Neutron radiative-capture reactions on nuclei of relevance to $0\nu\beta\beta$, dark matter and neutrino/antineutrino searches

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Muon-generated so-called spallation neutrons and (α,n) neutrons
are a source of background in rare event searches,
even if the associated experiments are mounted deep underground in mines

The spallation neutron energy spectrums extends up to a few GeV,
but only low-energy neutrons up to ~20 MeV are of concern

The (α,n) neutron energy spectrums extends only up to 10 MeV

OUTLINE

1. $^{40}Ar(n,\gamma)^{41}Ar$
2. $^{74,76}Ge(n,\gamma)^{75,77}Ge$
3. $^{128,130}Te(n,\gamma)^{129,131}Te$
4. $^{136}Xe(n,\gamma)^{137}Xe$
5. Future

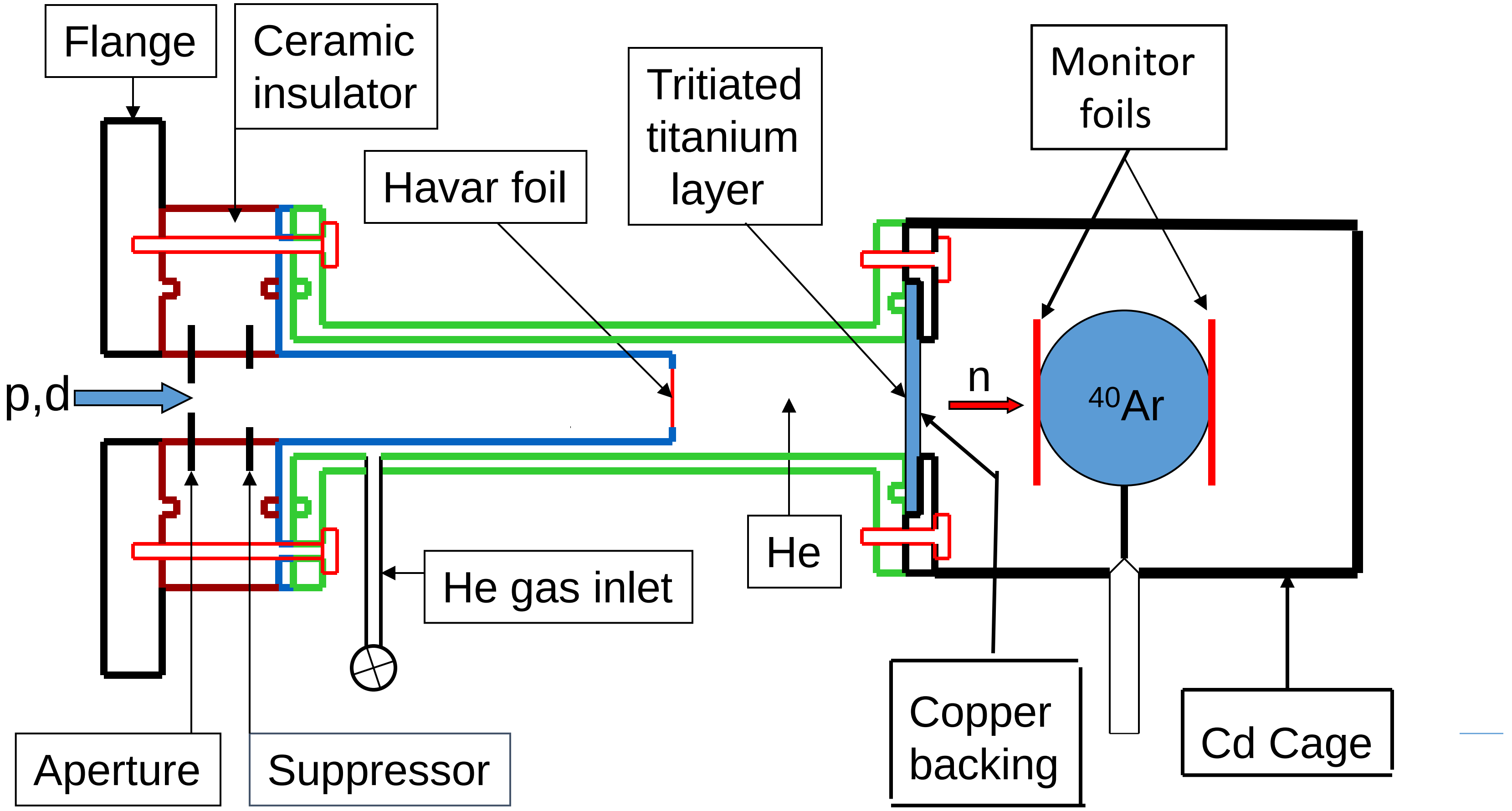
Neutron energy range : 0.4 MeV to 14.8 MeV

Neutron Source Reactions

$^{3}H(p,n)^{3}He$	0.4 - 3.6 MeV
$^{7}Li(p,n)^{7}Be$	0.58 MeV
$^{2}H(d,n)^{3}He$	4.2 - 7.6 MeV
$^{3}H(d,n)^{4}He$	14.8 MeV

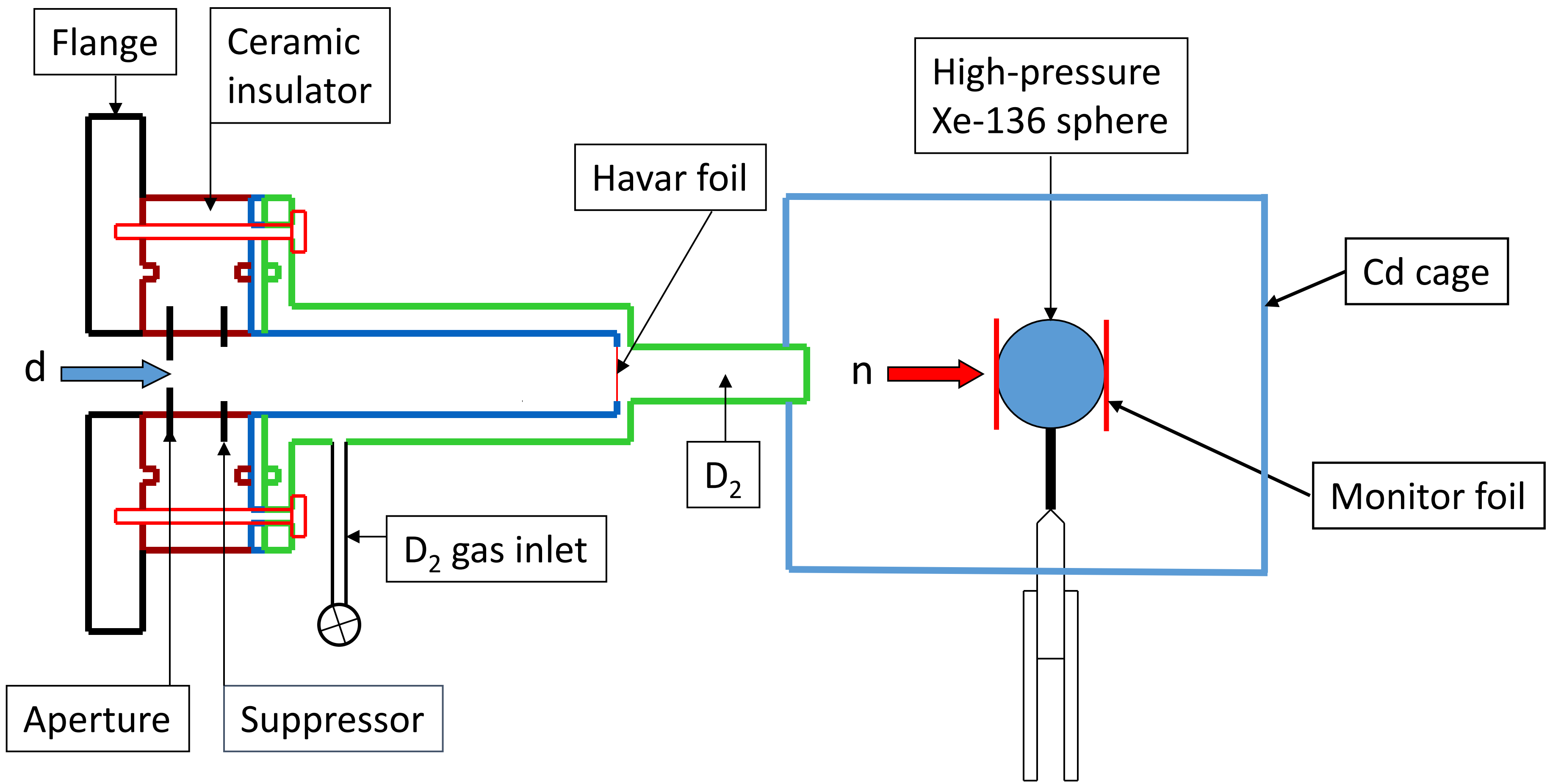

DENIS II
Atomic Beam
Polarized-Ion
Source
FN TANDEM
10 MV
MAGNET
#1
MAGNET
#2
MAGNET
#3
BEAM TRANSPORT
TOF Room

