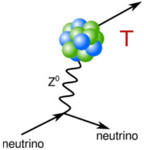
First constraints on coherent elastic neutrino-nucleus scattering at reactor site with the CONUS experiment

Aurélie Bonhomme
Max-Planck-Institut für Kernphysik, Heidelberg
on behalf of the CONUS collaboration

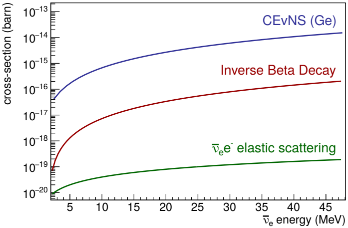
XIX Workshop on Neutrino Telescopes

Coherent elastic neutrino-nucleus scattering (CEνNS)



$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} \underbrace{\left[N - (1 - 4\sin^2\theta_w) Z\right]^2}_{\sim N^2} \underbrace{F^2(q^2)}_{\to 1} M \left(1 - \frac{MT}{2E_\nu^2}\right)$$

- For low momentum transfer, interaction with the nucleus as a whole
  $\rightarrow$ **cross-section enhancement**



- Full **coherency** feature: $\sigma \propto N^2$
  $\sin^2(\theta_w) \sim 0.238$ at low energies and $F(q^2) \sim 1$
  fully coherent for $E_\nu \lesssim$ **30 MeV**
- Only observable experimentally accessible:
  low energy **recoil of the nucleus**! $T_{max} \propto 1/A$
  $\Rightarrow$ **very low energy threshold** required!

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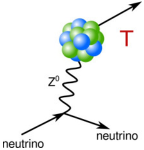

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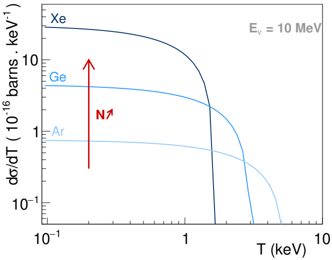

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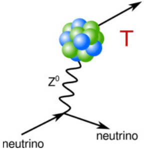

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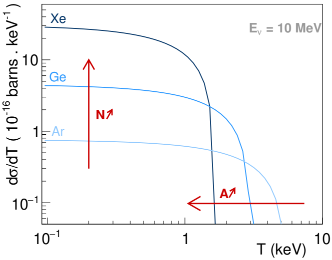
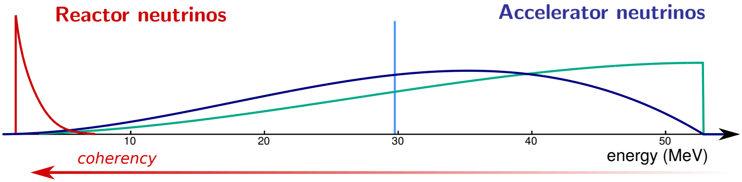


Detecting CEνNS: how and why?



$\bar{\nu}_e$ from β-decays of fissile isotopes

running: **CONUS**, TEXONO...
future: RICOCHET, NUCLEUS

ν_μ, $\bar{\nu}_\mu$ and ν_e from π-decay at rest

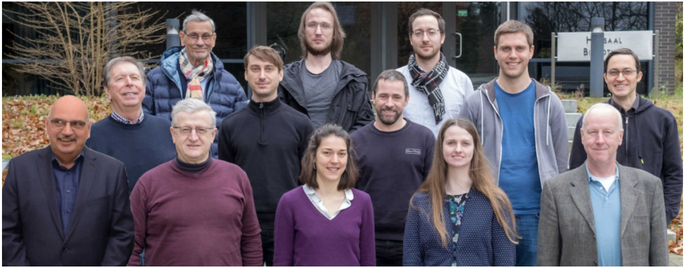
COHERENT @SNS: first observation
Akimov et al., Science, 357, 6356, (2017)

Compact experiments, complementary approaches!

