Coherent elastic neutrino nucleus scattering: recent results and perspectives

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Astroparticle Physics in Germany - Status and perspectives
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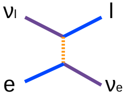
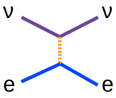
The **Standard Model** predicts six neutrino interactions with matter:

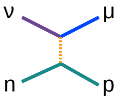
Five well established interactions:



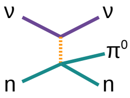
inverse muon decay
(Inv. tauon decay)



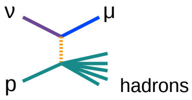
elastic neutrino-
electron scattering



(quasi)-elastic neutrino
nucleon scattering

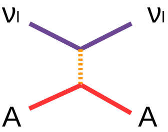


nucleon excitation
+ resonance production



deep inelastic scattering
+ jet production

The last detected interaction: Coherent elastic neutrino nucleus scattering (**CEvNS**)

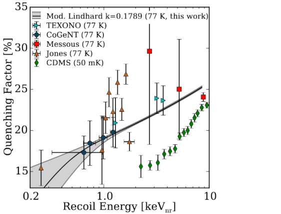


coherent elastic neutrino
nucleus scattering

- Predicted 1974 (*D.Z.Freedmann, Phys. Rev. 9 (1974) 5*), but eluded till 2017.
- Purely neutral current weak interaction, where a Z^0 is exchanged with nucleus; the cross section is enhanced: $\sigma_{\nu A}^{tot} \approx \frac{G_F^2}{4\pi^2} \cdot N^2 \cdot E_\nu^2$
  $\rightarrow \mathcal{O}(\sigma) \sim 10^2$-$10^3$ larger than IBD or ν-e scattering
- Ideal probe to test SM and BSM predictions, but also important role in cosmology and astrophysics

Detector requirements:

- Cross section: $\sigma_{\nu A}^{tot} \propto E_\nu^2 \cdot N^2$
  - → maximize E_ν, but coherency condition: $E_\nu \leq \frac{1}{2R_A} \approx \frac{197}{2.5\sqrt[3]{A}}$ [MeV]
  - → maximize N, but maximum recoil energy: $\langle E_{rec} \rangle = \frac{2}{3} \cdot \frac{E_\nu^2}{m_n \cdot A}$
- Quenching of E_{rec} by 60-90% possible



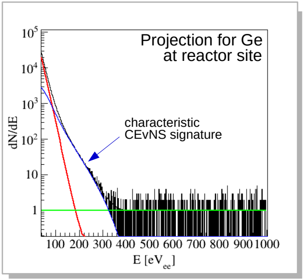
B.Scholz et al., Phys. Rev. D 94, 122003 (2016)

Background mitigation:

- strong (anti-)neutrino sources located at surface
- detectors must be operated at shallow depths:
  - → strong cosmogenic bg components
  - → neutrons correlated with source strength
- new shield design concepts ('virtual depth')

(Anti-)neutrino source requirements:

- High & variable (anti-)neutrino flux
- Ideal neutrino kinetic energy: few 1-10's MeV



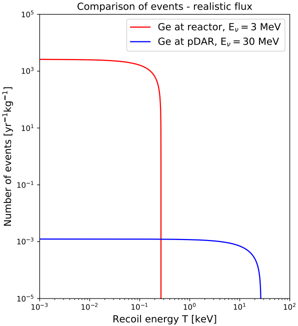
(Anti-)neutrino sources for CEvNS detection

parameter	I **π-DAR ν's** (DAR=decay-at-rest)	II **reactor ν's**	III **natural ν's** (sol.,atm.,DSNB,SN)
ν flux, Φ_ν	1×10^{15}/s $\rightarrow$ $2\times10^{7}/(\mathrm{s\cdot cm^2})$ in 20 m dist.	$2\times10^{20}/(\mathrm{s\cdot GW})$ $\rightarrow$ **$1\times10^{13}/(\mathrm{s\cdot cm^2})$** in 15 m dist.	^{8}B:$5\times10^6/(\mathrm{s\cdot cm^2})$ DSNB:ν_e $<1.2/(\mathrm{s\cdot cm^2})$ DSNB:$\bar{\nu}_e$ $<70/(\mathrm{s\cdot cm^2})$ SN(10kpc): 10^{12} cm^{-2}
ν variability	high, **pulsed-beam**	mediocre	steady-s./1 pulse (SN)
ν extension	small 1/R dep; ster. ν	small 1/R dep; ster. ν	diffuse no 1/R dep.
ν flavor	ν_μ,ν_e,$\bar{\nu}_\mu$	$\bar{\nu}_e$	$\bar{\nu}_e$,ν_α,$\bar{\nu}_\mu$
ν ener., E_ν	$<$50 MeV coh.-decoh. reg.	$<$8 MeV full coh. reg.	^{8}B: $<$16 MeV DSNB: $<$100 MeV atm: $<$1 GeV SN:$\langle E\rangle$ $\leq$25 MeV coh.-decoh. reg.
location	access restr.	high access restr.	no restriction
background	shallow depth neutrons, NIN	shallow depth neutrons	**deep undergr.** few high-energy n

