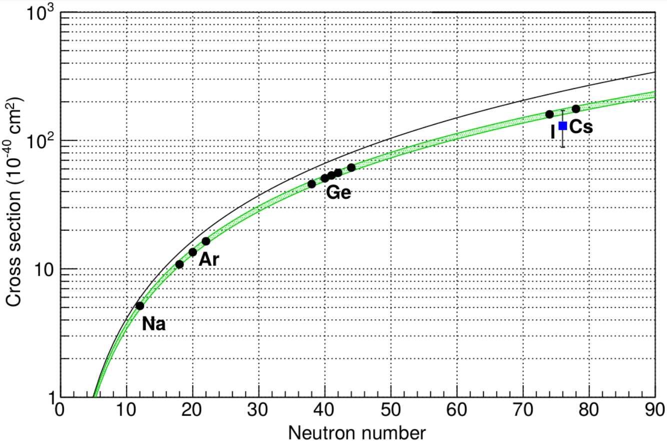
First CEvNS Observation [5]

- ◇ 2015: CsI[Na] starts collecting data
- ◇ 2017: CEvNS observed at 6.7σ
- ◇ 2019: Decommisioning of CsI[Na] (June 10)
- ◇ Below shows SM prediction and data



[5] D. Akimov et al., "Observation of coherent elastic neutrino-nucleus scattering", Science **357** (2017).

Testing N^2 dependence [6]



Black Curve	Form factor = 1	Black Circle	Theoretical prediction
Green Band	Klein-Nystrand form factor with uncertainty	Blue Square	COHERENT Data

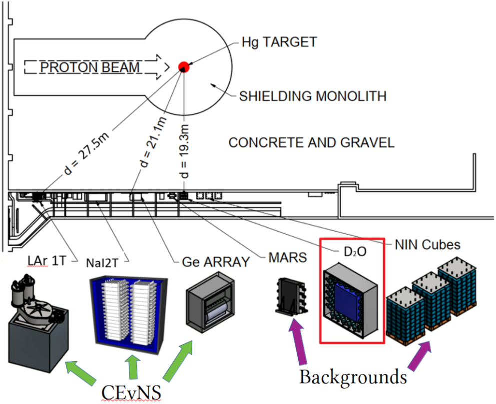
[6] D. Akimov et al., "COHERENT 2018 at the Spallation Neutron Source", arXiv:1803.09183v2, 2018.

More to do!

Dominant CsI systematics

Quenching factor	25%
ν flux	10%
Nuclear form factor	5%
Analysis acceptance	5%

- ◇ New QF data being analyzed
- ◇ **Normalize ν flux**
- ◇ Map N^2 dependence
- ◇ Measure Backgrounds
- ◇ Charged Current interactions



COHERENT Physics Sensitivity [7]

Topic	CsI	Ar	NaI	Ge	Nubes	D_2O
Non-standard neutrino interactions	✓	✓	✓	✓		
Weak mixing angle	✓	✓	✓	✓		
Accelerator-produced dark matter	✓	✓	✓	✓		
Sterile oscillations	✓	✓	✓	✓		
Neutrino magnetic moment		✓	✓	✓		
Nuclear form factors	✓	✓	✓	✓		
Inelastic CC/NC cross-section for supernova		✓			✓	✓
Inelastic CC/NC cross-section for weak physics		✓	✓		✓	✓

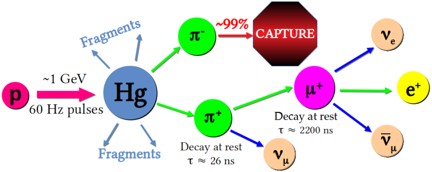
Dark shaded elements: stronger results by looking at the **combined** data

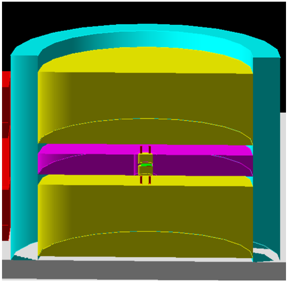
[7] D. Akimov et al., "The COHERENT experiment at the Spallation Neutron Source", White Paper (2018).

