Università di Genova

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COHERENT ELASTIC SCATTERING OFF NUCLEUS OF ^{51}Cr NEUTRINOS

Lea Di Noto

University and INFN Genova (ITALY)

2nd Magnificent CEvNS workshop

Chapel Hill, 11th November 2019

INFN

Istituto Nazionale di Fisica Nucleare

OUTLINE

The talk is based on the published paper

- Motivations
- The idea
- The ^{51}Cr source
- The flux measurement
- The detector
- Simulation results
- Conclusions

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Regular Article - Experimental Physics

Coherent elastic nuclear scattering of ^{51}Cr neutrinos

C. Bellenghi[1,2], D. Chiesa[3,4], L. Di Noto[5,6], M. Pallavicini[5,6], E. Previtali[3,4], M. Vignati[2,a]

[1] Dipartimento di Fisica, Sapienza Università di Roma, Rome 00185, Italy
[2] INFN Sezione di Roma, Rome, Italy
[3] Dipartimento di Fisica, Università di Milano - Bicocca, Milano 20126, Italy
[4] INFN Sezione di Milano Bicocca, Milano, Italy
[5] Dipartimento di Fisica, Università di Genova, Genova 16146, Italy
[6] INFN Sezione di Genova, Genova, Italy

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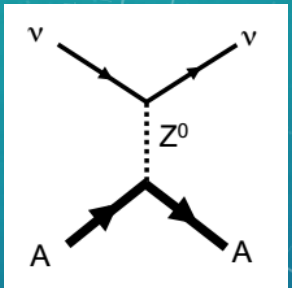
COHERENT ELASTIC NEUTRINO-NUCLEUS SCATTERING

It occurs if the condition is satisfied: $qR \cong 1$ $\quad E_\nu < 50$ -100 MeV



The cross section is high

$$\frac{d\sigma_\nu}{dE_R} = \frac{G_F^2}{4\pi} Q_{SM}^2 m_N \left(1 - \frac{E_r m_N}{2E_\nu^2}\right) \underbrace{F^2(E_r)}_{\text{Form factor}}$$

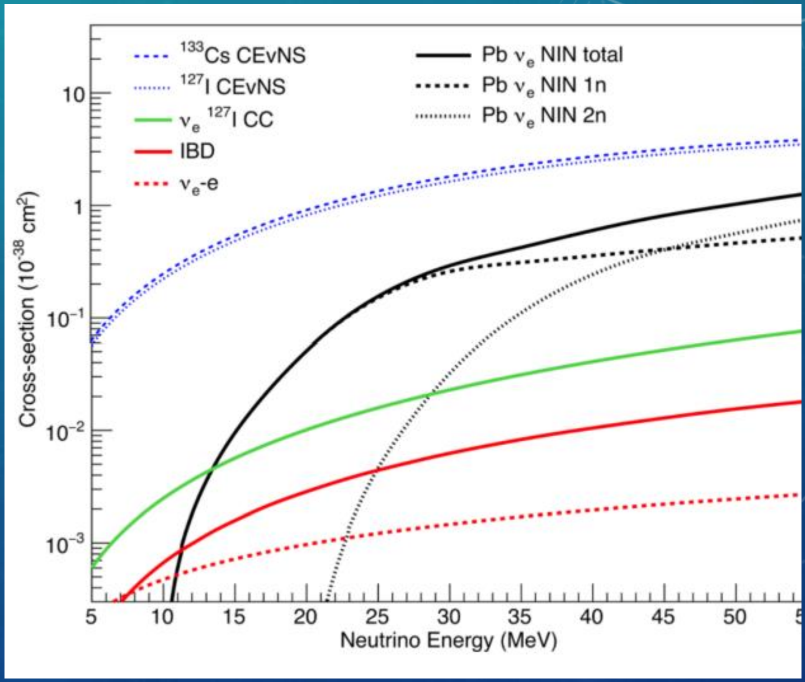
$$Q_{SM}^2 = [N - (1 - s_W^2)Z]^2 \simeq N^2$$

Maximum recoil energy

$$T_{max} \leq \frac{E_\nu}{1 + \frac{M_A}{2E_\nu}}$$

Total cross section

$$\sigma_{SM} \simeq \frac{G_F^2}{4\pi} N^2 E_\nu^2 \simeq 0.4 \times 10^{-44} N^2 E_\nu^2 \text{ cm}^2$$