Weinberg angle measurements
Beyond Standard Model: Non Standard Interactions, Neutrino Magnetic Moments...
Nuclear structure
Reactor investigations

The CONUS collaboration

CONUS



Collaboration:

H. Bonet, A. Bonhomme, C. Buck, J. Hakenmüller, J. Hempfling, J. Henrichs, G. Heusser, T. Hugle, M. Lindner, W. Maneschg, T. Rink, H. Strecker - **Max Planck Institut für Kernphysik (MPIK), Heidelberg**

K. Fülber, R. Wink - **Preussen Elektra GmbH, Kernkraftwerk Brokdorf (KBR), Brokdorf**

Scientific cooperation:

R. Nolte, E. Pirovano, M. Reginatto, M. Zboril, A. Zimbal - **Physikalisch-Technische Bundesanstalt (PTB), Braunschweig**

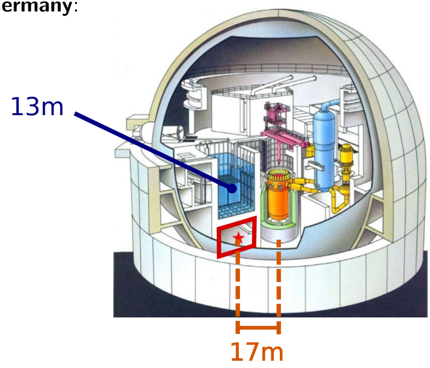
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

Preussen Elektra

The CONUS experimental site

The Brokdorf nuclear power plant (KBR) in Germany:

- site @17m from the **3.9 GW$_{th}$ reactor core**
  ✓ **high $\bar{\nu}_e$ flux**: 10^{13} $\bar{\nu}_e$ s^{-1}cm^{-2}
- high duty-cycle
  ✓ 1 month/year of **reactor-off**
- shallow-depth site (24 m w.e.)
  x sensitive to **cosmic-induced background**
- reactor environment
  x **potential reactor-induced** background



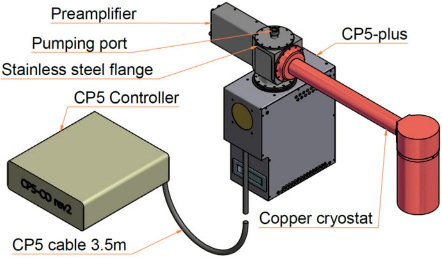
Reactor site: $\neq$ **laboratory conditions!**
no fresh air supply, changes in environmental conditions, no remote control, no cryogenic liquids allowed, earth quake safety requirements, restricted access...

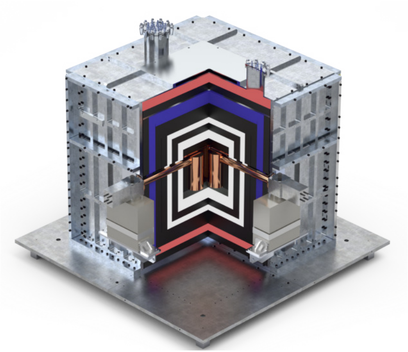
The CONUS experimental setup

arXiv:2010.11241

4 p-type point contact HPGe (1kg each)

- very low background components
- pulser resolution (FWHM) $< 85\,\mathrm{eV_{ee}}$
  $\rightarrow$ threshold $\lesssim 300\,\mathrm{eV_{ee}}$
- electric cryogenic cooling



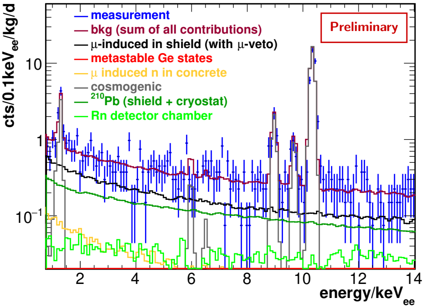


Passive + active shield

- Lead with low ^{210}Pb content
- Borated PE, pure PE
- Active μ-veto (plastic scintillator)
- Flushing with air bottles