Geant4 SNS ν flux simulation

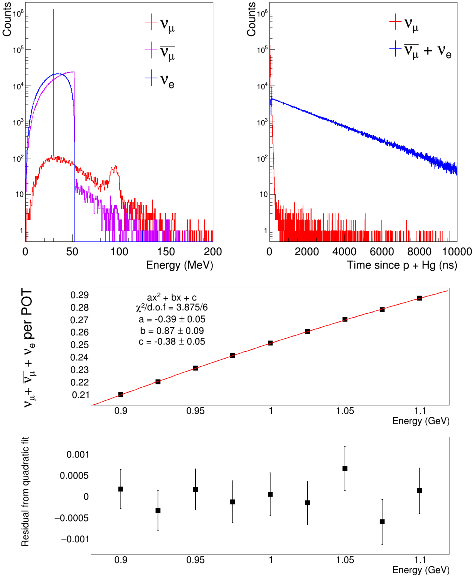
- ◇ Simulate incident protons and a simplified target geometry
- ◇ Bertini intra-nuclear cascade model
- ◇ Calculated $4.3 \times 10^7 \, \frac{\textbf{neutrinos}}{\textbf{cm}^2\textbf{s}}$ at 20 m
- ◇ LAHET also uses Bertini model
- ◇ Discrepancy: LAHET vs. world data
- ◇ **No data for pion production from 1 GeV protons on Hg**

$\Longrightarrow$ Conservative 10% uncertainty





Neutrino Production & Proton Energy Dependence



- ◇ Simulation results for single protons (no beam pulse width)
- ◇ ν (or $\pi^\pm$) flux depends on E_{proton}
- ◇ Protons traveling through target and shielding will fall below 1 GeV

Improving ν flux uncertainty: Simulation

- Investigate discrepancy with world data
- Compare to LAHET predictions
- Store production angle in simulation
- HARP: forward pion production [8]
  - Proton energies from 3 - 12 GeV
  - Targets listed in table
  - Comparisons to Bertini model!

Beryllium
Carbon
Nitrogen
Oxygen
Aluminum
Copper
Tin
Tantalum
Lead

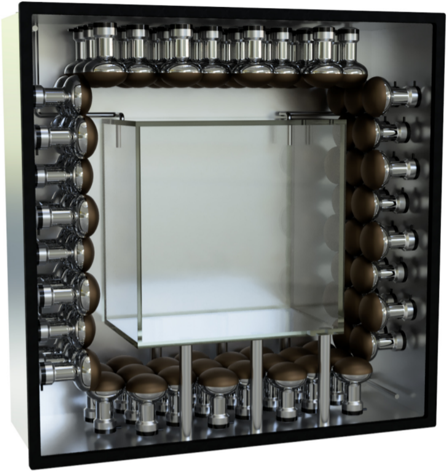
Model	Be (3 GeV)		Ta (3 GeV)		Be (5 GeV)		Ta (5 GeV)		Be (8 GeV)		Ta (8 GeV)		Be (12 GeV)		Ta (12 GeV)	
	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-	π^+	π^-
Bertini	0.35	1.02	0.45	0.53	0.70	1.12	0.29	0.35	1.22	1.54	0.84	1.08	1.75	1.81	1.27	1.50

[8] M. Apollonio et al., "Forward production of charged pions with incident protons on nuclear targets at the CERN Proton Synchotron", Phys. Rev. **C80**, 035208 (2009).

Improving ν flux uncertainty: Experiment

- Add D_2O detector in Neutrino Alley
  - $\nu_e + d \rightarrow p + p + e^-$ cross section calculated to 2-3%
  - Measurements have been consistent with calculations
- π^+ and μ^+ decay are well-known
  - $3 \times (\nu_e \text{ flux}) \approx \nu_e + \nu_\mu + \bar{\nu}_\mu$ flux
  - Normalizing SNS ν flux measures the $\pi^\pm$ production from 1 GeV protons incident on Hg!

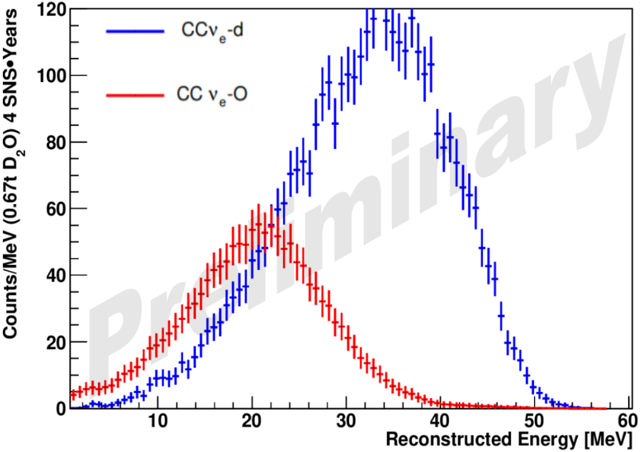
Planned D_2O detector



Mockup from Eric Day, CMU

- 670-kg D_2O in acrylic vessel
- 80 8” biakali PMTs
- 10 cm H_2O “tail-catcher”
- **Geant4 simulations underway**
- Background: beam neutrons