DOI: 10.1126/science.aao0990

Both cross-section and maximum recoil energy increase with neutrino energy

DIFFERENT SOURCES

Energy scale

From **stopped pions** $\bar{\nu}_\mu, \nu_e, \nu_\mu$ 1 10^{15} s^{-1} 50 MeV

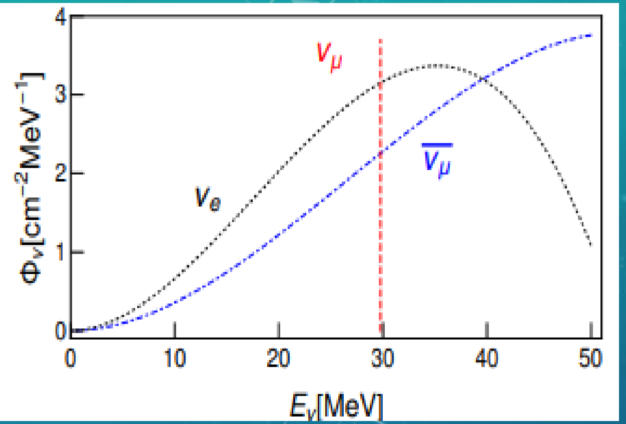
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)



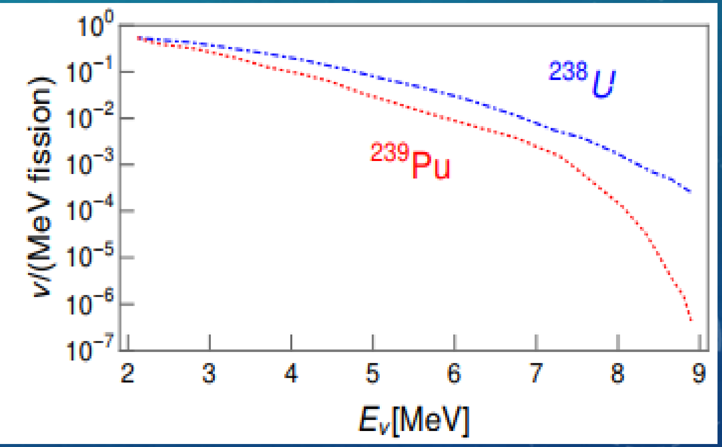
COHERENT exp

Flux normalisation precision: 10%

From **reactor**:

$\bar{\nu}_e$ high flux 2 10^{20} s^{-1} few MeV

The flux depends on models: precision at several %



CONNIE, CONUS, RICOCHET, NUCLEUS, MINER, .. exp

with **artificial sources**:

Source	Half-life	Progeny	Production	E_ν
^{37}Ar	35.04 days	^{37}Cl	^{40}Ca(n, α)^{37}Ar	811 keV (90.2%), 813 keV (9.8%)
^{51}Cr	27.70 days	^{51}V	n capture on ^{50}Cr	747 keV (81.6%), 427 keV (9%), 752 keV (8.5%)
^{65}Zn	244 days	^{65}Cu	n capture on ^{64}Zn	1343 keV (49.3%), 227 keV (50.7%)

THE IDEA

THE SOURCE

→Electron capture decaying isotope ^{51}**Cr** source
→Half-life 27.7 days
→5 MCi (single activation at reactor)
→Neutrino energy 747 keV (81%) and 752 keV (9%)

LOW THRESHOLD DETECTOR

Recoil energy O(10) eV

Volume: 2000 cm^3
Cryogenics phonon detectors
(Germanium or sapphire)
or CCD detectors

