The COHERENT Experiment

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DPF 2019, Northeastern University, Boston
Aug 1, 2019
A CEvNS interaction is a NC scatter off a nucleus where all target nucleons recoil in phase

- The coherence criterion is only valid at low enough momentum transfers that the de Broglie wavelength is larger than the target nucleus: $Q^2 < (50 \, \text{MeV})^2$
- Coherence also enhances the cross section

$$\sigma \approx \frac{G_F^2 N^2}{4\pi} E_{\nu}^2$$
The CEvNS cross section is very large compared to other neutrino process below $E_\nu = 50$ MeV
- Three orders of magnitude larger than inverse beta decay for CsI

The $N^2$ dependence is testable using a variety of detector materials
- Each measurement carries its own challenges
- Higher nuclei have larger cross section, but less energetic recoils
- First measured by COHERENT in 2017!
CEvNS as a Probe of BSM Physics

- Neutrino-quark non-standard interactions
  - May explain tension in solar and reactor neutrino oscillation data

- Dark photon search
  - Could explain g-2 anomaly
  - Would distort CEvNS recoil distribution in characteristic way

- Dark matter search
  - Sub-GeV dark matter accessible with accelerators and nicely complements direct detection efforts
  - More in R. Tayloe’s talk this session

For more information, see: Phys. Rev. D96 115007
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JHEP 11 066
Phys. Rev. D92 095005
Nuclear Recoil Signature

- The struck nucleus acquires a small recoil energy
  - Max recoil energy is $2E_{\nu}^2/M$
  - Only $10^{-80}$ keV for typical nuclei at 30 MeV

1: Need a detector with very low threshold
  - Recent advances in dark matter detection has made keV-scale thresholds possible

2: Will need to place detector in a large neutrino flux
Low energy pions are a natural by-product of the SNS
- $\pi^+$ will stop and decay at rest with a well-known spectrum
- Very small contamination of neutrinos from other modes

Beam is pulsed, which reduces steady-state background and allows for in-situ background measurement

The SNS is an ideal location for COHERENT detectors
The COHERENT Detectors

- A hallway near the target hall was found to have a low neutron background, dubbed “neutrino alley”
- **Four detectors will measure CEvNS** on different nuclei, testing the $N^2$ cross section dependence
- **Two detectors study neutron backgrounds** in neutrino alley
- **One future detector will constrain the neutrino flux** to improve precision of other cross section results
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Will notably reduce our systematic errors – covered by R. Rapp this session
COHERENT Detection Strategies

WIMP experiments pioneered three detection principles

COHERENT looks for zaps and flashes

**Zap**
- Ionization
- e⁻, e⁻, e⁻

**Flash**
- Scintillation

**Burn**
- Heat

D. Pershey  The COHERENT Experiment
Expected CEvNS Rates

- CEvNS nuclear recoil energies without detector effects
- Higher mass nuclei see more CEvNS
Expected CEvNS Rates

- CEvNS nuclear recoil energies without detector effects
- Higher mass nuclei see more CEvNS – but need lower thresholds!
Measuring CEvNS with CsI

- 14.6 kg low-background CsI crystal was deployed
- It is shielded from neutron and gamma backgrounds with low-activity lead
- Detector activity is recorded by single PMT with uniform light yield across detector
- Deployed June 2015 and decommissioned June 2019
A likelihood fit in recoil energy and arrival time gives an excess of $134 \pm 22$ counts.

Data is consistent with the standard model prediction of $173 \pm 48$ to within $1\sigma$.

Background-only hypothesis rejected at $6.7\sigma$.

CsI dataset has since doubled and we are working on releasing data.
Measuring CEvNS with Liquid Argon (LAr)

- A LAr detector with 610 kg of fiducial volume will be developed soon.
- Simulations predict a 4.3 PE/keV$_{ee}$ light yield allowing a 20 keV$_{nr}$ threshold.
- Plan to fill with underground-source argon to reduce $^{39}$Ar decay background.