Background suppression

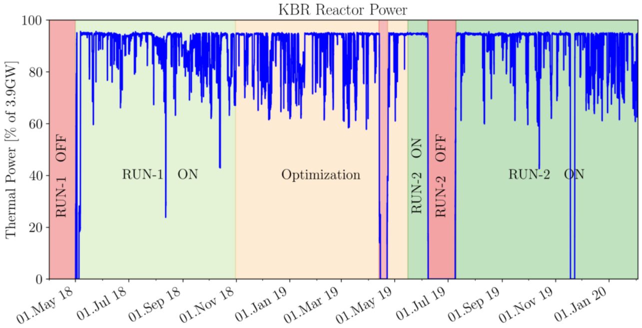
- External natural radioactivity and cosmogenic background: reduced by 10^4
- Reactor correlated components (neutrons, gammas) negligible contribution compared to CEνNS Eur. Phys. J. C 79, 699 (2019)
- Residual background well understood, described by MC simulations



Background level in [0.5 – 1] keV$_{ee}$:
10 counts/kg/d/keV$_{ee}$, **stable**

Data selection

Phys. Rev. Lett. 126, 041804 (2021)



Data quality cuts:

- No noise-temperature correlation
- Discrimination of microphonic and spurious events via time difference

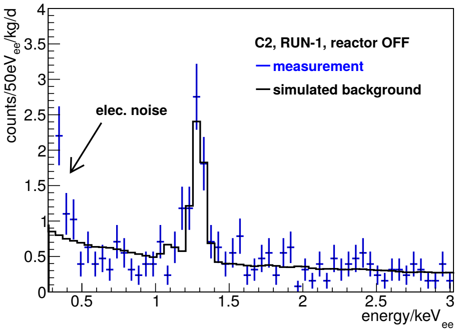
Run-1 + Run-2 exposure: **248.7 kg d (reactor-on)**
58.8 kg d (reactor-off)

Region of interest for CEνNS

Phys. Rev. Lett. 126, 041804 (2021)

Region Of Interest (ROI):

- Trigger efficiency ~100 %
- Electronic noise component described by an exponential, contribution $< 4\times$ MC



Det.	RUN	ON [d]	OFF [d]	ROI [keV$_{ee}$]
C1	1	96.7	13.8	0.296 - 0.75
C2	1	14.6	13.4	0.311 - 1.00
C3	1	97.5	10.4	0.333 - 1.00
C1	2	19.6	12.1	0.348 - 0.75
C3	2	20.2	9.1	0.343 - 1.00
Total		**248.7**	**58.8**	

Likelihood analysis Phys. Rev. Lett. 126, 041804 (2021)

Simultaneous fit (ON/OFF) – all detectors and runs:

$$\log \mathcal{L} = \log \mathcal{L}_{\mathrm{ON}}(s, b, p^1_{thr}, p^2_{thr}, \{\phi_i\}) + \log \mathcal{L}_{\mathrm{OFF}}(b, p^1_{thr}, p^2_{thr}, \{\phi_i\}) + \sum_{pulls} \frac{(\phi_i - \phi_0)^2}{2\sigma_i^2}$$

s: free signal normalization

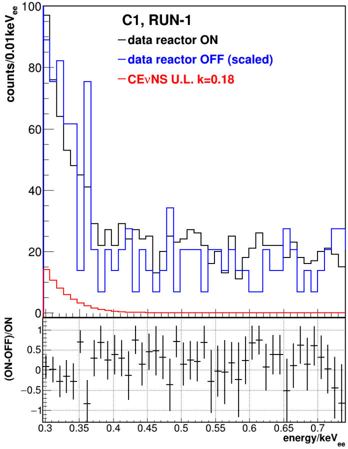
- Theoretical prediction for CEνNS
- $\bar{\nu}_e$ reactor spectrum (thermal power, fission fractions and Huber/Mueller + Daya Bay)
- Detector response