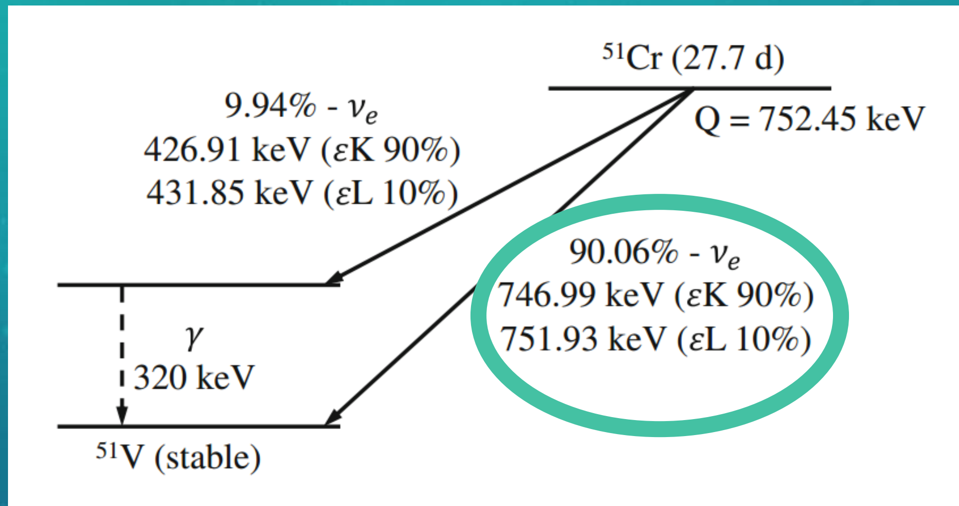
energy threshold: as low as possible

CALORIMETRIC ACTIVITY MEASUREMENT
per mill precision

KEY POINTS FOR A PRECISE MEASUREMENT:
→ Precise (<1%) knowledge of the neutrino spectrum and flux
→ Background rejection

THE ^{51}CR NEUTRINO SOURCE

The **neutrino** spectrum consists in four mono-energetic lines:



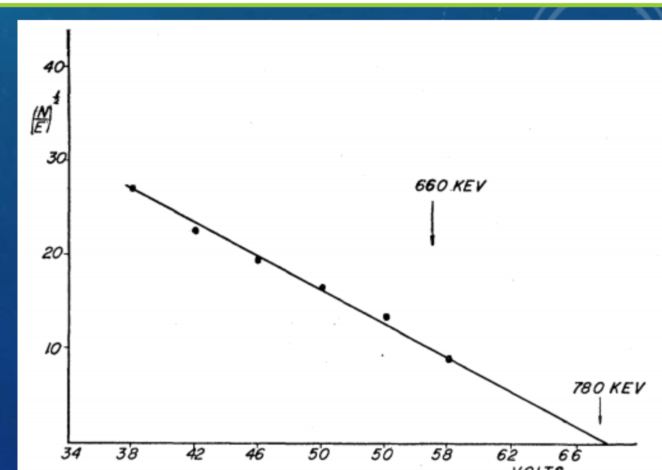
Associated gamma emission

- 320 keV
- Bremsstrahlung up to 780 keV from K capture

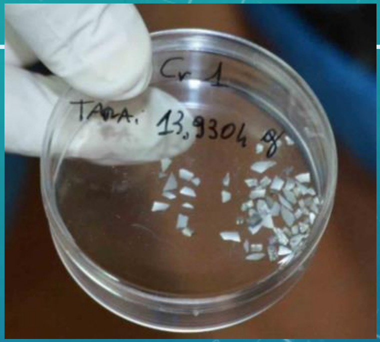
  branching ratio: 8 10^{-4} for gamma with E>320 keV

Impurities can be activated during the irradiation

Gamma spectrum from internal bremsstrahlung



THE SOURCE PRODUCTION



The GALLEX (INFN) sample:

Mass: 36 kg

with 3.6 g/cm^3 effective density in metallic chips of 1-5 mm

Isotopic composition: ^{50}Cr 38.6% ^{52}Cr 60,7% ^{53}Cr 0,7% ^{54}Cr < 0,3%
enriched in ^{50}Cr and depleted in isotope ^{53}Cr (high neutron capture cross section)

Activation of the sample at reactor

GALLEX:
Siloé reactor in Grenoble with an
estimated neutron flux 2 10^{14} neutrons cm^{-2} s^{-1}
23.8 Days of irradiation
Final activity of ^{51}Cr: 1.7 MCi

Challenging numbers:
neutron flux 5 10^{14} neutrons cm^{-2} s^{-1}
24 days of irradiation
Final activity of ^{51}Cr: 3.5-7 MCi

THE IRRADIATION PROCESS

The activation rate

$$R = N \int \varphi(E)\sigma(E)dE$$

depends on :

- $\varphi(E)$, the **averaged thermal neutron** flux (in GALLEX $5\ 10^{13}$ n/cm2 s)
- the average lifetime of neutron in the reactor
- the neutron absorption length for ^{50}Cr and ^{53}Cr (24% higher)

  95% ^{50}Cr enriched : 0.7 cm

The ^{51}Cr lifetime is reduced due to neutron capture (small effect)

Source activity

$$A(t) = R\left(1 - e^{-\lambda t_{irr}}\right)e^{-\lambda t}$$

The efficiency depends on the geometry and on the source properties

We can improve with:

→ Higher intense flux (new reactor)

→ Optimized geometry and source

→ More cycles (since ^{51}Cr lifetime and neutron capture from ^{51}Cr)

Suitable research reactors

- High Flux Isotope Reactor (HFIR) at Oak Ridge (USA), 85 MW power $1.2\text{-}2.5\times10^{15}$ n/cm^{2}s
- BR2 reactor at Mol (Belgium), 100 MW
- Jules Horowitz Reactor (France) under construction

To be investigated!!