- Large mass allows for several thousand CEvNS collected per year!
Measuring CEvNS with Ge

- We will implement 16 kg of high-purity Ge PPC detectors
  - Mass-produced and purchased from Canberra Industries
  - Will be placed in a radiological shield in neutrino alley

- Array of detectors will record $\approx 570$ CEvNS events per year
- Technology will push the threshold to $\approx 2.5 \text{ keV}_{nr}$
Measuring CEvNS with Na

- We are repurposing hundreds of NaI crystals for a CEvNS measurement
  - A 185 kg prototype is running with plans to implement 3.3 t
- CEvNS signal clearly visible despite large steady-state backgrounds
- Na is the lightest CEvNS target COHERENT will probe
  - Great handle for studying $N^2$ cross section dependence
Summary

☐ The business of measuring CEvNS has just started
  • Gives us a new handle to probe fundamental physics beyond the standard model

☐ CEvNS was first observed by COHERENT with our CsI detector

☐ We’re not stopping there
  • CsI dataset has since doubled
  • Implement detectors with different targets and larger masses
Thank You from the COHERENT Collaboration!

~80 members
~20 institutions
4 countries
Sub-GeV Dark Matter Searches with COHERENT

- The Lee-Weinberg bound\(^1\) requires mass of a simple WIMP dark matter particle is greater than 1 GeV

- A Lower-mass DM may explain galactic rotation curves
  - However, an additional portal particle mediating interactions between DM and standard model particles is needed
  - Such a sub-GeV portal is easily accessible with accelerators

- CEvNS-like cross section enhancement make COHERENT detectors uniquely sensitive to 1-100 MeV dark matter particles

\(^1\) Lee and Weinberg, PRL 39 165
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Physics With a LAr Prototype Detector

- A LAr prototype has collected production data since 2017
  - 29 kg of LAr with a threshold near 20 keV$_{nr}$

- Run with partial shielding to study neutron interactions in detector

- Observed data is consistent with simulated neutron prediction

- Detector was later upgraded with a lower threshold

- A CEvNS analysis is underway
  - Expect to see 120 CEvNS on a large background
Reducing Flux Uncertainty with D$_2$O Detector

- For most CEvNS detectors, the flux uncertainty dominates the error budget for determining the CEvNS cross section.
- The theoretical uncertainty on $\nu_e + d \rightarrow e + p + p$ is known precisely, to 2-3%.
  - Measuring the rate in a detector with a large mass fraction of deuterium could determine the flux to similar precision.
  - Use heavy water Cherenkov!

- Will achieve reasonable statistics within two years.
- $\nu_e + ^{16}\text{O}$ background is manageable and low energy.
The NIN-Cubes Background Detectors

- CEvNS detectors are shielded with lead to reduce environmental gamma and neutron backgrounds.

- Unfortunately, lead is a neutron-rich nucleus with a (relatively) large neutrino cross section:
  - $\nu + ^{208}\text{Pb} \rightarrow \nu + ^{208-\alpha}\text{Pb} + an + b\gamma$
  - $\nu + ^{208}\text{Pb} \rightarrow e + ^{208-\alpha}\text{Bi} + an + b\gamma$
  - The Neutrino-Induced Neutron (NIN) processes

- NIN-Cubes in neutrino alley currently working to measure the NIN cross section.

- Also interesting for the HALO experiment, which uses NIN interactions to detect bursts of neutrinos from supernovae.
Background Detectors – MARS

- We implemented the MARS detector to study the ambient neutron flux and spectrum throughout the hall
  - Important background for CEvNS searches

- Uses plastic scintillator separated by layers of Gd paint

- Searches for prompt neutron recoil energy coincident with a neutron capture

- MARS designed to be semi-portable, to measure the neutron flux at multiple position
Physics Bonus Round: $\nu_e$ CC on $^{40}$Ar

- LAr detector will see about 340 $\nu_e$ CC events / year
- XSec measurement piggybacks on CEvNS physics goals

- Very interesting for DUNE!

- $\pi$-DAR beam profile is very similar to supernova flux shape