Simulated D_2O Energy Reconstruction



Predicted 4 years run-time to get to few-% statistical precision

Figure from Jason Newby, ORNL

Summary

- SNS is an excellent stopped-pion source of neutrinos
- COHERENT uses the SNS neutrinos to study CEvNS
- First CEvNS observation in 2017, 44 years after initial prediction
- CsI systematics are under investigation
- Precision CEvNS measurements: CsI, LAr, NaI, Ge
- Charged-current and neutrino-induced-neutron studies
- Planned normalization of the ν flux from SNS using D_2O
- Measurement of $\pi^{\pm}$ production for 1 GeV protons on Hg target!

Summary

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Thank You!

Backup Slides

COHERENT data made public!

COHERENT Collaboration data release from the first observation of coherent elastic neutrino-nucleus scattering

Akimov, D; Albert, J.B.; An, P.; Awe, C.; Barbeau, P.S.; Becker, B.; Belov, V.; Blackston, M.A.; Bolozdynya, A.; Brown, A.; Burenkov, A.; Cabrera-Palmer, B.; Cervantes, M.; Collar, J.I.; Cooper, R.J.; Cooper, R.L.; Cuesta, C.; Daughhetee, J.; Dean, D.J.; del Valle Coello, M.; Detwiler, J.; D'Onofrio, M.; Eberhardt, A.; Efremenko, Y.; Elliott, S.R.; Etenko, A.; Fabris, L.; Febbraro, M.; Fields, N.; Fox, W.; Fu, Z.; Galindo-Uribarri, A.; Green, M.P.; Hai, M.; Heath, M.R.; Hedges, S.; Hornback, D.; Hossbach, T.W.; Iverson, E.B.; Kaemingk, M.; Kaufman, L.J.; Klein, S.R.; Khromov, A.; Ki, S.; Konovalov, A.; Kovalenko, A.; Kremer, M.; Kumpan, A.; Leadbetter, C.; Li, L.; Lu, W.; Mann, K.; Markoff, D.M.; Melikyan, Y.; Miller, K.; Moreno, H.; Mueller, P.E.; Naumov, P.; Newby, J.; Orrell, J.L.; Overman, C.T.; Parno, D.S.; Penttila, S.; Perumpilly, G.; Radford, D.C.; Rapp, R.; Ray, H.; Raybern, J.; Reyna, D.; Rich, G.C.; Rimal, D.; Rudik, D.; Salvat, D.J.; Scholberg, K.; Scholz, B.; Sinev, G.; Snow, W.M.; Sosnovtsev, V.; Shakirov, A.; Suchyta, S.; Suh, B.; Tayloe, R.; Thornton, R.T.; Tolstukhin, I.; Vanderwerp, J.; Varner, R.L.; Virtue, C.J.; Wan, Z.; Yoo, J.; Yu, C.-H.; Zawada, A.; Zderic, A.; Zettlemoyer, J.

Release of COHERENT Collaboration data associated with the first observation of coherent elastic neutrino-nucleus scattering (CEvNS), as published in Science (DOI: 10.1126/science.aao0990) and also available as arXiv:1708.01294[nucl-ex].

This data set should enable researchers to extend the study of CEvNS as desired. Future COHERENT Collaboration results will have similar data releases.

Example code can be accessed at https://code.ornl.gov/COHERENT/codeExamples_dataRelease_april2018.
The full data-release package, including data, code examples, and a descriptive accompanying document can be found at http://coherent.ornl.gov/data.

Further reading: Physics studies using COHERENT data

Average CsI neutron density distribution from COHERENT data

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Dipartimento di Fisica, Università degli Studi di Cagliari, and INFN, Sezione di Cagliari, Complesso Universitario di Monserrato - S.P. per Sestu Km 0.700, 09042 Monserrato (Cagliari), Italy

C. Giunti
INFN, Sezione di Torino, Via P. Giuria 1, I–10125 Torino, Italy

Y.F. Li and Y.Y. Zhang
Institute of High Energy Physics, Chinese Academy of Sciences, and School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, China
(Dated: 23 January 2018)

Using the coherent elastic neutrino-nucleus scattering data of the COHERENT experiment, we determine for the first time the average neutron rms radius of ^{133}Cs and ^{127}I. We obtain the practically model-independent value $R_n = 5.5^{+0.9}_{-1.1}$ fm using the symmetrized Fermi and Helm form factors. We also point out that the COHERENT data show a 2.3σ evidence of the nuclear structure suppression of the full coherence.