Recently a new ^{51}Cr source has been produced in Russia (Dimitrovgrad)!!!

By BEST experiment (3.2MCi) 5th July 2019

THE BYOLOGICAL SHIELD

For gamma emitted

- from ^{51}Cr decay (320 keV) BR 10% 3.8 10^{16} gamma/s
- from internal Bremsstrahlung (max 750 keV) 1.3 10^{13} gamma/s
- from the activated impurities ^{110m}Ag (max 1.5 MeV) 1 10^{10} gamma/s

Made of tungsten alloy (the SOX shield might be adapted)

- for temperature
- for higher density

If we consider the same activation factor of GALLEX

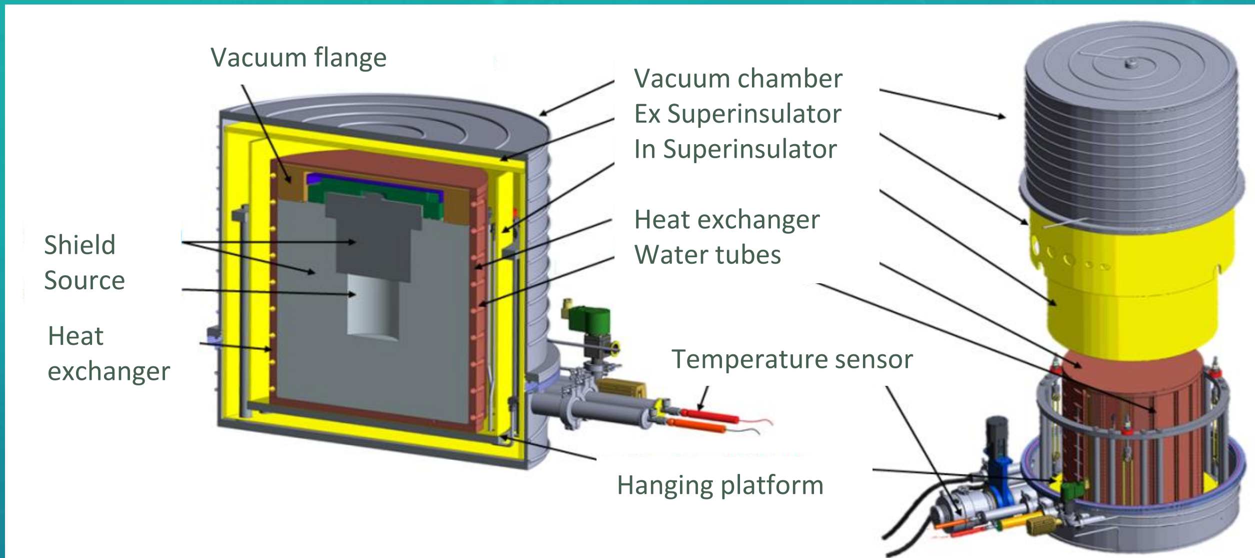
The total gamma flux must be reduced for:
→ the dosimetric issue (dose < 100 uSv at contact)
8 cm are enough (attenuation factor of 2000)

→ reducing background (for maximizing the S/N ratio)
more stringent requirement

GALLEX SAMPLE CONTAMINATION

Nucleus	Meanlife	Energy [keV]	Source activity (GBq) After extraction
^{24}Na	14.8 h	1368.5	0.10 ± 0.02
		2753.9	0.07 ± 0.01
		average:	0.08 ± 0.01
^{46}Sc	83.9 d	1121	0.13 ± 0.02
^{48}Sc	43.7 h	983.5	0.05 ± 0.03
		1037.5	0.07 ± 0.03
		1312.1	0.10 ± 0.01
		average:	0.095 ± 0.01
^{60}Co		1173.2	0.02 ± 0.01
		1332.5	0.04 ± 0.01
		average:	0.030 ± 0.007
^{64}Cu	12.7 h	1345.8	210 ± 20
^{77}Ge	11.3 h	2342.3	0.5 ± 0.2
^{76}As	43.7 h	1212.7	6 ± 3
		1216.0	3 ± 1
		2096.3	1.5 ± 0.2
		average:	1.6 ± 0.2
^{97}Zr	17.0 h	1749.9	0.40 ± 0.15
^{110m}Ag	249.8 d	657.7	4 ± 2
		763.9	10 ± 3
		818	
		884.7	4.3 ± 0.5
		937.5	4.2 ± 0.5
		1384.3	5.0 ± 0.5
		1475.7	5.1 ± 0.5
		1505.0	4.3 ± 0.5
		1562.3	4.0 ± 0.5
		average:	4.35 ± 0.25
^{124}Sn	60.2 d	1368	
		1437	0.4 ± 0.15
		1691	0.36 ± 0.05
		1919	
		2039.6	0.4 ± 0.03
		2091	0.51 ± 0.08
		2185	
		2294	
		average:	0.40 ± 0.03