- **π-DAR and reactor ν's** most appealing for SM and BSM physics due to high fluxes
- **Natural sources:** Next Gen. DM experiments will see CEvNS neutrino floor

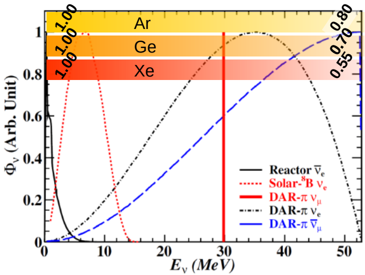
CEvNS detection approaches: advantages and complementarities

Main sources: π-DAR vs. reactor



- π-DAR:
  - $\rightarrow$ take advantage of $\sigma \propto E_\nu^2$
  - $\rightarrow$ detector threshold can be higher
- Reactor:
  - $\rightarrow$ For same distance more intense ν flux (10^2-10^3x higher)
  - $\rightarrow$ Full coherent regime

Coherency vs. decoherency



S. Kerman et al., Phys. Rev. D 93, 113006 (2016)

source	coh. prob. $<\alpha>$ Ar	Ge	Xe
reactor $\bar{\nu}_e$	1.00	1.00	1.00
solar ^{8}B ν_e	0.99	0.99	0.98
π-DAR ν_μ	0.91	0.86	0.80
π-DAR ν_e	0.89	0.83	0.76
π-DAR $\bar{\nu}_\mu$	0.85	0.79	0.71

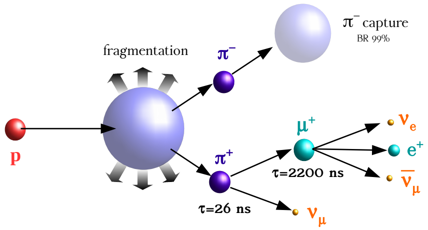
Overview: CEvNS experiments and pilot projects

ID	Experiment	Location	Dist.source	Mean E	Target	Mass
I	COHERENT [O]	SNS, Oak Ridge	20-30 m	40 MeV	CsI, Ar	14.6kg/22kg
	COHERENT [P]				Ge, NaI	10kg/2tons
II	CONUS [O,G]	Brokdorf:3.9GW	17 m	4 MeV	Ge	4kg
	TEXONO [P]	KuoSheng:2.9GW	25 m	4 MeV	Ge	1-2kg
	νGEN [P]	Kalinin:3GW	10 m	4 MeV	Ge	1.6kg
	RED-100 [P]	Kalinin:3GW	25 m	4 MeV	Xe	100kg
	CONNIE [P]	Angra:3.8GW	30 m	4 MeV	Si	1g→100g
	MINER [P]	TAMU:1 MW	2-3 m	4 MeV	Ge/Si	1kg
	Richochet A [P]	MIT R:5MW	4 m	4 MeV	Ge,Zn	5kg,5kg
	Richochet B [P]	Chooz:8.6GW	70-400 m	4 MeV	Ge,Zn	5kg,5kg
	Basket [R]	Chooz:8.6GW	70-400 m	4 MeV	Li2WO4	
	ν-CLEUS [P,G]	Chooz:8.6GW	70-100 m	4 MeV	$CaWO_4$,	1g→10kg
					Al_2O_3	1g→10kg
III	XENONnT [P,G]	LNGS	$15*10^7$ km	6 MeV	Xe	8tons
	PANDA-X [P]	CJPL	$15*10^7$ km	6 MeV	Xe	4tons
	LUX-ZEP. [P]	SURF	$15*10^7$ km	6 MeV	Xe	10tons
	DARWIN [R,G]	LNGS	$15*10^7$ km	6 MeV	Xe	50tons

- **Status:** O=operational, P=in preparation, R=R&D phase
- **Contributions** from German institutes denoted with **G**

The COHERENT experiment at SNS, Oak Ridge (USA)

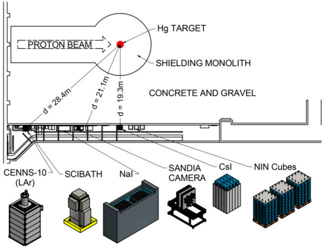
π-DAR (anti-)neutrino production:



- Pulsed-beam of low-energy protons ($\sim$GeV) hit heavy element target
- Multiple ν flavors, several 10's MeV
- Strong time correlation of prompt and delayed ν signals
  $\rightarrow$ bg suppression by 10^3-$10^4\times$
- SNS: proton energy=1.0 GeV,
  repetition rate=60 Hz,
  pulse width=700 ns

Description of COHERENT's approach:

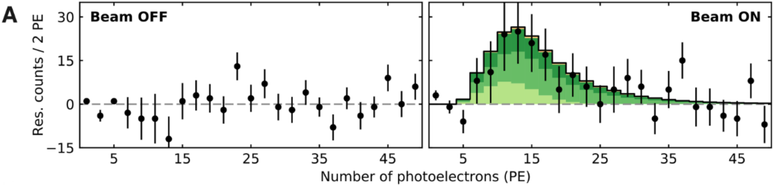
- Multiple targets: CsI, NaI, Ar, Ge ($\rightarrow \sigma \propto N^2$)
- Distance from π-DAR: 20-30 m;
  overburden: 8 m w.e.
- Main bg: different types of neutron sources:
  $\rightarrow$cosmic/ambient & beam-related (NIN):
- Data collection start:
  $\rightarrow$ 14.6 kg CsI(Na): Sept 2015;



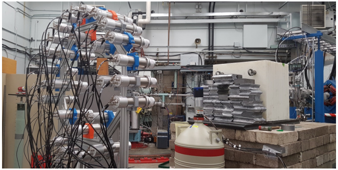
COHERENT: First observation of CEvNS

Observation (published August 3, 2017):

- Dataset: 15 months of data with 14.6 kg of CsI(Na), in (16-50) MeV
- Observation: 6.7 σ (above non-presence), 2D profile likelihood fit
- Number of events: (134±22) events observed, (173±48) predicted (within 1 σ)



Further COHERENT's plans (2018+):

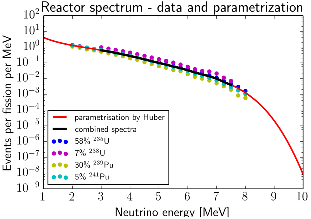


- Explore N^2 dependency within 'Neutrino Alley':
  → 22 kg LAr: start early 2018; plans for 1 ton
  → 10 kg PPC Ge: in prep.
  → 2 tons NaI(Tl): in prep.
- Quenching meas.: for Ge and NaI; improve for CsI
- Neutron bg: meas. NIN in ^{56}Fe, ^{208}Pb

The CONUS experiment at the NPP Brokdorf (GER)

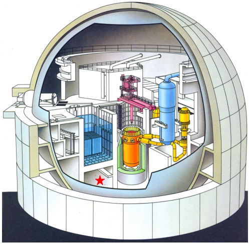
Anti-neutrino production at a commercial reactor:

- Number of $\bar{\nu}$'s produced in β-decays of fission products from ^{235}U, ^{239}Pu, ^{238}U and ^{241}Pu: $\sim$6 ν's/fission
  $\rightarrow$total flux: 2×10^{20} s^{-1}GW^{-1}
  $\rightarrow$available flux: $10^5\times$ higher than at
  a π-DAR source at similar distance
- Anti-neutrino energy up to 8 MeV
  $\rightarrow$ purely coherent regime
  $\rightarrow$ but: lower detector thresholds required



Parametr./Data: from P.Huber and N.Haag

Description of CONUS's approach:



- Target: PPC Ge detectors, total mass=4 kg
  (Reactor safety: Strong regulations to detector setup)
- Reactor: 3.9 GW (max), high duty cycle
  (time-resolved information available for CONUS)
- Distance from reactor core (orange): 17 m;
  overburden: 10-45 m w.e.
- Most troublesome bg: reactor-correlated neutrons:
  (neutron/γ meas. on/off site, in/outside shield)

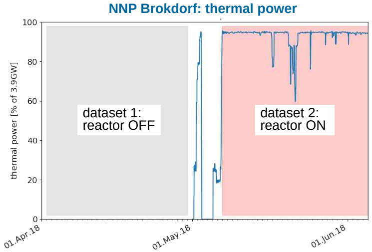
CONUS: First results

First 'rate-only' analysis: (published June 8, 2018)

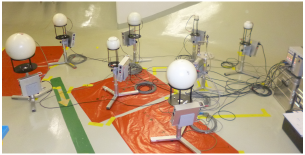
- Datasets: reactor OFF=114.4 kg·d;
  reactor ON= 112.3 kg·d
- Rate-only analysis: periods and number of events

period	counts
reactor ON	653
reactor OFF	582
diff: ON-OFF (exposure corr.)	84

→ statistical significance: **2.4** σ (1st hint!)