$^{3}H(p,n)^{3}He$ & $^{3}H(d,n)^{4}He$



Thanks to R. Reifarth for providing the argon cell

$^{2}H(d,n)^{3}He$



Thanks to C. Romig for providing the xenon cell

I. $^{40}Ar(n,\gamma)^{41}Ar$

1. GERDA: $0\nu\beta\beta$ decay search of ^{76}Ge @ LNGS

2. LBNE: Large-Baseline Neutrino Experiment @ DUSEL/SURF/Homestake mine in SD

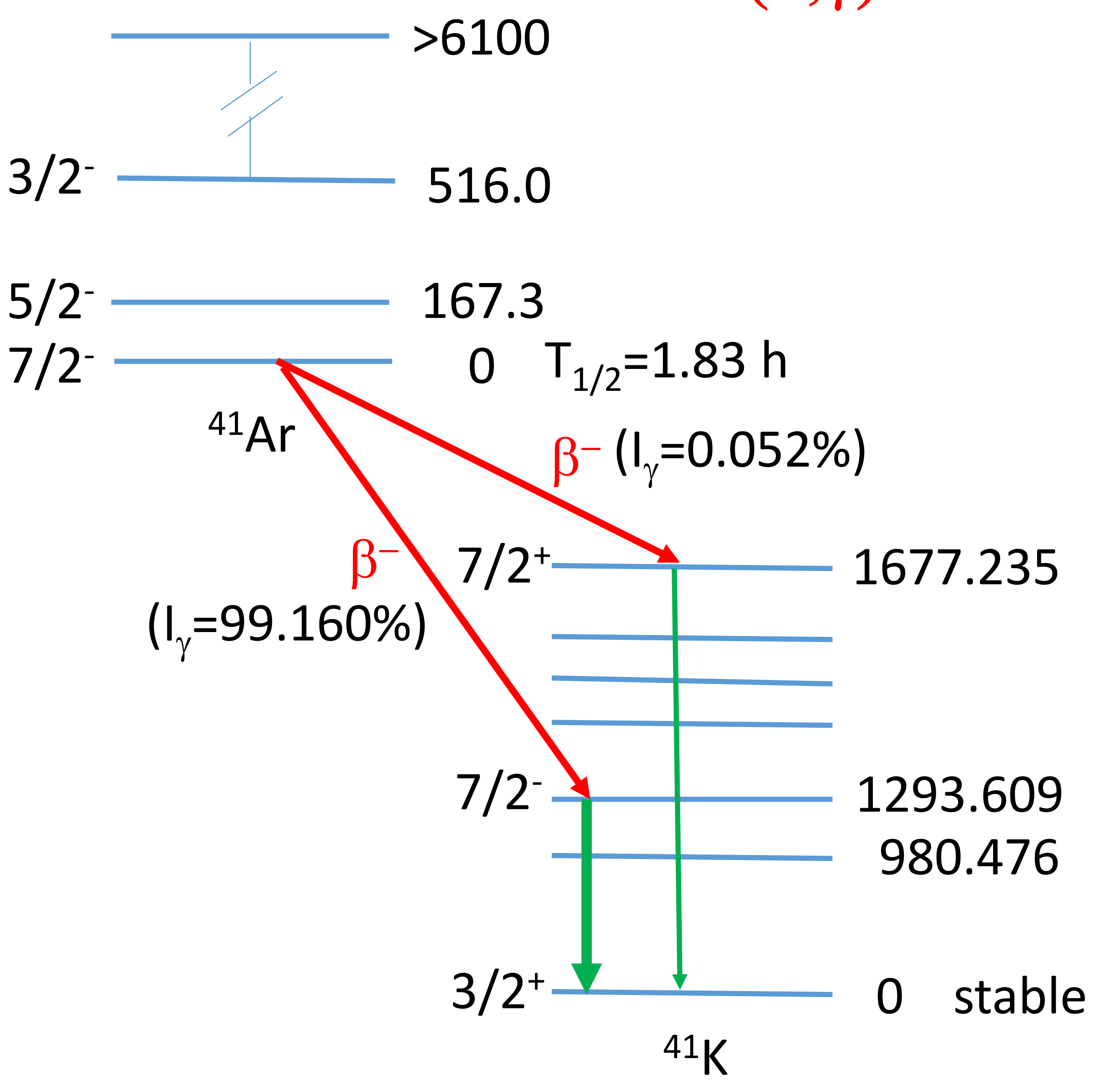
GERDA:
GERmanium
Detector
Array

LAr

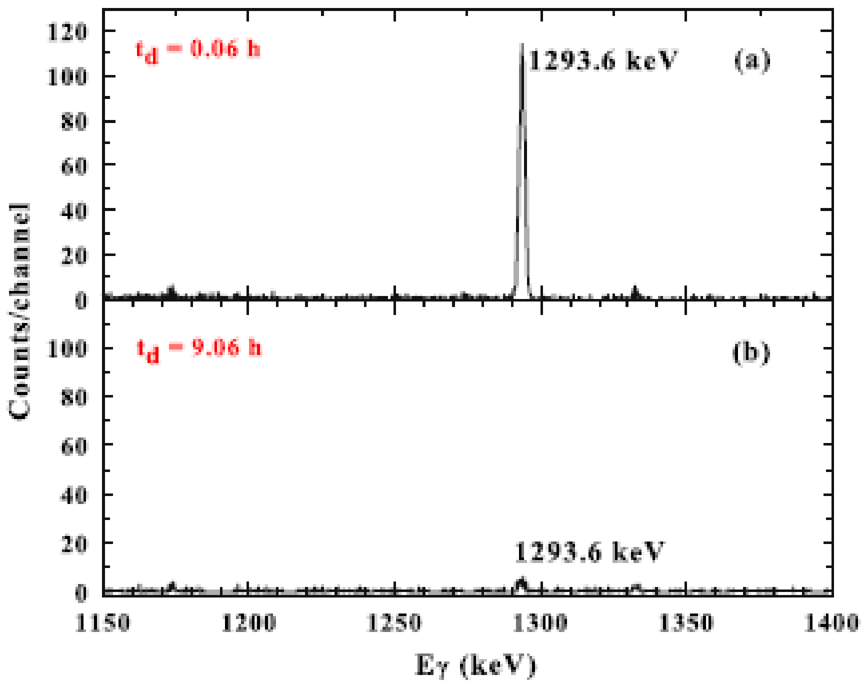
Enriched
HPGe
Detectors

$^{40}Ar(n,\gamma)^{41}Ar$

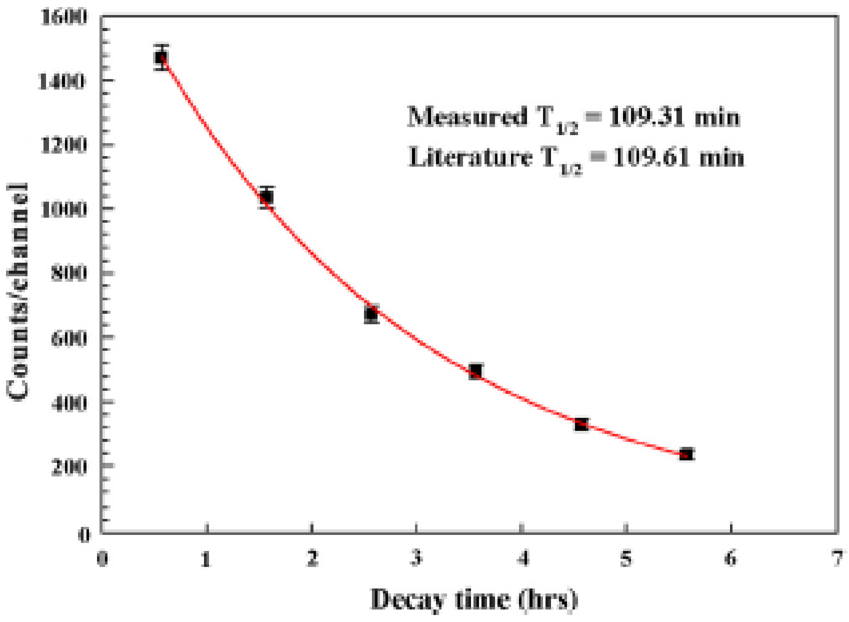
^{76}Ge: $0\nu\beta\beta$ Q-value: 2039 keV




CANBERRA



t_d = 0.06 h
1293.6 keV
(a)
t_d = 9.06 h
(b)
1293.6 keV
Counts/channel
Eγ (keV)
0
20
40
60
80
100
120
1150
1200
1250
1300
1350
1400

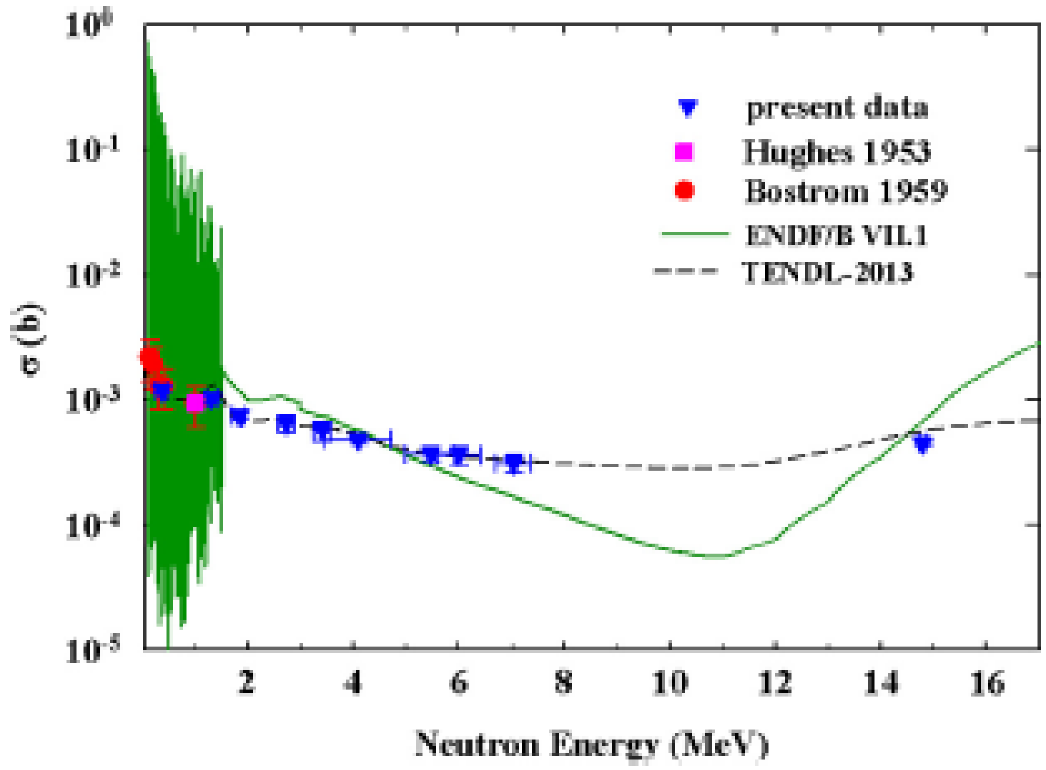

Measured $T_{1/2}$ = 109.31 min
Literature $T_{1/2}$ = 109.61 min
Counts/channel
Decay time (hrs)
0
200
400
600
800
1000
1200
1400
1600
0
1
2
3
4
5
6
7