THE ACTIVITY MEASUREMENT

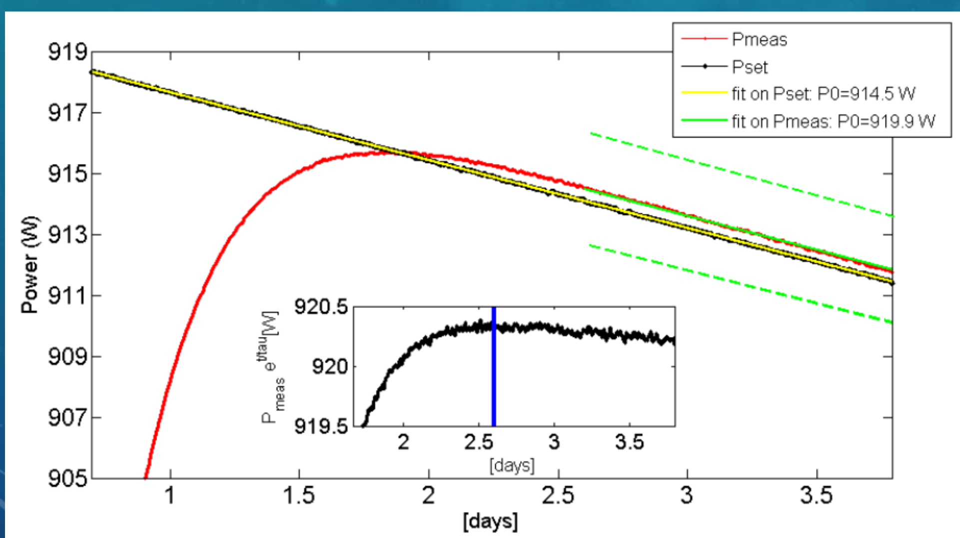


The heat contribution from impurities is negligible

36.51 keV for each decay
expected power 422 W for 5 MCi

$$P_g = \dot{m} \cdot [h(p, T_{out}) - h(p, T_{in})]$$

After the thermalization phase (2-3 days) the measured power follows:

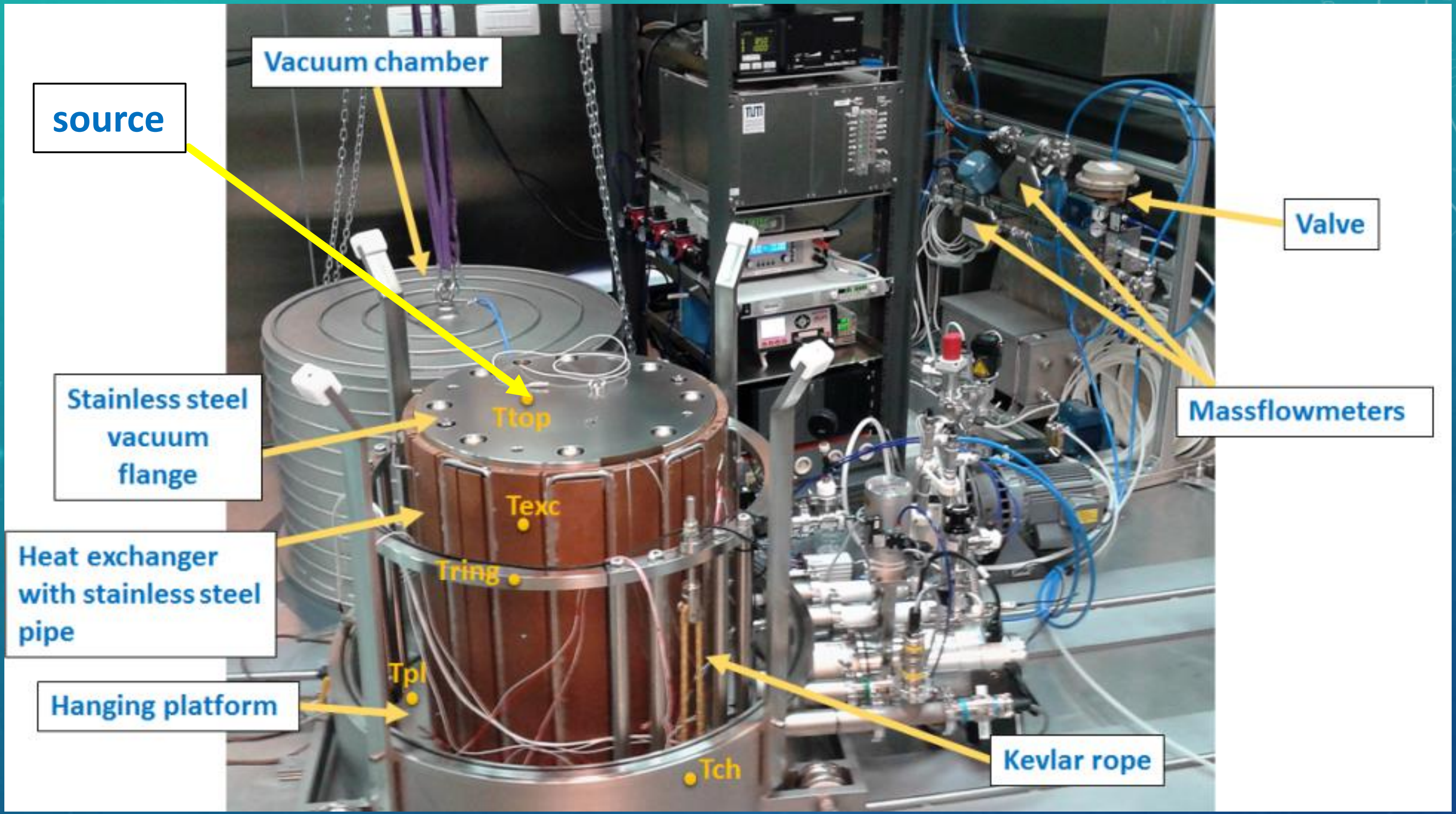


$$P_m = P_g e^{-\frac{(t-\Delta t)}{\tau}} - P_{lost}$$

The precision depends only on

- P_{lost}
- the delay time Δt, (minimized and measured in the calibration phase)

THE SOX CALORIMETER



Ref: K. Altenmüller et al., JINST **13**(09), P09008 (2018)

It was calibrated and tested with an electrical heat source and **0.2% precision** was achieved,

THE DETECTOR

FOR LOW ENERGY NUCLEAR RECOIL

2000 cm^3 of volume with a very low threshold

$$T_{\max} \leq \frac{E_\nu}{1 + \frac{M_A}{2E_\nu}}$$

The neutrino energy is not high-→ it is fundamental push the threshold down

→ **Cryogenics phonon detector**
germanium, silicon, sapphire (Al_2O_3), ..

The minimum recoil threshold is related to:
- mean energy fluctuations in the absorber related to T and the heat capacity
- temperature fluctuations

The heat capacity (C) depends on the mass and on temperature

$$\Delta T = \frac{E_R}{C(T)} e^{-t/\tau} \qquad \tau = C(T)/G(T),$$

→ **CCD detectors**:
very low noise, but the conversion efficiency has to be measured at low energy
a threshold of **5 eV** have been demonstrated on 5 g (CONNIE experiment)

WHICH THRESHOLD VALUE?

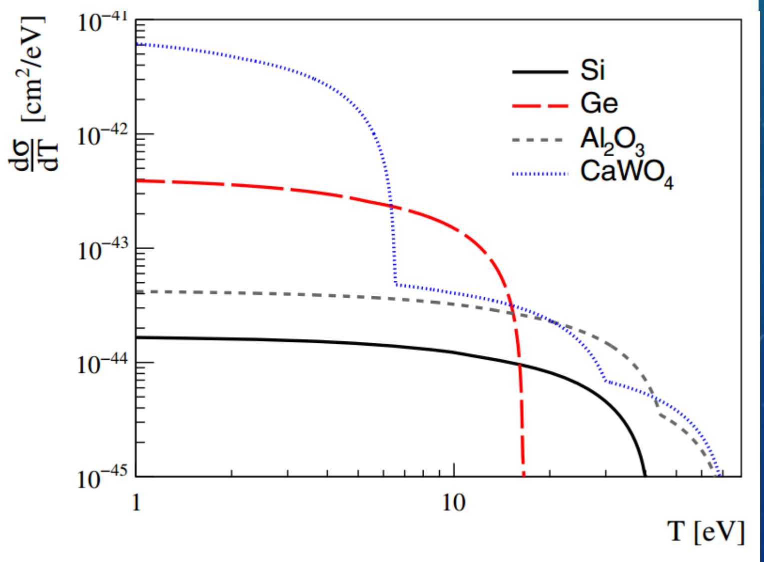
- An energy threshold of **20 eV** has been already demonstrated on a 0.5 g ($5 \times 5 \times 5$ mm^3) **sapphire Al_2O_3** target