Further CONUS's plans (2018+):



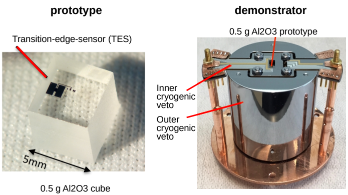
- Ongoing data collection: reactor ON tripled
- Ongoing analyses:
  → quantify systematics (detector + ν-flux)
  → rate + shape analysis
  → set up of background model
- Neutron bg: meas. with n/γ-spectrometer on-site

The ν-CLEUS project at the NPP Chooz (FRA)

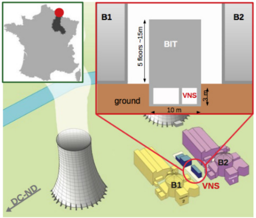
Prototype detector:

- Technology: inspired by CRESST exp.
- Proof of principle:
  - Al_2O_3 cube of 0.5 g, operated at 10 mK
  - Achieved energy threshold: 20 eV
- Scalability:
  - usage large Si/Ge wafers for detectors
  - array fabrication with dicing after TES deposition

From prototype to demonstrator:



Description of ν-CLEUS approach:

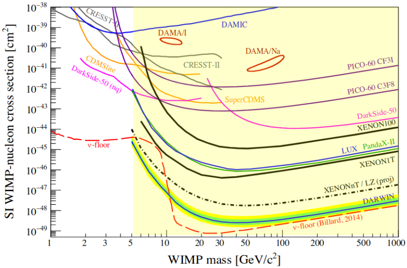


- Target: $CaWO_4+Al_2O_3$ (1.); Ge+Si wavers (2.)
  1.stage: demonstrator with mass$\sim$10 g
  2.stage: array with mass$\sim$1 kg
- Reactors: $2\times$ 4.25 GW (max), high duty cycle
- 70-100 m dist. from reactor cores; overburden: $<$5 m w.e.
- Bg under study: muonic and neutronic bg

CEvNS detection with XENONnT and DARWIN

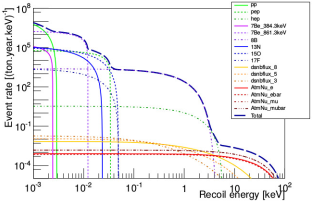
Dark matter 'neutrino floor':

- νA and $\nu\chi$ (WIMS's) produce similar nuclear recoils
  → CEvNS of solar (^{8}B, hep), atm. & DSNB ν's: bg and signal
- Hypothetical disentanglement: directional detectors (solar ν's), annual modulation
- Timeline: Next Gen. LXe DM detectors will see 'CEvNS light' first.



XENONnT and DARWIN:

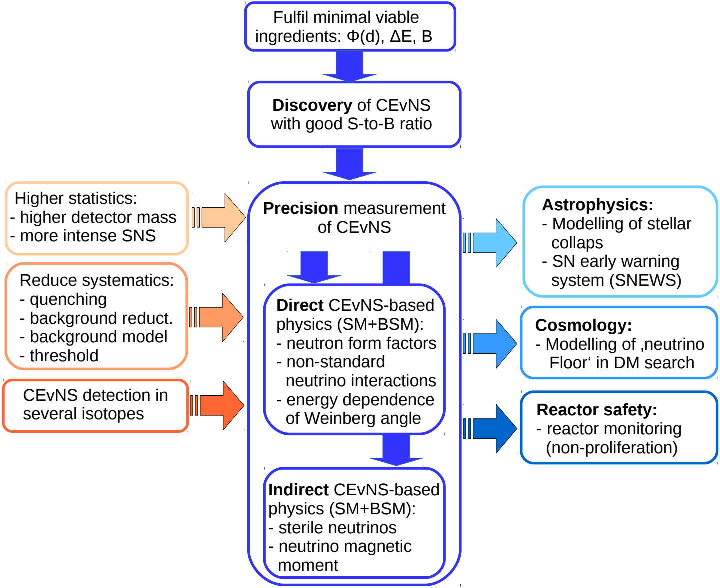
- Total mass: 8tons (X), 50tons (D)
- Expected shape of recoil spectrum:



source	expected rate
^{8}B ν	X:$\sim$5/(20 ton$\times$y)
	D:$\sim$100/(400 ton$\times$y)
CNO ν	D: 3σ in (200 ton$\times$y)
SN(10kpc)	X:$\sim$10-100/(5 ton$\times$100s)

→ solar CEvNS rate low, but bg low
→ SN signal cmp. with large size LSc detectors; SNEWS (multi-messenger)