Indium and gold monitor foils for neutron flux determination

Activation formula

$$\phi_{\mathrm{n}} = \frac{A_{\mathrm{m}}\lambda_{\mathrm{m}}}{N_{\mathrm{m}}\sigma_{\mathrm{m}}\epsilon_{\mathrm{m}}I_{\gamma\mathrm{m}}(1-e^{-\lambda_{\mathrm{m}}t_i})e^{-\lambda_{\mathrm{m}}t_d}(1-e^{-\lambda_{\mathrm{m}}t_{\mathrm{m}}})},$$

$$\sigma_{Ar} = \frac{A_{\mathrm{Ar}}\lambda_{\mathrm{Ar}}}{N_{\mathrm{Ar}}\phi_{\mathrm{n}}\epsilon_{\mathrm{Ar}}I_{\gamma\mathrm{Ar}}(1-e^{-\lambda_{\mathrm{Ar}}t_i})e^{-\lambda_{\mathrm{Ar}}t_d}(1-e^{-\lambda_{\mathrm{Ar}}t_{\mathrm{m}}})}$$



Megha Bhike, B. Fallin, W. Tornow, Phys. Lett. B 736, 316 (2014)

II. $^{74,76}Ge(n,\gamma)^{75,77}Ge$

1. GERDA $0\nu\beta\beta$ of ^{76}Ge
2. MAJORANA $0\nu\beta\beta$ of ^{76}Ge

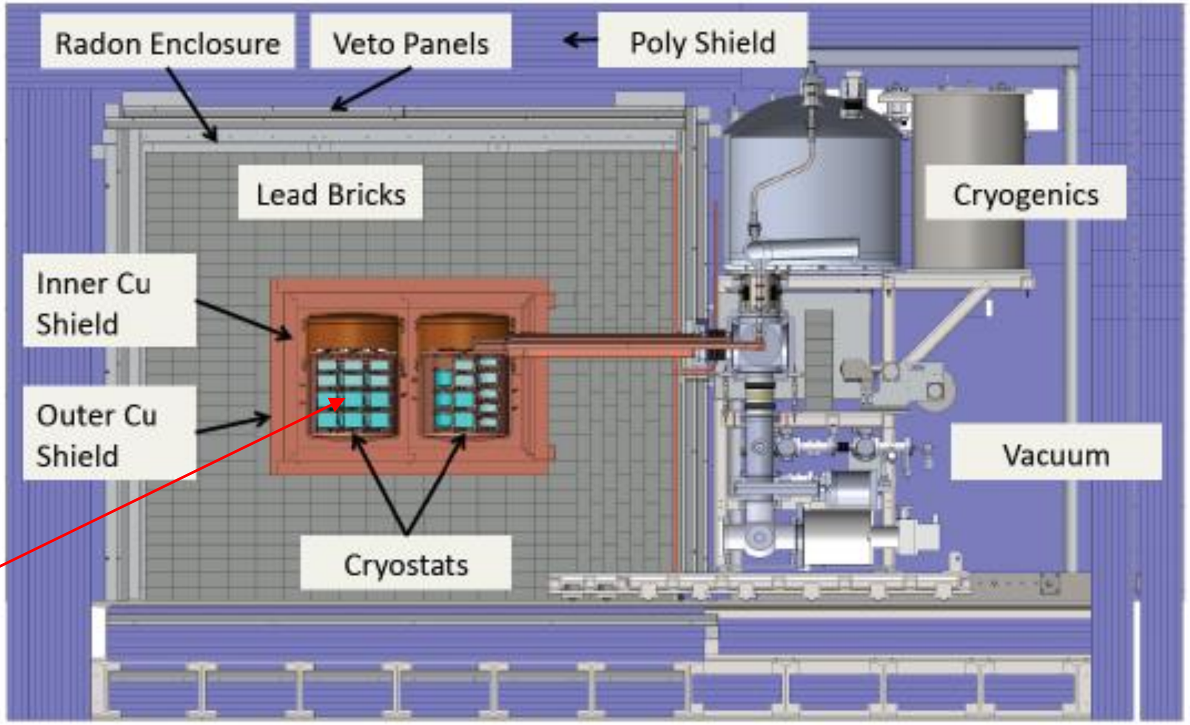
Q=2039 keV

86% ^{76}Ge and 14% ^{74}Ge

GERDA:
GERmanium
Detector
Array

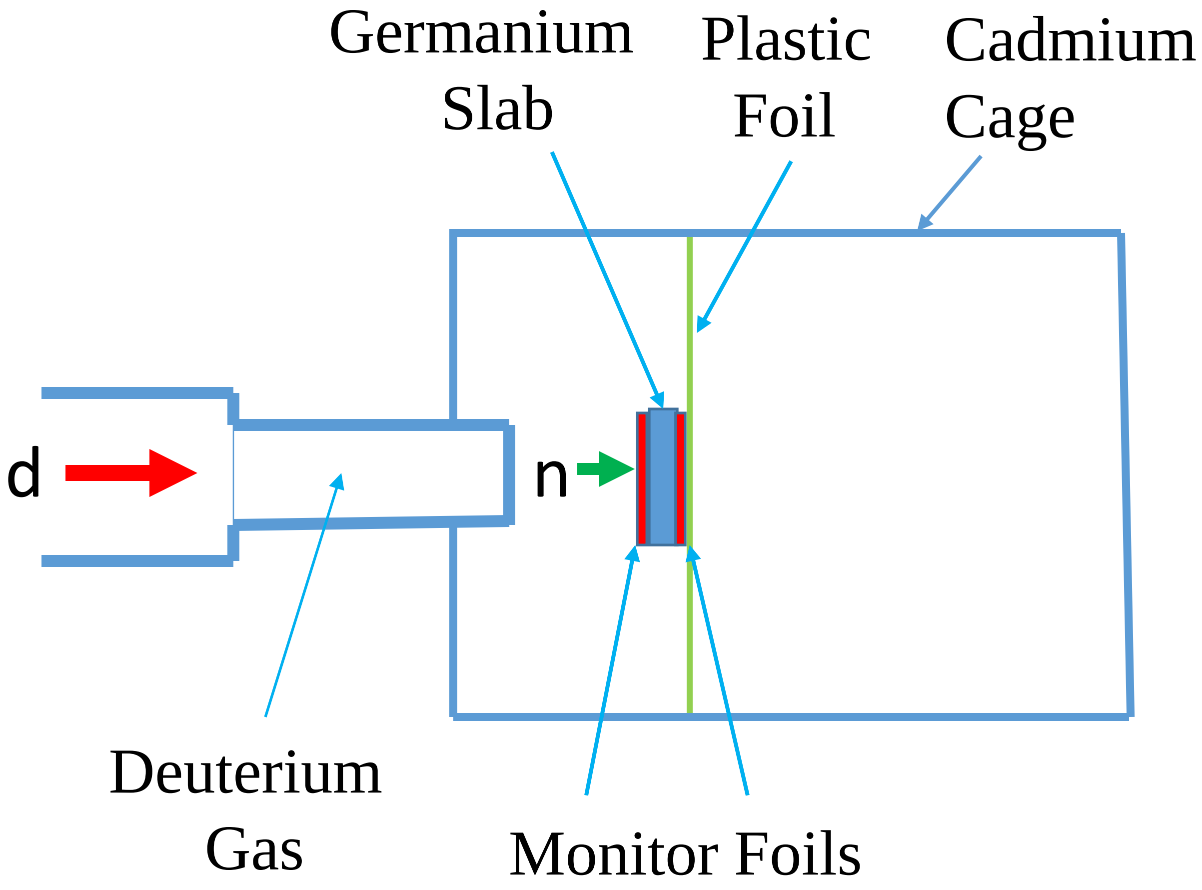
LAr

Enriched
HPGe
Detectors

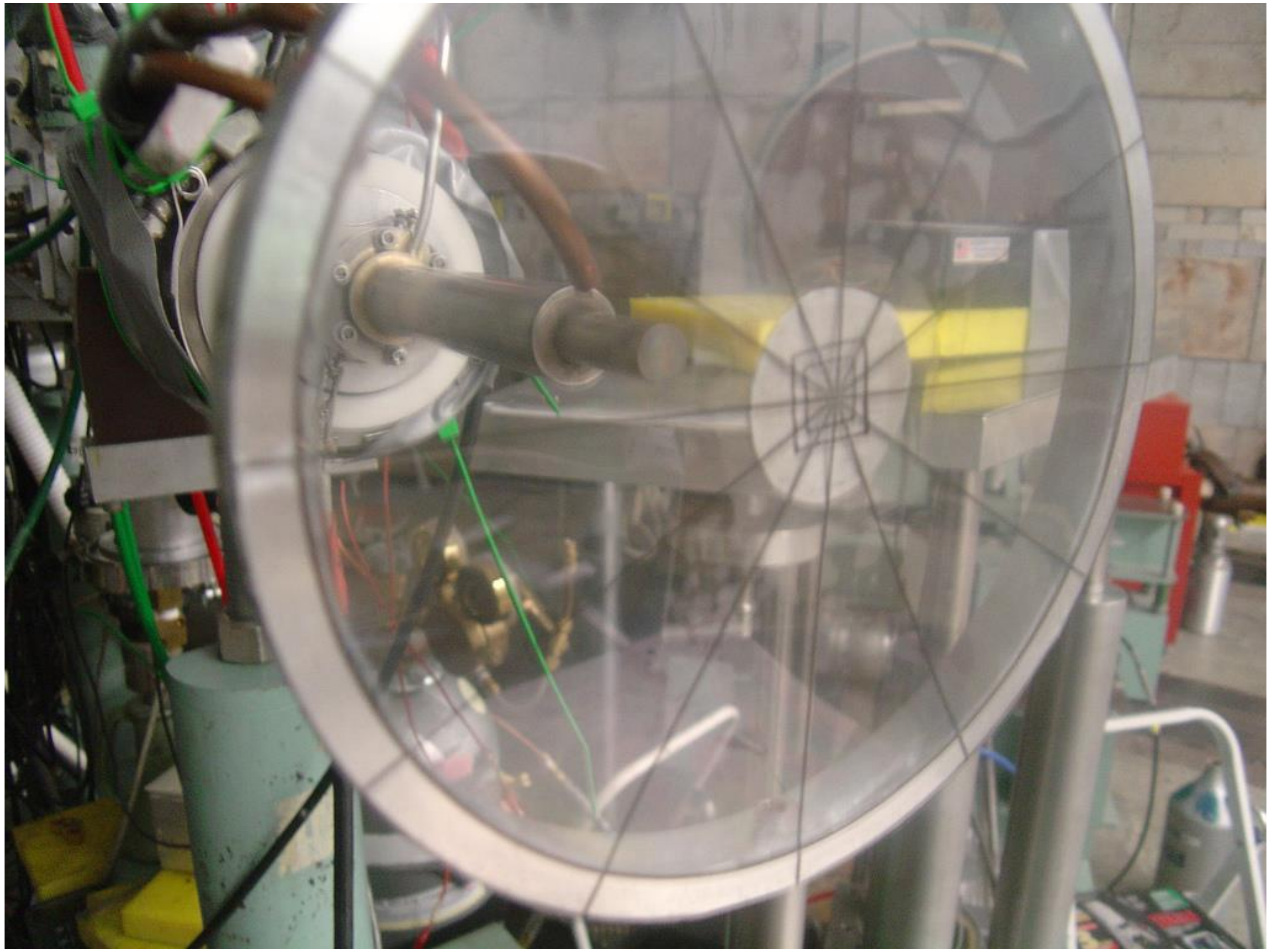


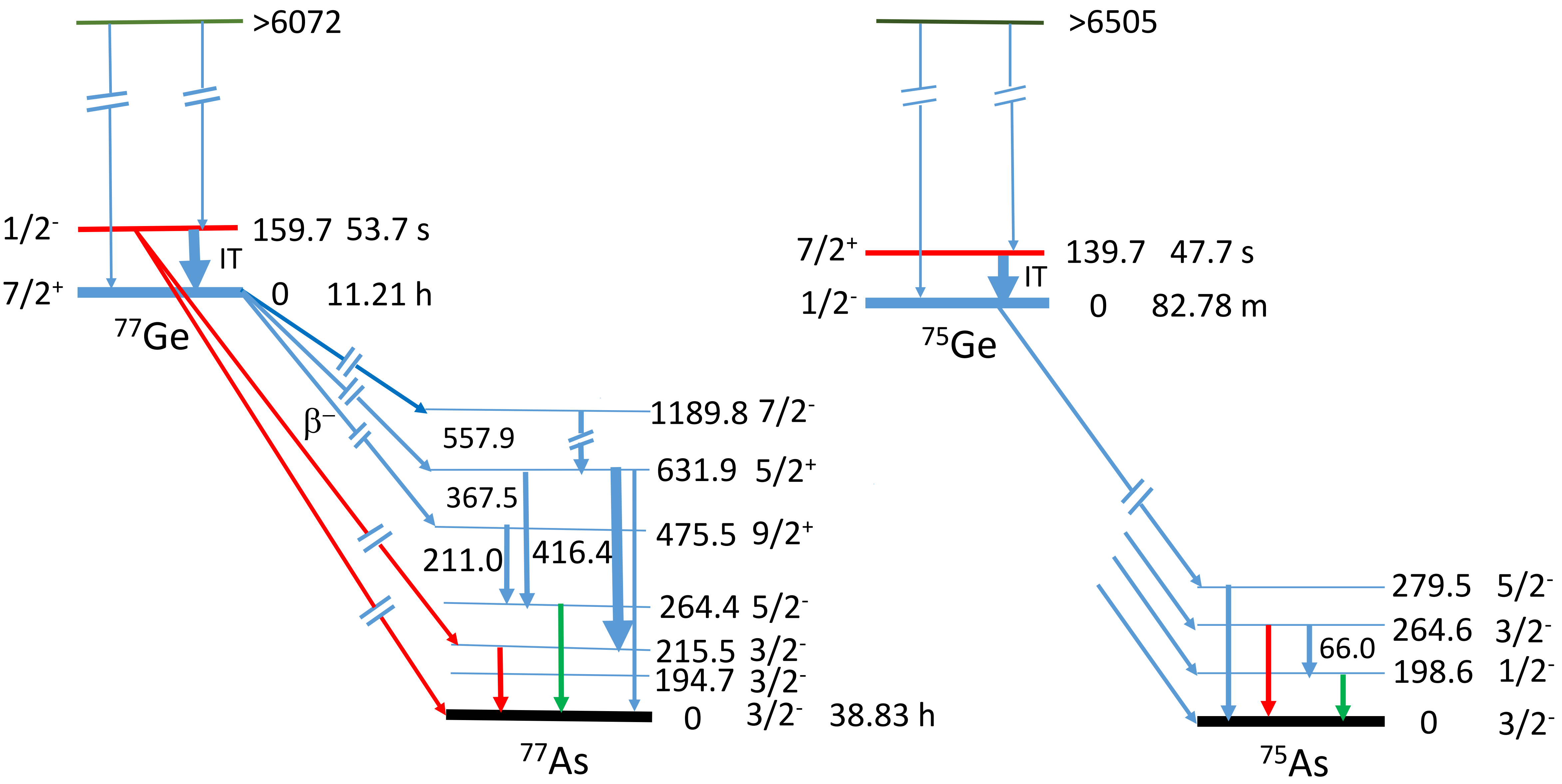
Enriched
HPGe
Detectors

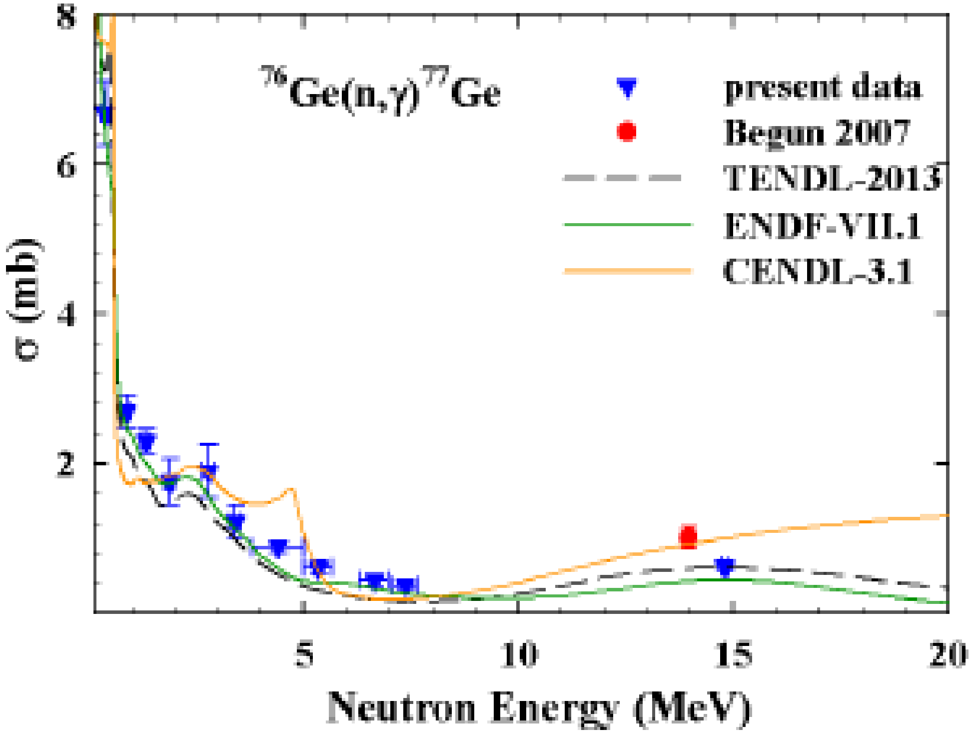
MAJORANA DEMONSTRATOR @ SURF

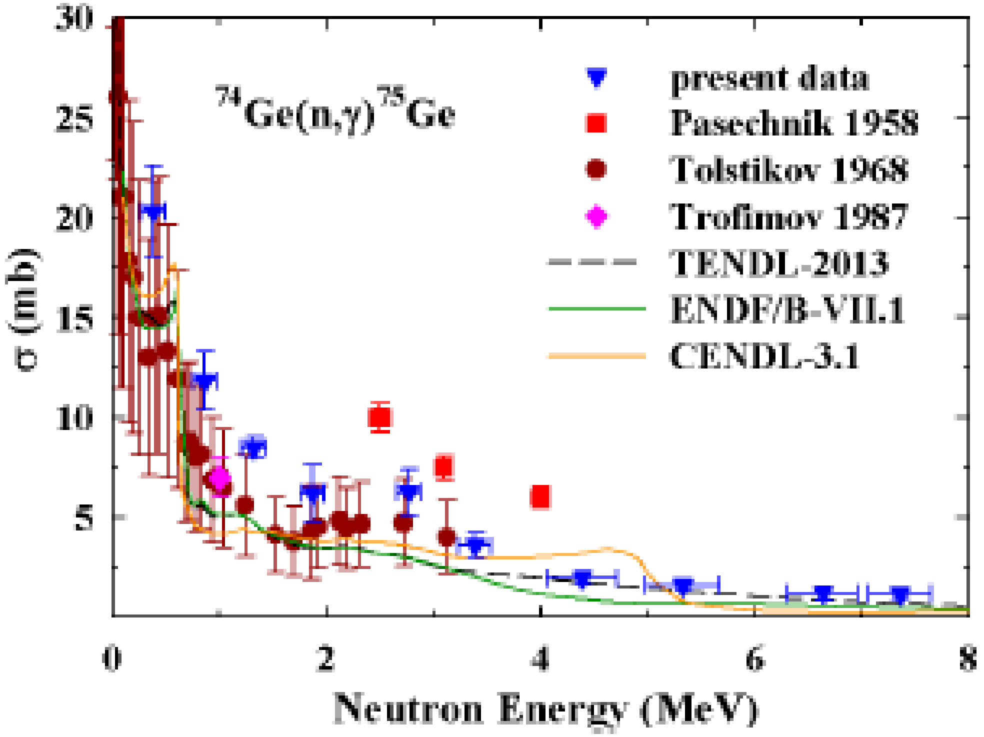