b: free background normalization

- MC modelling
- p^1_{thr}, p^2_{thr}: electric noise description

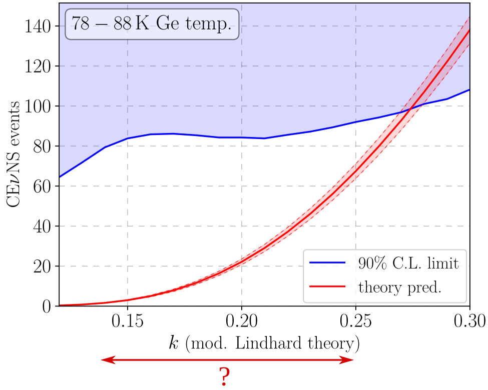
Nuisance parameters for systematic uncertainties:

ϕ_{rea}: reactor neutrino spectrum ($\sigma_{rea} \sim 3\,\%$)
ϕ_{det}: active volume, DAQ: (σ_{det} = 1-5 %)
ϕ_{escale}: energy scale uncertainty: (σ_{escale} = 10-20 $\mathrm{eV_{ee}}$)



First CEνNS constraint from CONUS

Phys. Rev. Lett. 126, 041804 (2021)



Best CEνNS limit at reactor:

$< 0.4\ \mathrm{d^{-1}kg^{-1}}$ (90 % C.L.)

Signal expectation:
depends on the **quenching factor**

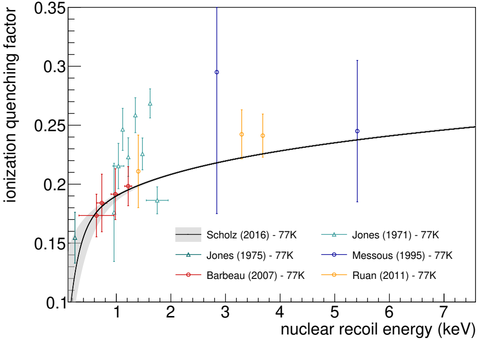
k > 0.27 disfavored
for k = 0.18: limit 7x above prediction

→ **Need for a more precise measurement of the quenching factor in the keV range**

Quenching factor measurements

Detector response: quenching of the $\bar{\nu}_e$ signal:

$$\underbrace{E_{nr}}_{\text{total recoil energy}} = E_{others} + \underbrace{E_{ioniz}^{meas}}_{\text{visible in HPGe}} \Rightarrow \text{need to know } \mathbf{Q} \equiv E_{ioniz}^{meas}/E_{nr}$$

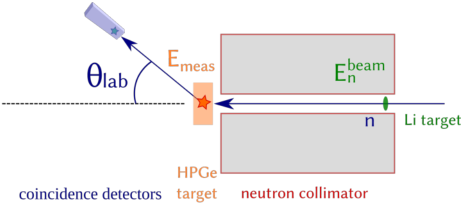


- **Experimentally**:
  Extensively measured for 10-100 keV
  Data lacking in the keV range
- **Theoretically**:
  Lindhard parametrization of Q:
  $\rightarrow Q(E) = f(\mathbf{k})$
  Validity at low energy?

Quenching factor measurements

Direct, model-independent meas. using **neutrons** (nuclear recoils):

$$\mathbf{Q} \equiv \frac{E^{meas}_{ioniz}}{E_{nr}(\theta_{lab}, E_n)}$$



Scientific cooperation with PTB*:

- Pulsed proton beam (tandetron)
  1.25 MHz repetition frequency
  2 ns resolution
- Mono-energetic neutrons via Li(p,n) reaction (hundreds of keV)
  $\rightarrow \sim$ keV recoils in Ge
  $\sim 10^3 n.cm^{-2}.s^{-1}$ on Ge target
  3 % width @ 500keV