Physics potential from CEvNS detection and applications



CEvNS-based search for NSI's

Non-standard-interactions in neutrino-quark sector:

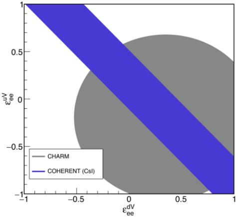
- $$\frac{d\sigma_{\nu A}}{d\Omega} \propto Q_W^2 \propto [N \cdot (1 + 2\epsilon_{\alpha\beta}^{uV} + 4\epsilon_{\alpha\beta}^{dV}) + Z \cdot ((4 sin^2\theta_W - 1) + 4\epsilon_{\alpha\beta}^{uV} + 2\epsilon_{\alpha\beta}^{dV})]^2$$
- Especially ϵ_{ee} and $\epsilon_{e\tau}$ not well constrained; In case of degeneracy, use of diff. isot. helps
- $\epsilon \approx \frac{M_W^2}{M_{NSI}^2}$; If $\epsilon = 0.01$, than TeV scale (LHC!)

NSI Parameter Limit	Source
$-1 < \varepsilon_{ee}^{uL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.4 < \varepsilon_{ee}^{uR} < 0.7$	
$-0.3 < \varepsilon_{ee}^{dL} < 0.3$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$-0.6 < \varepsilon_{ee}^{dR} < 0.5$	
$\lvert\varepsilon_{\mu\mu}^{uL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{uR} < 0.003$	
$\lvert\varepsilon_{\mu\mu}^{dL}\rvert < 0.003$	NuTeV νN, $\bar{\nu} N$ scattering
$-0.008 < \varepsilon_{\mu\mu}^{dR} < 0.015$	
$\lvert\varepsilon_{e\mu}^{uP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\mu}^{dP}\rvert < 7.7 \times 10^{-4}$	$\mu \to e$ conversion on nuclei
$\lvert\varepsilon_{e\tau}^{uP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{e\tau}^{dP}\rvert < 0.5$	CHARM $\nu_e N$, $\bar{\nu}_e N$ scattering
$\lvert\varepsilon_{\mu\tau}^{uP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering
$\lvert\varepsilon_{\mu\tau}^{dP}\rvert < 0.05$	NuTeV νN, $\bar{\nu} N$ scattering

S. Davidson et al., JHEP 03 (2003) 011

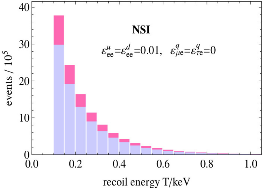
Sensitivity of CEvNS-based search for NSI:

- NSI results with π-DAR source:
  $\rightarrow$ 14.6 kg CsI detector at SNS



D. Akimov et al., Science 10.1126, aao0990 (2017)

- NSI prediction for reactor neutrinos:
  $\rightarrow$ Pro: form factor can be neglected
  $\rightarrow$ Example: 250 kg·yr ^{nat}Ge



M.Lindner et al., arXiv:1612.04150 [hep-ph]

Summary: CEvNS in 2018 and beyond

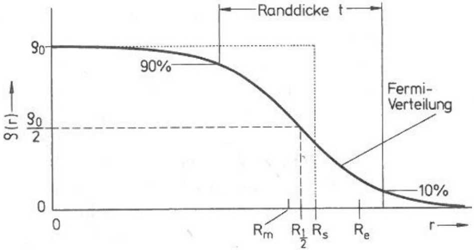
- Importance of CEvNS detection:
  - measurement of predicted rate: valuable *per se*
  - signal absence *or* any deviation: physics beyond SM
  - Many applications: DM bg & SN collapse model, EM neutrino properties, nuclear form factors, reactor safety
  - Instrumentation: dawn of kg-sized neutrino detectors
- Experimental status of CEvNS detection:
  - 1st observation at π-DAR in CsI by COHERENT coll. in 2017/08
  - 1st hint of observation at reactor site in Ge by CONUS coll. in 2018/06
  - few new results to be expected in 2018/2019
- Largest obstacles for detection of CEvNS:
  - detectors: achieve low threshold, stable operation
  - bg suppression: muonic (due to shallow depth), neutronic from source
  - systematics: quenching factor (few efforts by COHERENT ongoing); ν flux calculation (for both reactor and π-DAR ν sources)
- Germany's commitment in CEvNS detection:
  - reactor and DM experiments covered
  - opportunities at the European Spallation Source in Lund, SWE (2019/2023)
  - opportunities for theoretical studies ($\rightarrow$ talk by W. Rodejohann)

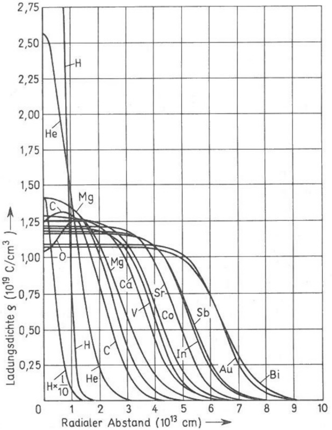
Thank you for your attention !