10 mm x 10 mm x 2 mm slabs of GERDA and MAJORANA Germanium




>6072
1/2-
159.7 53.7 s
IT
7/2+
0 11.21 h
77Ge
β−
1189.8 7/2-
557.9
631.9 5/2+
367.5
475.5 9/2+
211.0
416.4
264.4 5/2-
215.5 3/2-
194.7 3/2-
0 3/2- 38.83 h
77As
>6505
7/2+
139.7 47.7 s
IT
1/2-
0 82.78 m
75Ge
279.5 5/2-
264.6 3/2-
66.0
198.6 1/2-
0 3/2-
75As





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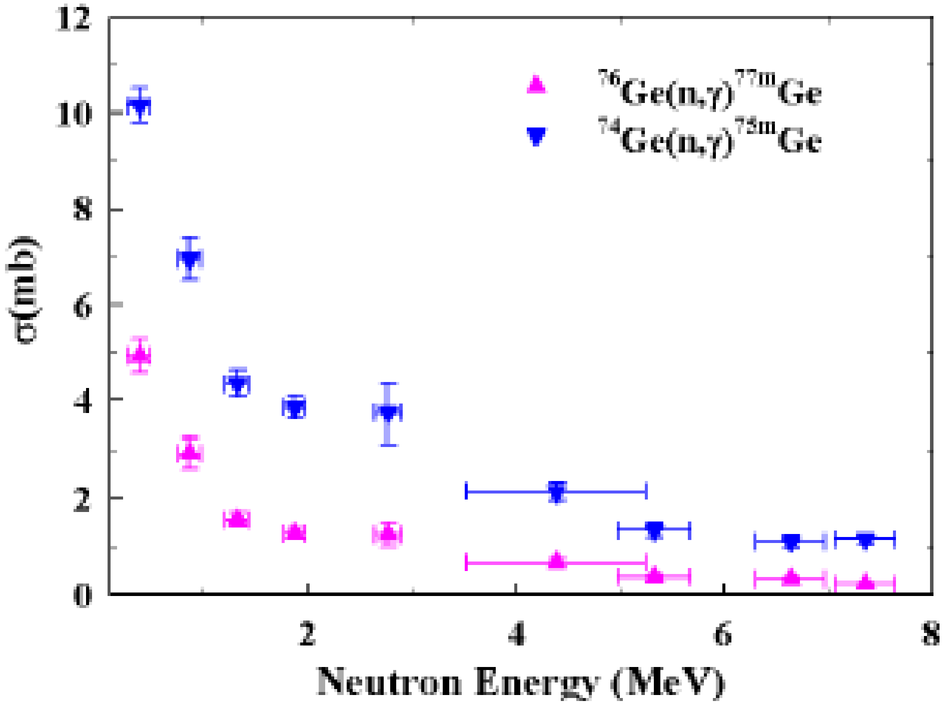


12
10
8
6
4
2
0
σ(mb)
2
4
6
8
Neutron Energy (MeV)
76Ge(n,γ)77mGe
74Ge(n,γ)75mGe

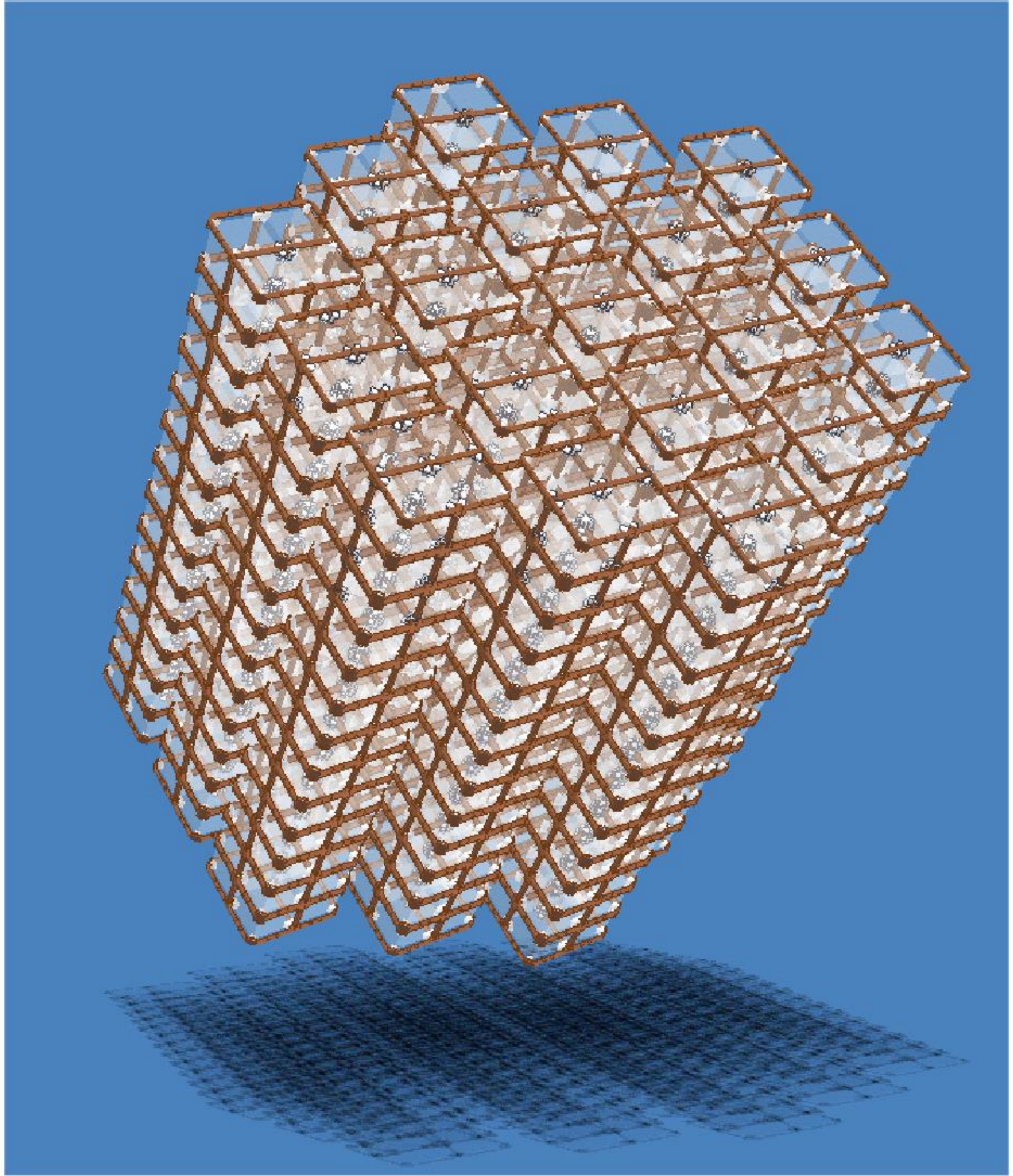
III. $^{128,130}Te(n,\gamma)^{129,131}Te$