COHERENT constraints on nonstandard neutrino interactions

Jiajun Liao and Danny Marfatia

Department of Physics and Astronomy, University of Hawaii-Manoa, Honolulu, HI 96822, USA

Abstract

Coherent elastic neutrino-nucleus scattering consistent with the standard model has been observed by the COHERENT experiment. We study nonstandard neutrino interactions using the detected spectrum. For the case in which the nonstandard interactions (NSI) are induced by a vector mediator lighter than 50 MeV, we obtain constraints on the coupling of the mediator. For a heavier mediator, we find that degeneracies between the NSI parameters severely weaken the constraints. However, these degeneracies do not affect COHERENT constraints on the effective NSI parameters for matter propagation in the Earth.

COHERENT constraints to conventional and exotic neutrino physics

D.K. Papoulias [1]* and T.S. Kosmas [1]†
[1] *Theoretical Physics Section, University of Ioannina, GR-45110 Ioannina, Greece*

The process of neutral-current coherent elastic neutrino-nucleus scattering, consistent with the Standard Model (SM) expectation, has been recently measured by the COHERENT experiment at the Spallation Neutron Source. On the basis of the observed signal and our nuclear calculations for the relevant Cs and I isotopes, the extracted constraints on both conventional and exotic neutrino physics are updated. The present study concentrates on various SM extensions involving vector and tensor nonstandard interactions as well as neutrino electromagnetic properties, with an emphasis on the neutrino magnetic moment and the neutrino charge radius. Furthermore, models addressing a light sterile neutrino state and scenarios with new propagator fields—such as vector Z' and scalar bosons—are examined, and the corresponding regions excluded by the COHERENT experiment are presented.

A COHERENT enlightenment of the neutrino Dark Side

Pilar Coloma,[1,*] M. C. Gonzalez-Garcia,,[2,3,4,†] Michele Maltoni,,[5,‡] and Thomas Schwetz[6,§]
[1] *Theory Department, Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510, USA*
[2] *Departament de Fisíca Quàntica i Astrofísica and Institut de Ciencies del Cosmos, Universitat de Barcelona, Diagonal 647, E-08028 Barcelona, Spain*
[3] *Institució Catalana de Recerca i Estudis Avançats (ICREA), Pg. Lluis Companys 23, 08010 Barcelona, Spain.*
[4] *C.N. Yang Institute for Theoretical Physics, Stony Brook University , Stony Brook, NY 11794-3840, USA*
[5] *Instituto de Física Teórica UAM/CSIC, Calle de Nicolás Cabrera 13–15, Universidad Autónoma de Madrid, Cantoblanco, E-28049 Madrid, Spain*
[6] *Institut für Kernphysik, Karlsruher Institut für Technologie (KIT), D-76021 Karlsruhe, Germany*

In the presence of non-standard neutrino interactions (NSI), oscillation data are affected by a degeneracy which allows the solar mixing angle to be in the second octant (*aka* the dark side) and implies a sign flip of the atmospheric mass-squared difference. This leads to an ambiguity in the determination of the ordering of neutrino masses, one of the main goals of the current and future experimental neutrino program. We show that the recent observation of coherent neutrino–nucleus scattering by the COHERENT experiment, in combination with global oscillation data, excludes the NSI degeneracy at the 3.1σ (3.6σ) CL for NSI with up (down) quarks.