* Physikalisch-Technische Bundesanstalt Braunschweig, Germany

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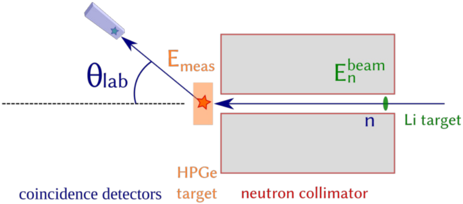
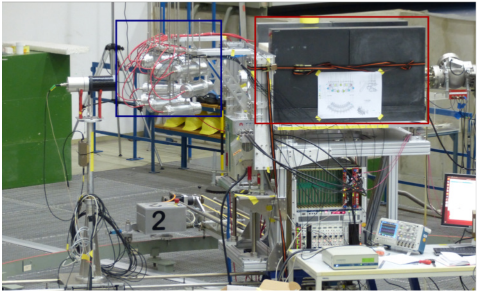




Experimental setup:

- Neutron collimation
  ⌀ 35 mm beam at HPGe target
- Dedicated thin HPGe target
  6 mm thick germanium crystal
  no material on beam axis
  FWHM: 135 eV @ 5.9 keV
- Liquid scintillators (LS) array
  low energy threshold, good PSD
  ∼ 70 % neutron detection eff.

Quenching factor measurements

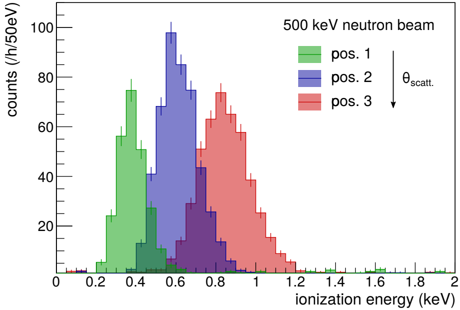
$$\mathbf{Q} \equiv \frac{\mathbf{E}^{\mathbf{meas}}_{\mathbf{ioniz}}}{\mathbf{E}_{\mathbf{nr}}(\theta_{\mathbf{lab}}, \mathbf{E}_{\mathbf{n}})}$$

$E_{nr}(\theta_{lab}, E_n)$: nuclear recoil energy

- Beam monitoring: detectors at 0°
  E_n from time-of-flight
- Scattering angles (θ_{lab}) at the 0.5° level

E^{meas}_{ioniz}: ionization energy

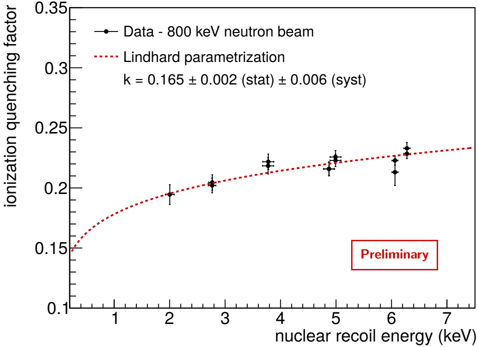
- Energy scale in HPGe:
  regular calibration with Fe-55
  Ge activation lines
- **Signal selection via triple coincidence:**
  beam stop
  target HPGe
  LS detectors



Quenching factor measurements

$\sim$16 h beam exposure (Oct. 2020) $\rightarrow$ probe **nuclear recoils between 0.8 and 6 keV**

- beam energy varied between 250 keV – 800 keV
- angles varied between 18° and 45°



Combined analysis (96 points) with full treatment of systematic uncertainties on-going

Conclusions and perspectives

- Promising **CEνNS neutrino detection channel** now experimentally accessible
  $\Rightarrow$ beam–/reactor–based experiments are complementary

- **CONUS experiment**, measuring reactor-$\bar{\nu}_e$ (NPP in Brokdorf) since April 2018
  – **best limit on CEνNS with reactor neutrinos** **Phys. Rev. Lett. 126, 041804**
  – detailed description of the Ge detectors **arXiv:2010.11241**
  – extended correlated background studies **Eur. Phys. J. C 79, 699 (2019)**

- **Much more improvements to come in the near future:**
  – Beyond Standard Model analyses
  – Extended dataset + reactor-OFF (reactor shut-down end of 2021)
  – DAQ upgrades: pulse shape studies
  – **Quenching factor measurements** in germanium

Thank you!