1. CUORE: Cryogenic Underground Observatory for Rare Events @ LNGS

2. SNO+: Sudbury Neutrino Observatory @ Creighton mine in Sudbury, Ontario, Canada

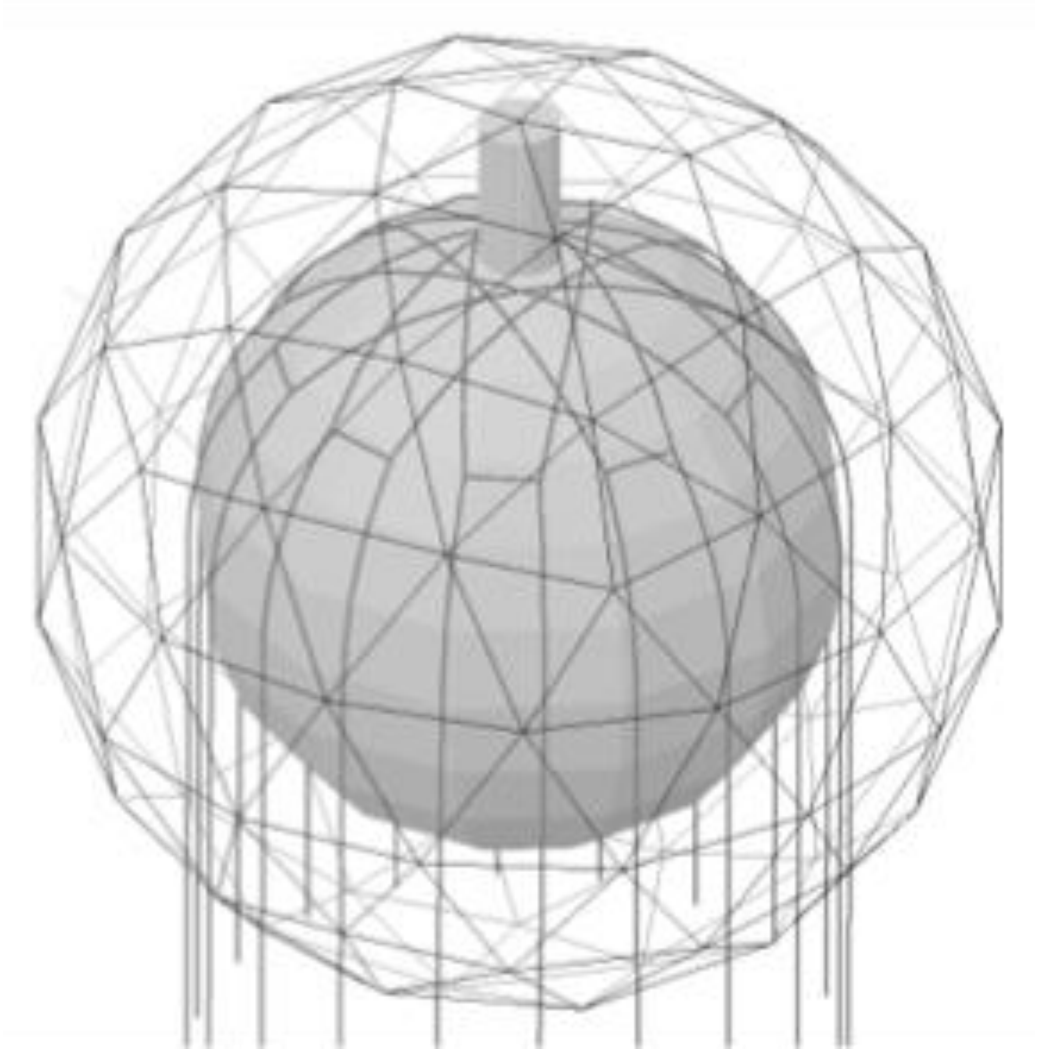
$0\nu\beta\beta$ of ^{128}Te and ^{130}Te Q=867 keV and 2528 keV