Addendum: slide 1

Nuclear radius definitions and examples

from: R.Hofstädter, Ann.Rev.Nucl.Sci. 7 (1957) 231



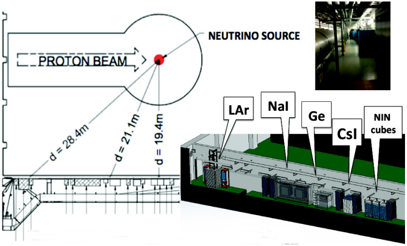


- For r=$R_{1/2}$: $\rho_{Z(N)}$ reduced by 50%
- In interval t=4.4 z: $\rho_{Z(N)}$ reduced from 90% to 10%
- Quadratic averaged radius $R_m = \langle r^2 \rangle = \int_0^\infty r^2 \rho_{Z(N)}(r) 4\pi r^2 dr$

π-DAR neutrino sources for CEvNS detection

π-DAR facilities worldwide (past, operational, near-future):

facility	location	proton energy [GeV]	repetition rate [Hz]	pulse width	Target
LAMPF^{p}	USA	0.8	120	600 μs	Various
ISIS^{p}	U.K.	0.8	50	400 ns	Tantalum
SNS^{o}	USA	1.0	60	700 ns	Mercury
MLF^{o,nf}	Japan	3.0	25	120-200 ns	Mercury
CSNS^{nf}	China	1.6	25	500 ns	Tungsten
ESS^{nf}	Sweden	2.0	14	2 ms	Tungsten



The **COHERENT experiment** at SNS:
←'Neutrino alley'

CEvNS-based measurement of neutron form factors

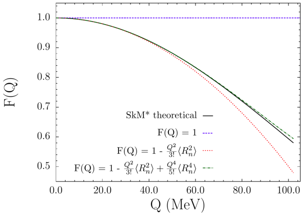
Remarks about nuclear form factors:

- Diff. of scattering on extended/pointlike objects
- Fourier trans. of the nucleon density distributions:

$$F_{Z(N)}(Q^2) = \frac{1}{Z(N)} \int dr^3 e^{i\mathbf{q}\cdot\mathbf{r}} \rho_{Z(N)}(r)$$
$$\approx 1 - \frac{Q^2}{3!}\langle R_n^2 \rangle + \frac{Q^4}{5!}\langle R_n^4 \rangle - \ldots$$

- $F_Z(Q^2)$ measurement via elastic ν-e scattering, $F_N(Q^2)$ via hadronic methods (e.g. n scattering) $\rightarrow$ Extraction of $\rho_{Z(N)}$ requires theor. models

Example: modeled form factor of ^{40}Ar

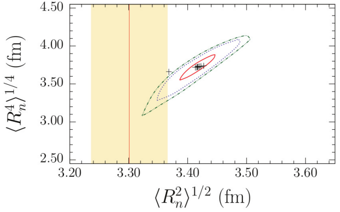


K. Patton et al., Phys. Rev. C 86 (2012) 024612

Model-independent ρ_N determination via CEvNS:

- $\frac{d\sigma_{\nu A}}{d\Omega} \propto Q_W^2 \cdot F^2(Q^2)$
  $\propto [N \cdot F_N(Q^2) + (4sin^2\theta_W - 1) \cdot Z \cdot F_Z(Q^2)]^2$
  $\propto N^2 \cdot F_N^2(Q^2)$
- For reactor anti-neutrinos: $Q^2 \approx 0, \rightarrow F_N(Q^2) = 1$
- For π-DAR neutrinos: $Q^2 > 0, \rightarrow F_N(Q^2) < 1$
  If syst. small, 2.& 4. momentum measurable

Example: 3.5 ton Ar, 16 m dist. at SNS, 1 yr exposure

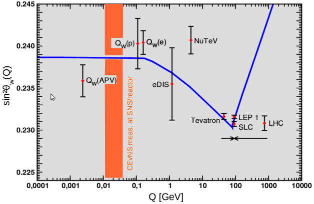


G. McLaughlin, AIP Conf. Proc., 2015

CEvNS-based measurement of $\sin^2\theta_W$ at low Q-value

Weak mixing angle:

- $\frac{d\sigma_{\nu A}}{d\Omega} \propto Q_W^2 \propto [N + Z \cdot ((4sin^2\theta_W - 1)]^2$
- Past measurements of $sin^2\theta_W$ and precision:
  - $\mathcal{O}$ (Q)=100 GeV: $\pm$0.1% (1σ)
  - $\mathcal{O}$ (Q)=0.001-10 GeV: $\pm$1-few % (1σ)
- Distortion at low Q due to BSM effects possible
- Q in CEvNS-based measurement at SNS/reactor: $\sim$0.01-0.04 GeV
  $\rightarrow$ independent probe!