Integrated Protons on Target from SNS

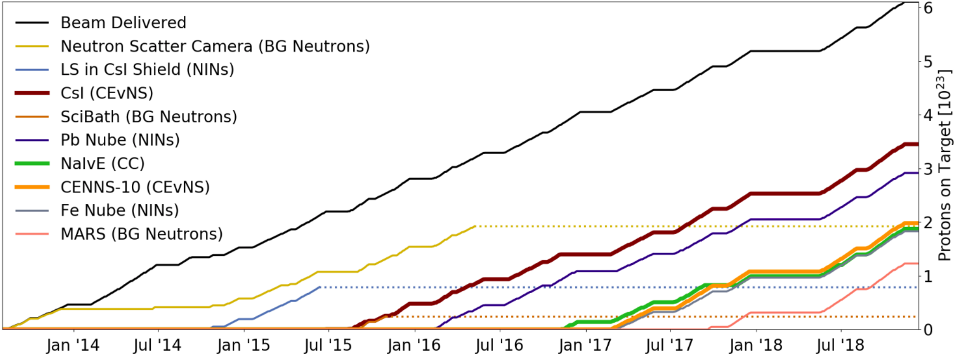
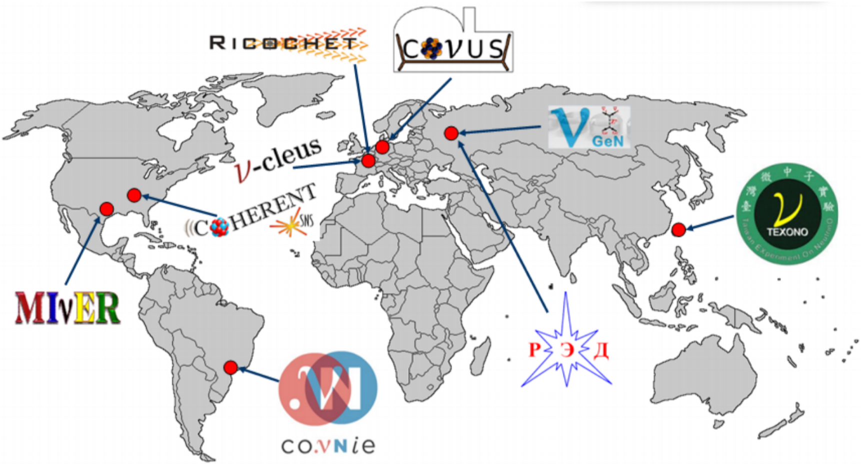


Figure from Gleb Sinev, Duke

Other CEvNS experiments



CsI[Na] Quenching Factor

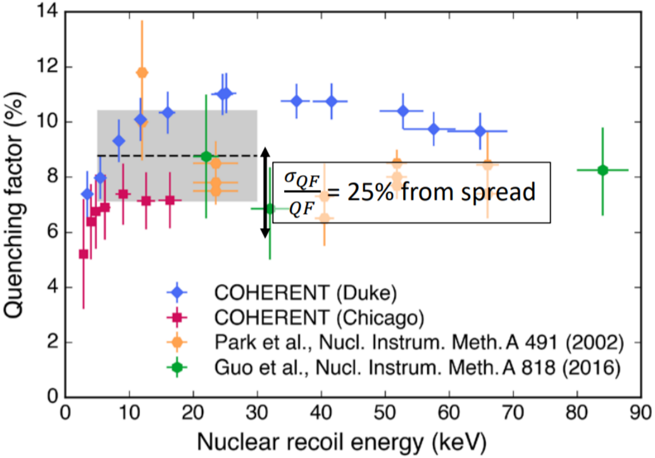


Figure from Supplemental Materials[9]

[9] D. Akimov et al., "Observation of coherent elastic neutrino-nucleus scattering", Science **357** (2017).

Neutron Backgrounds at the SNS

In situ measurement of CsI neutron backgrounds

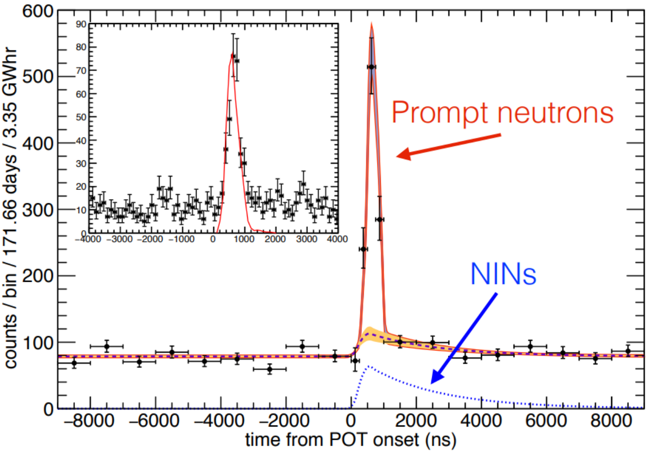


Figure from Supplemental Materials[10]

[10] D. Akimov et al., "Observation of coherent elastic neutrino-nucleus scattering", Science **357** (2017).