Using Tellurium of natural abundance: 31.7% ^{128}Te and 34.1% ^{130}Te



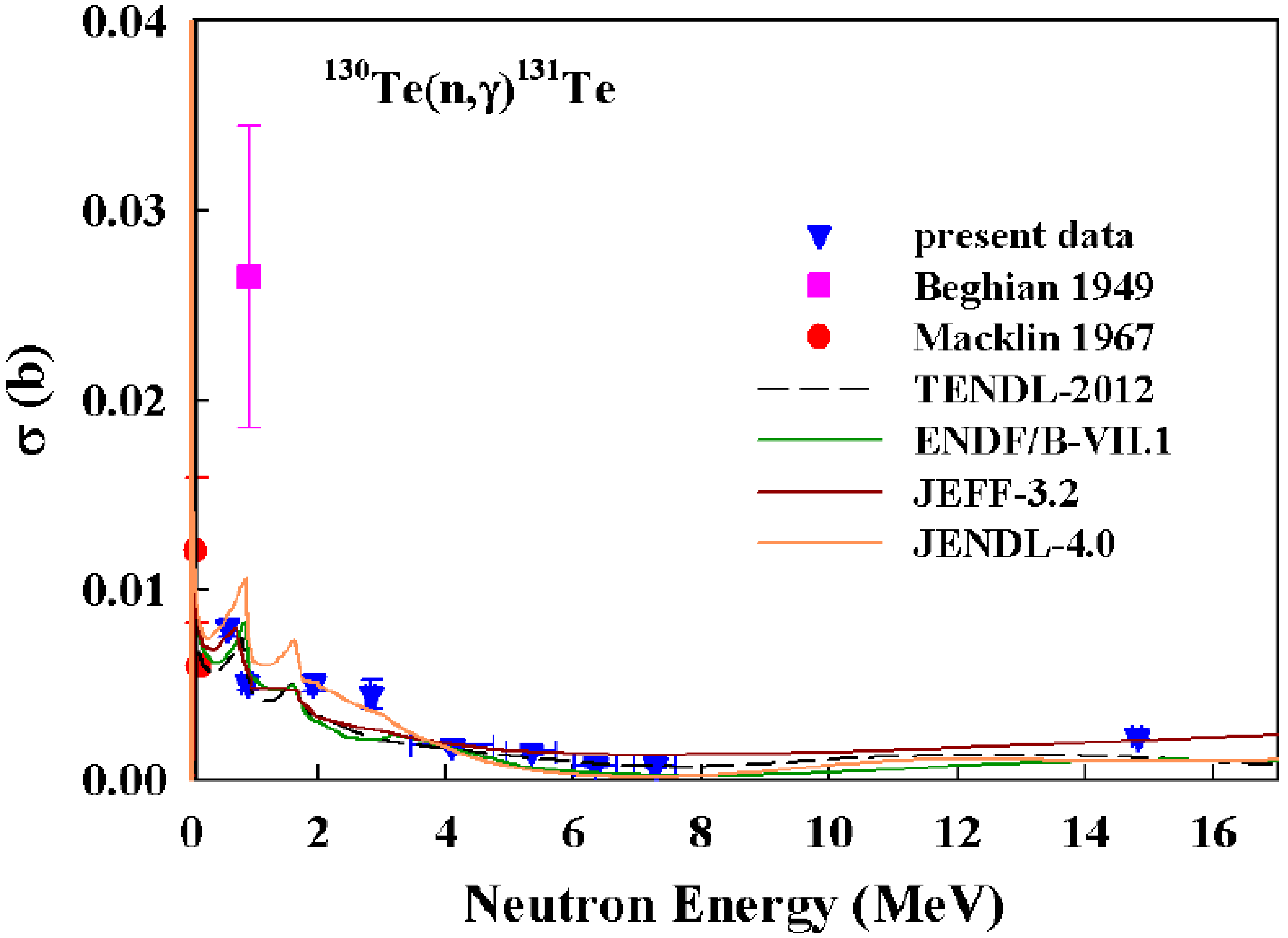
CUORE

988 750 g TeO_2 bolometers

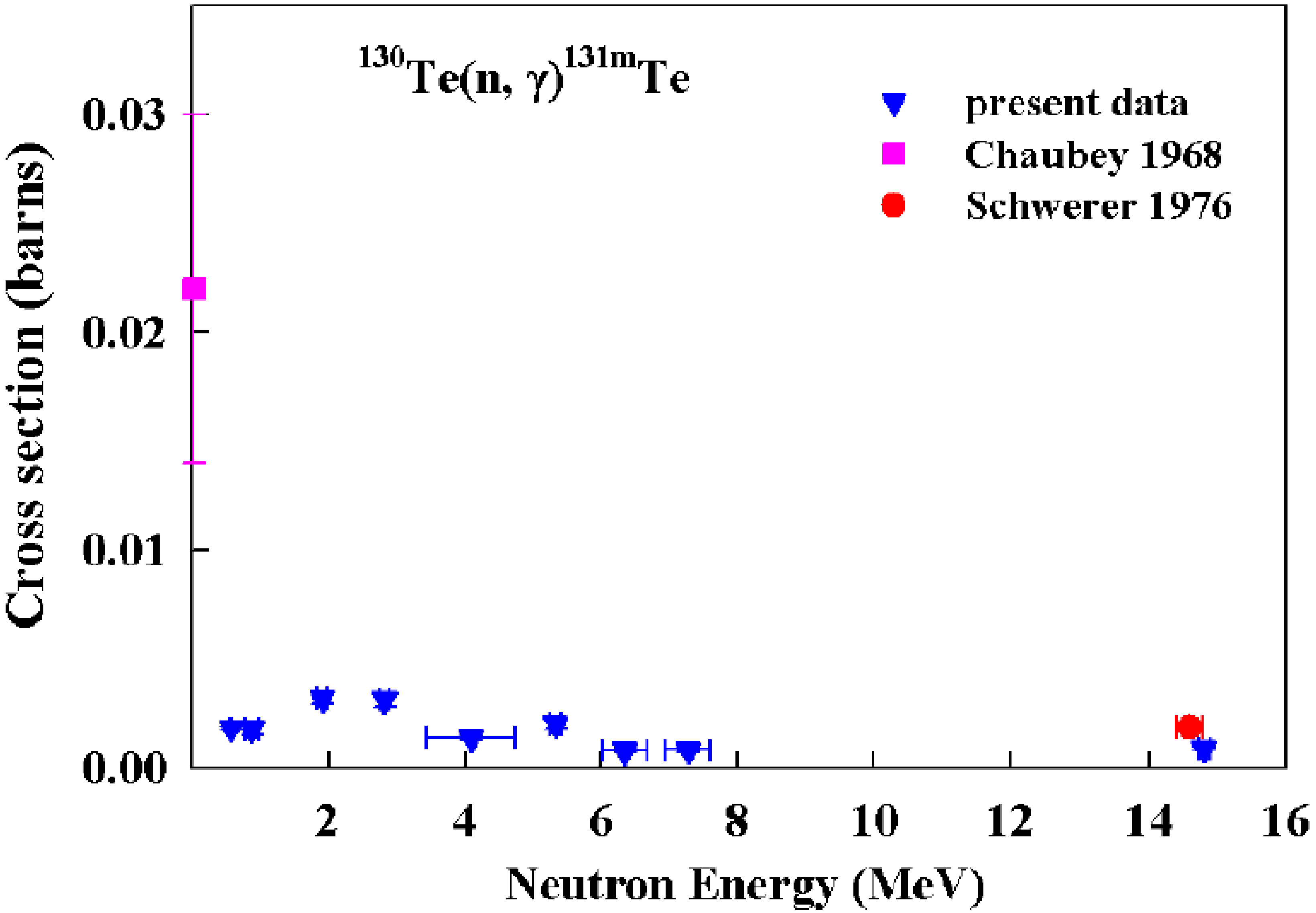


SNO+

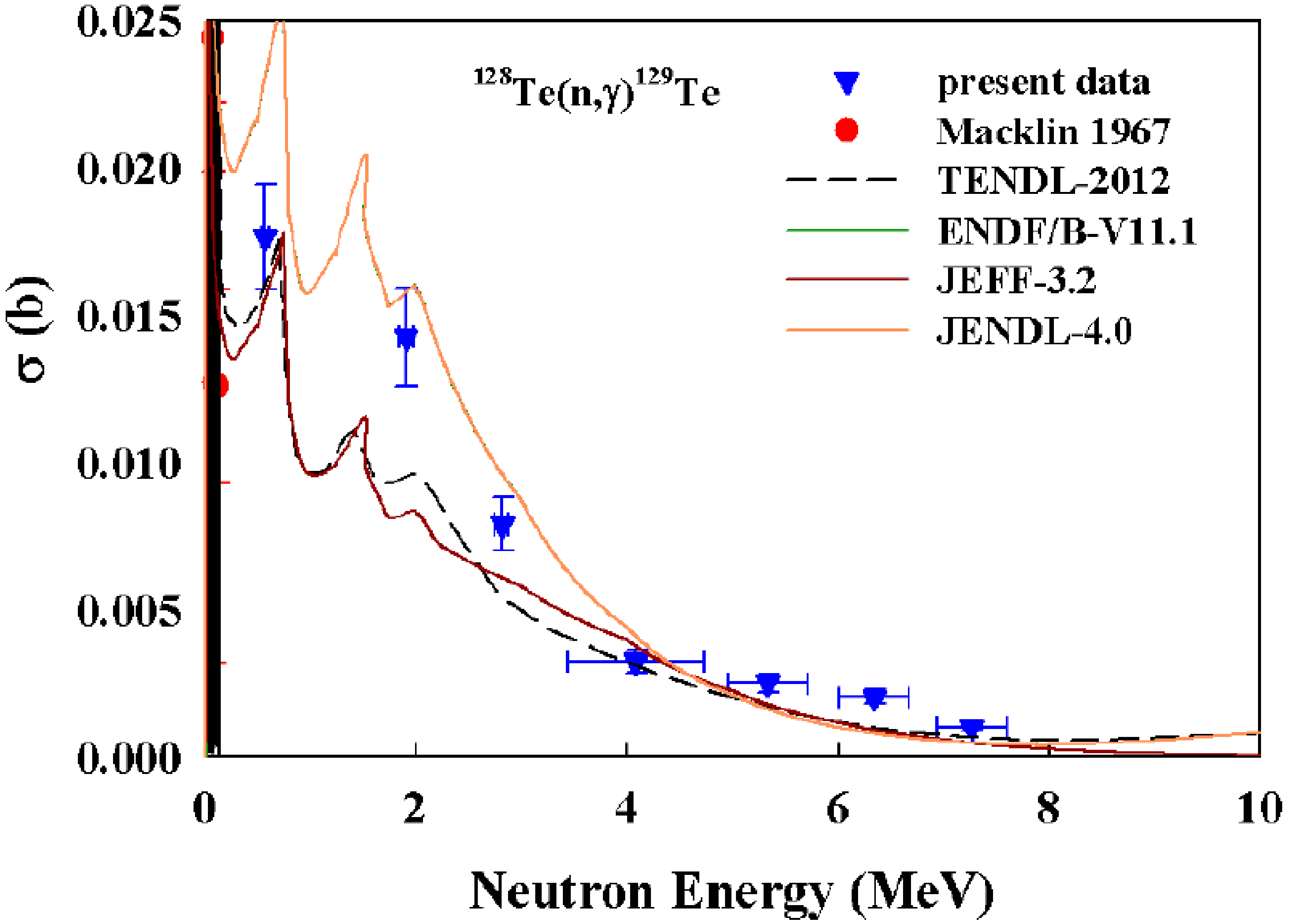
Tellurium loaded
Liquid Scintillator



$^{130}Te(n,\gamma)^{131}Te$
present data
Beghian 1949
Macklin 1967
TENDL-2012
ENDF/B-VII.1
JEFF-3.2
JENDL-4.0
σ (b)
Neutron Energy (MeV)
0.04
0.03
0.02
0.01
0.00
0
2
4
6
8
10
12
14
16



$^{130}Te(n, \gamma)^{131m}Te$
present data
Chaubey 1968
Schwerer 1976
Cross section (barns)
0.00
0.01
0.02
0.03
Neutron Energy (MeV)
2
4
6
8
10
12
14
16



$^{128}Te(n,\gamma)^{129}Te$
present data
Macklin 1967
TENDL-2012
ENDF/B-V11.1
JEFF-3.2
JENDL-4.0
σ (b)
0.025
0.020
0.015
0.010
0.005
0.000
0
2
4
6
8
10
Neutron Energy (MeV)