NUCLEUS experiment PRD 96, 022009 (2017)
CRESST experiment EPJC 77:63 (2017)

- **60 eV** have been demonstrated on a 33.4 g (20 mm × 20 mm) **Germanium target**

EDELWEISS experiment PRD 99, 082003 (2019)

^{51}Cr source



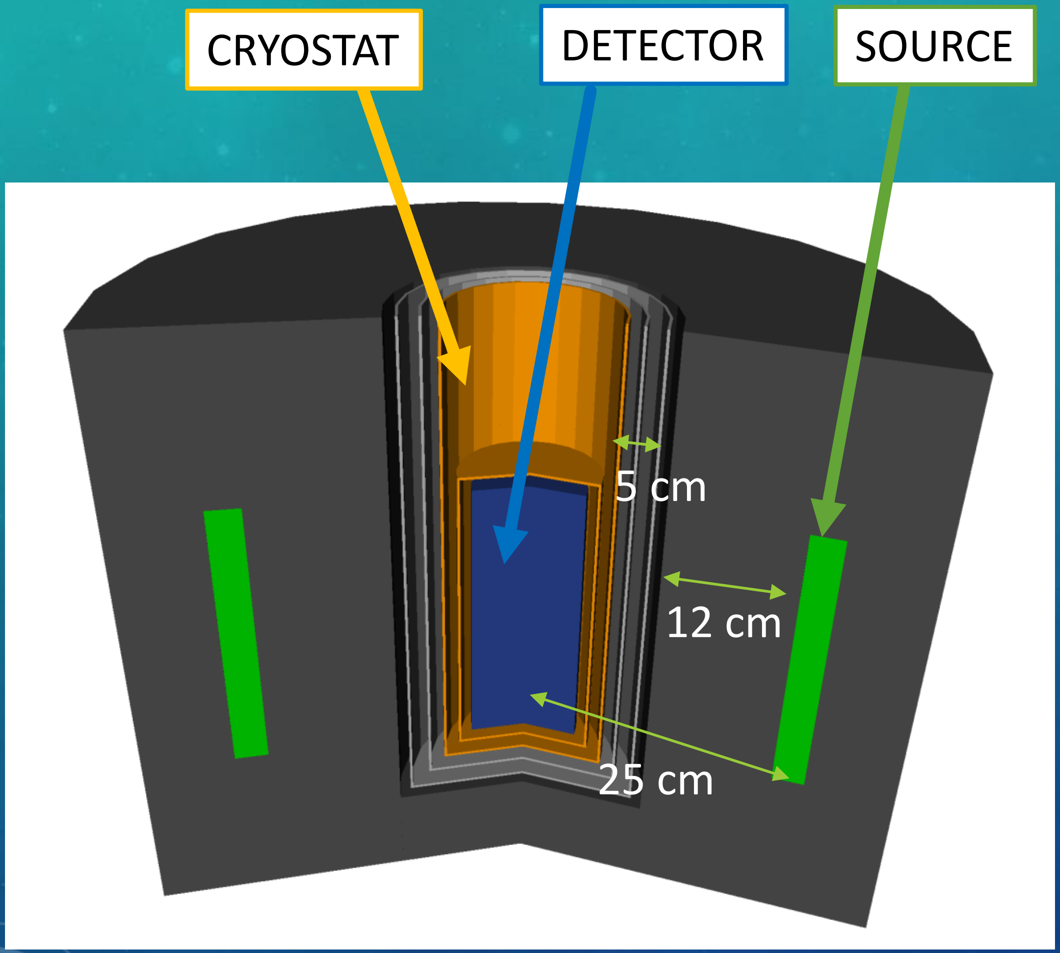
The challenge is scaling the detector mass to few kg!

By realizing arrays of thousands of small mass detectors

New developments are expected in these years…the threshold might be pushed down!