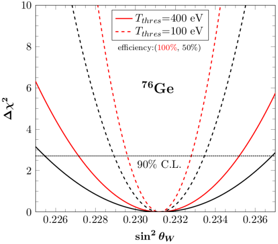


J.Erler, A.Freitas, PDG 2016, ch.10

Sensitivity of CEvNS-based θ_W measurements at SNS/reactor:

- Stat. uncertainty: 1 kg Ge det. 20 m from 3 GW reactor with E_{rec}^{th}=0.4 keV, 50% efficiency and 1 yr exp.$\rightarrow$ $\pm$1% stat. uncer. on $sin^2\theta_W$
- Stat.+syst. uncer.: π-DAR at SNS: total uncertainty of $\pm$10% on rate $\rightarrow$ total uncertainty of $\pm$5% on $sin^2\theta_W$

$\rightarrow$ reduction of systematics crucial!



T.S.Kosmas et al., Phys.Lett.B 750 (2015) 459-465

CEvNS-based search for sterile neutrinos

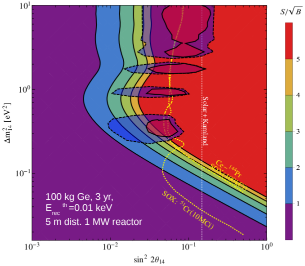
Sterile neutrino search:

- ν rate anomalies found by Gallium / ν-beam / short-baseline reactor exp.
- Preferred regime for sterile neutrino: $\Delta m^2_{14} > 1\,\mathrm{eV}^2$, $\sin^2(2\theta) \approx 0.1$
- Almost 10 new short baseline experiments start in 2016/2017:
  $\rightarrow$ look for $1/(R+\epsilon)^2$ rate change; use vertex reco., segmentation, det. movement

source	distance	detector	det.channel	exp.site
$\bar{\nu}$'s/ν's radioact. s.	4-12 m	100 t LSc	IBD, ES ν_e-e	deep ug.
reactor $\bar{\nu}$'s	6-12 m	1 t Gd-LS, Gd-PS	IBD	shallow d.
	6-12 m	1 t ^{6}Li-LS, ^{6}Li-PS	IBD	
reactor $\bar{\nu}$'s	2-10 m	100 kg Ge	CEvNS (flavor-blind)	shallow d.

Sensitivity of CEvNS-based measurement at reactor:

- Reactor: 1 MW-class TRIGA-type reactor:
  $\Phi_{\bar{\nu}} = 1.5 \times 10^{12}/(\mathrm{s \cdot cm^2})$ at 1 m distance
- Ge detectors: $E^{th}_{rec} = 0.01\text{-}0.1\,\mathrm{keV}$
- Shield thickness around r.core: 2-3 m;
- Bg level: 100-1 cts/(kg·keV·d) below 1 keV at 2-10 m distance from r.core
- Exposure: few 100 to 1000 kg·yr

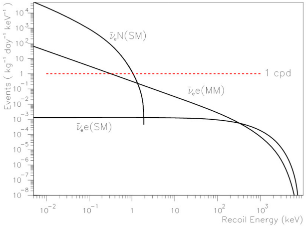


B.Dutta et al., arXiv:1511.02834 [hep-ex]

Differential cross section at low energies in Minimal Extended SM:

- $(\frac{d\sigma}{dT})_{tot} = [(\frac{d\sigma}{dT})_{\nu A} + (\frac{d\sigma}{dT})_{\nu e}]_{WI} + [(\frac{d\sigma}{dT})_{\mu_\nu} + (\frac{d\sigma}{dT})_{q_\nu}]_{EM}$

  - Neutrino magnetic moment:
    $$(\frac{d\sigma}{dT})_{\mu_\nu} = \frac{\pi\alpha^2}{m_e^2} \cdot (\frac{\mu_\nu}{\mu_B})^2 \cdot (\frac{1}{T} - \frac{1}{E_\nu}) \propto \frac{1}{T}$$
  - Neutrino millicharge:
    $$(\frac{d\sigma}{dT})_{q_\nu} = \frac{2\pi\alpha}{m_e^2} \cdot \frac{1}{m_e T^2} \cdot q_\nu \propto \frac{1}{T^2}$$



H.T.Wong et al., J. Phys. Conf. S. 39 (2006)

- Theoretical expectation for a Dirac neutrino:
  $\mu_\nu^D \approx 10^{-19}\mu_B$

- Direct experimental limits:

source	experiment	μ_ν lower limit (90% C.L.)
solar ν_e's	Borexino	$<5.4\times10^{-10}\mu_B$
"	Super-K	$<1.1\times10^{-10}\mu_B$
reactor $\bar{\nu}_e$'s	GEMMA	$<2.9\times10^{-11}\mu_B$
"	Texono	$<7.4\times10^{-11}\mu_B$
"	MUNU	$<9.0\times10^{-11}\mu_B$

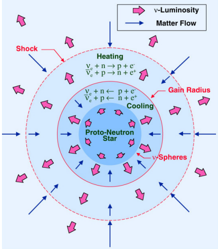
$\rightarrow$ **BUT**: Sensitivity scales with: $\mu_\nu \propto \frac{1}{\sqrt{N}} \cdot [\frac{B}{M \cdot t}]^{1/4}$

Application: modelling of stellar collapse

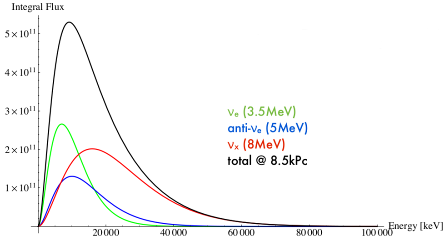
Stellar core collapse supernova: $M_{star} >$9 M_{sun}

- Evolution up to stellar collapse:
  - nuclear fusion up to iron: no net energy $\rightarrow$ only electrons degeneracy pressure
  - for iron core mass $>$ Chandrasekhar limit (1.3 M_{sun}), the star collapses
- Evolution during stellar collapse:
  - iron core shrinks up to reaching nuclear density: strong interaction + neutron degeneracy prevents further collapse $\rightarrow$ outgoing shock waves
  - ν's carry away 99% of gravitational binding energy (10^{53} erg)
  - CEvNS interactions of ν's in Fe+Ni layers highly probable: opacity for ν: $\mathcal{O}$ (λ_ν)=1 km

  $\rightarrow$ Influence on ν transport / ν radiation pressure $\rightarrow$ Impact on light curve evolution



Credit:TeraScale Supernova Initiative



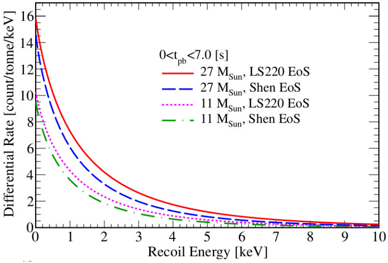
CEvNS detectors most suitable for its measurement

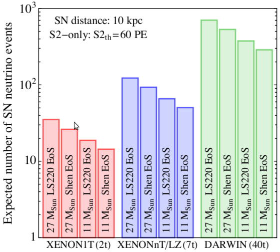
Dark Matter detectors for CEvNS detection from Supernovas

Neutrinos from a 10 kpc distant supernova (SN)

(Expected rate in our galaxy: 1 every 30 yr)

- SN detection via neutrino interactions excluding CEvNS:
  - Cherenkov and liquid scintillator detectors: IceCube (G2), Super-K (Hyper-K), LVD, BOREXINO, JUNO, Reno-50, KamLAND
  - Examples of expected neutrino fluence rates:
    Super-K: 50 kton $\rightarrow 10^3$-10^4
    Borexino: 300 ton $\rightarrow$ few 10^2's
- SN detection via CEvNS portal using DM detectors:
  - XENON: 1-5 tons $\rightarrow$ few 10's to few 10^2's

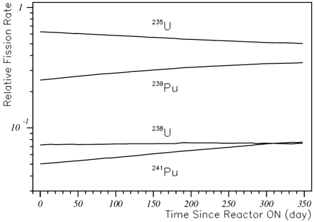


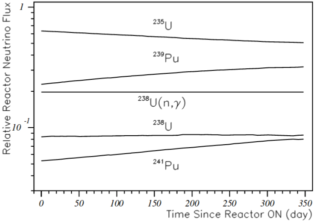


R. Lang et al., Phys. Rev. D 94 (2016) no.10, 103009

Reactor monitoring / non-proliferation of fissile products

Typical reactor cycle at Kuo-Sheng Nuclear Power Station in Taiwan





H.T.Wong et al. (TEXONO collaboration), Phys.Rev.D 75, 012001

Difference of neutrino spectrum from 235U and 239Pu