THE PROPOSED LAYOUT

for maximizing the detected event



Detector:
2000 cm^3 volume (5-10 kg)

Tungsten shield:
12 cm between source and detector

Ag gamma flux (GBq):
reduced of 10^{-6}

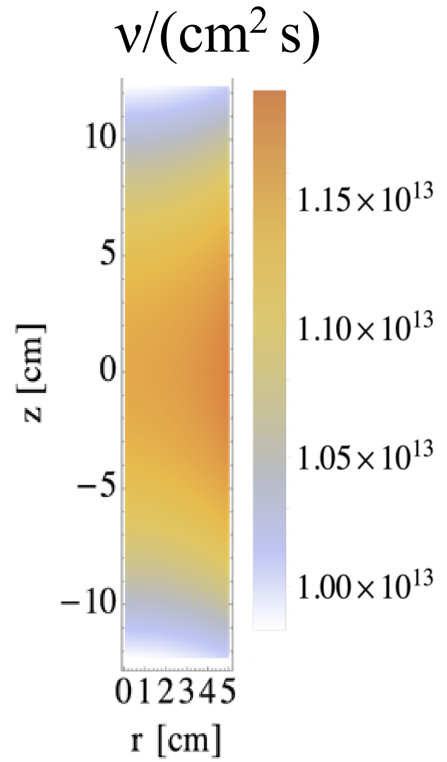
Cr Bremsstrahlung (PBq):
reduced of 10^{-11}

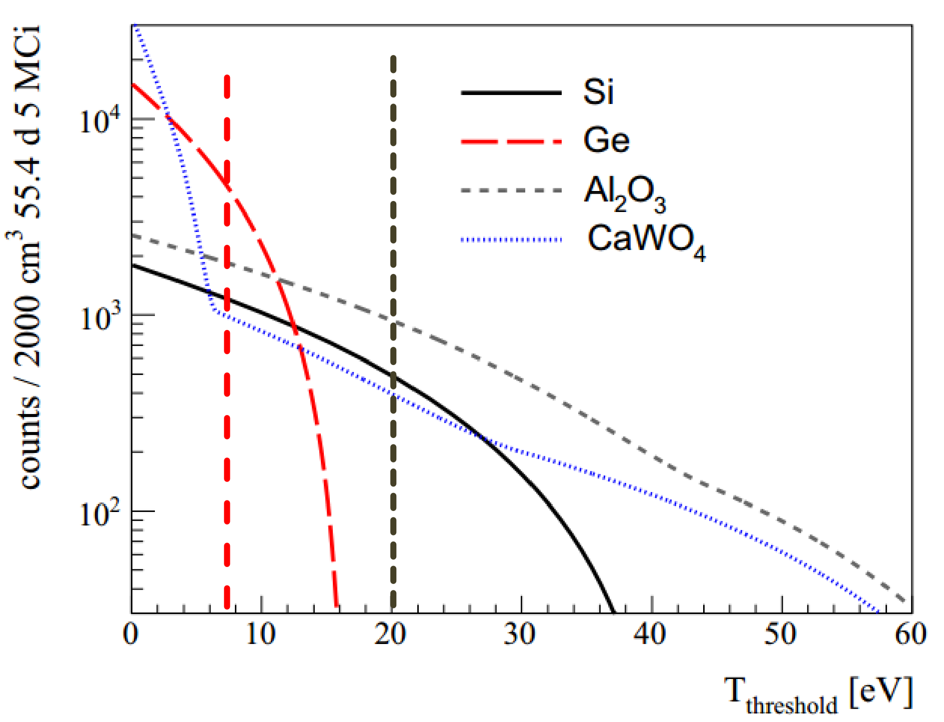
THE SIMULATION RESULTS

Initial activity: 5 MCi
Detector volume: 2000 cm^3
Exposure: 55 days (2 half lives)

Detector	Threshold [eV]	Counts in 55 days
Sapphire	20	900
Ge	8	3900

Neutrino flux in the detector





Average neutrino flux: $1\ 10^{13}$ ν/cm^2s

THE BACKGROUND

- **From gammas emitted by source impurities (^{110m}Ag, ..)**

  We extrapolated our Geant4 simulations to low energy (where they are not reliable)

  It seems that the Ag impurities in the GALLEX sample should be reduced from ppm to ppb for not generate a background
  More precise simulations are necessary

- **From environmental neutrons (if the measurement is performed not far from reactor)**

  hard to predict at these low energies

  it will measured by upcoming reactor experiment

  additional external absorber shield can be inserted in the design

THE BACKGROUND MUST BE CAREFULLY SIMULATED AND REDUCED

CONCLUSIONS

The proposed idea seems promising for achieving few percent cross section accuracy

Important advantages:

Very precise knowledge

- of the neutrino energy
- source activity

complementary information with antineutrino measurement from reactors

Critical points:

- source production
- background estimation

Next steps:

- deeper investigation for the source production
  - optimization for irradiation
  - impurities minimization)
- precise background simulation and estimation