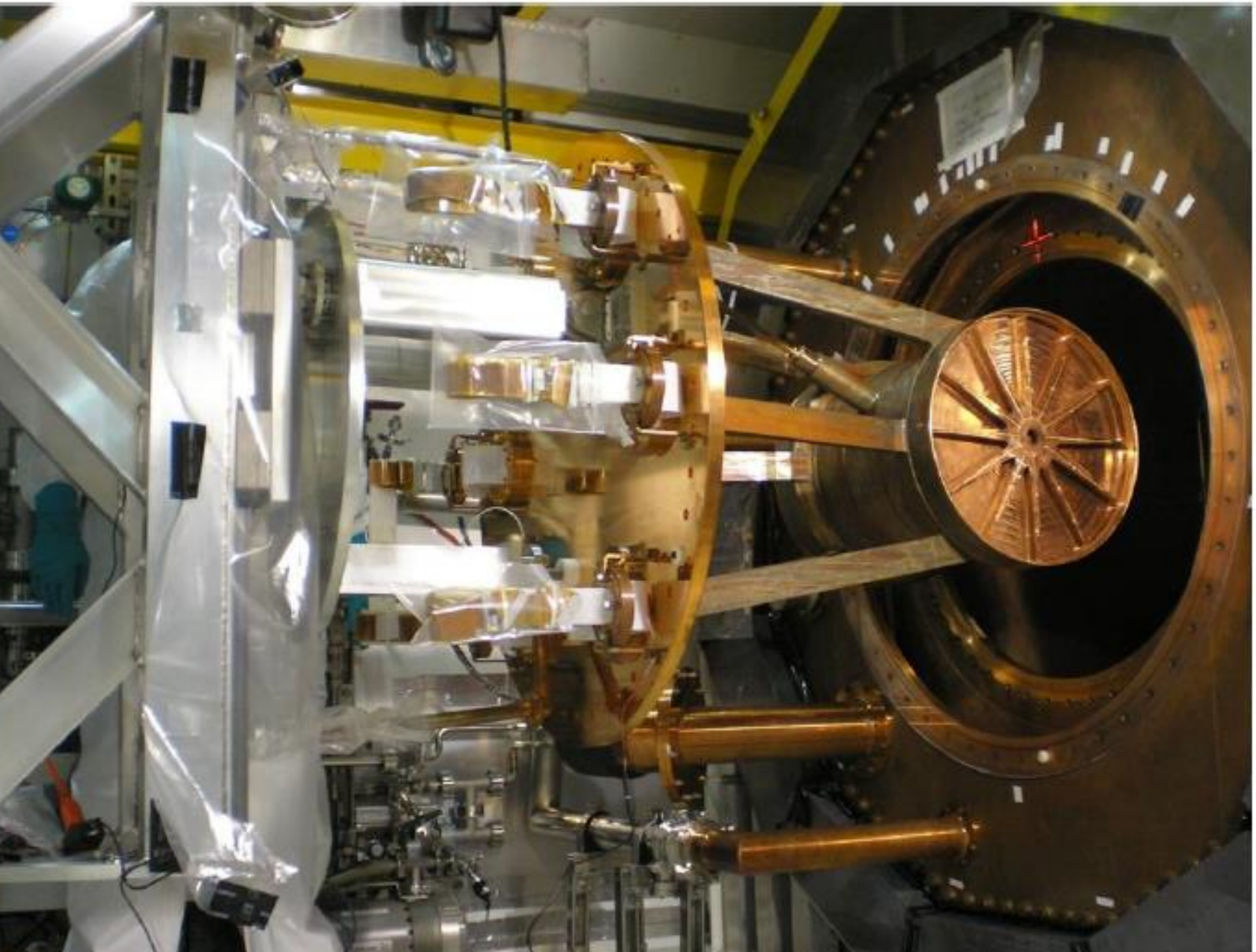
IV. $^{136}Xe(n,\gamma)^{137}Xe$

1. EXO-200: Enriched Xenon Observatory

2. KamLAND-Zen: Kamioka Liquid scintillator AntiNeutrino Detector-Zero neutrino

$0\nu\beta\beta$ of ^{136}Xe Q=2458 keV

EXO-200: 80.6% enriched in ^{136}Xe
KamLAND-Zen: 91.0% enriched in ^{136}Xe

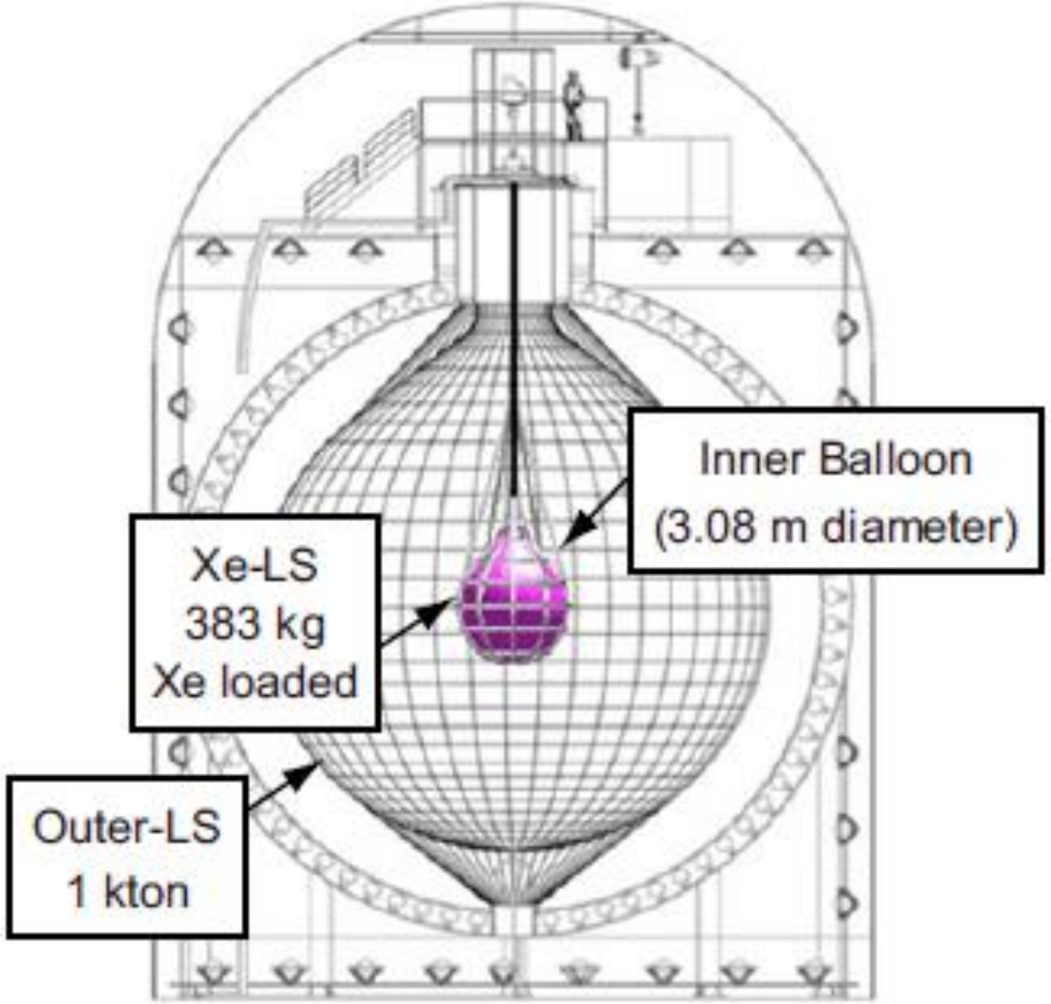


EXO-200

Xenon-based Time-Projection – Chamber

FV: 76.3 kg of ^{136}Xe

Waste Isolation Pilot Plant (WIPP) in Carlsbad, NM, USA

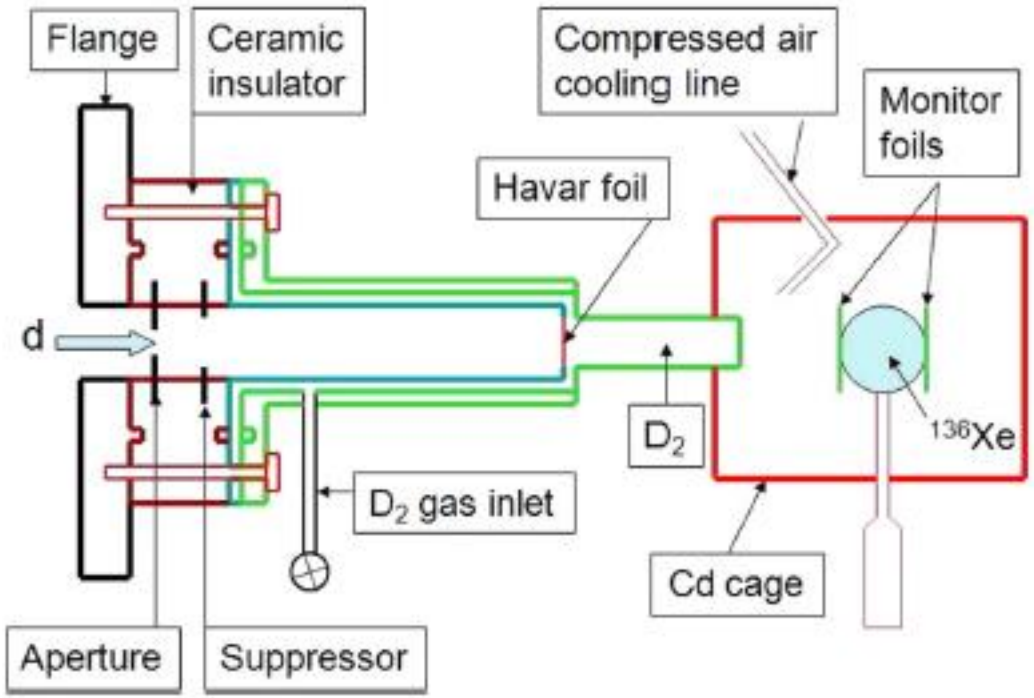


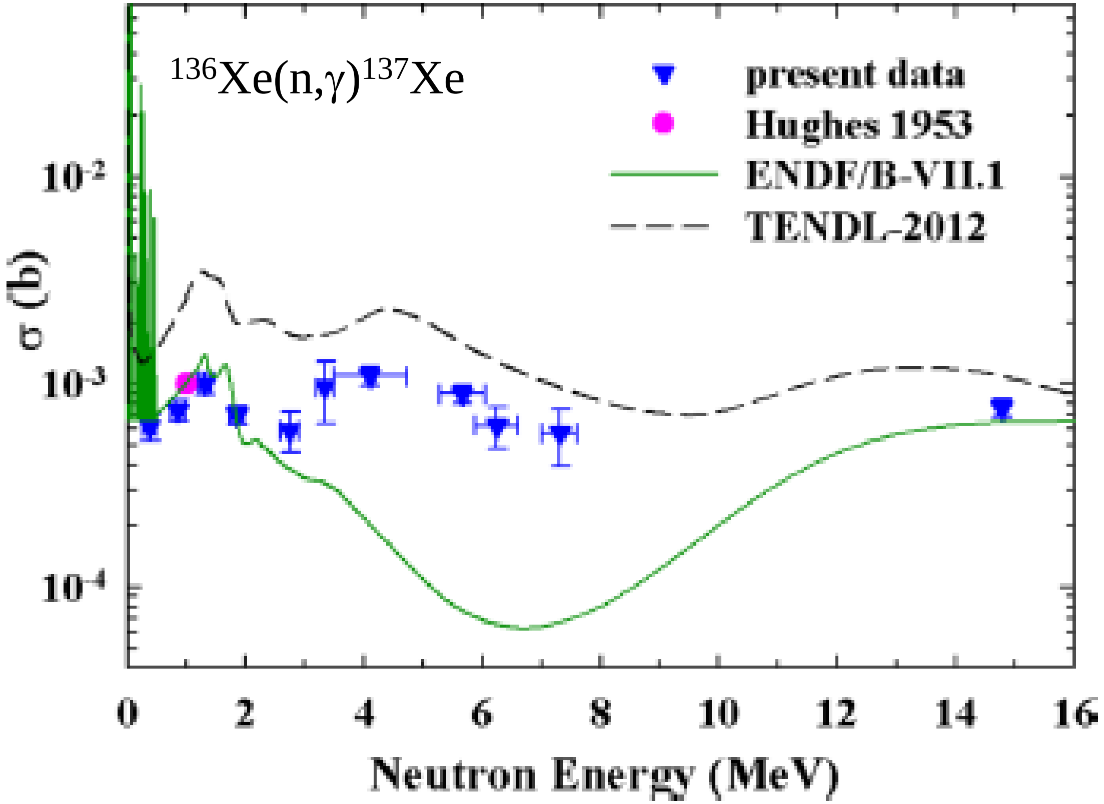
KamLAND-Zen

Xenon-loaded Liquid Scintillator

FV: 179 kg of ^{136}Xe

Kamioka Mine, Japan


Flange
Ceramic insulator
Compressed air cooling line
Monitor foils
Havar foil
d
D_2
^{136}Xe
D_2 gas inlet
Cd cage
Aperture
Suppressor



Megha Bhike and W. Tornow, Phys. Rev. C **89**, 031602(R) (2014)

Near Future

^{40}Ar(n,p)^{40}Cl: published

^{136}Xe(n,2n)^{135}Xe: published

^{76}Ge(n,2n)^{75}Ge: data taking completed

^{128,130}Te(n,2n)^{127,129}Te: data taking completed

^{134}Xe(n,γ)^{135}Xe: not done yet

^{134}Xe(n,2n)^{133}Xe: not done yet

^{63,65}Cu(n,γ)^{64,66}Cu: not done yet

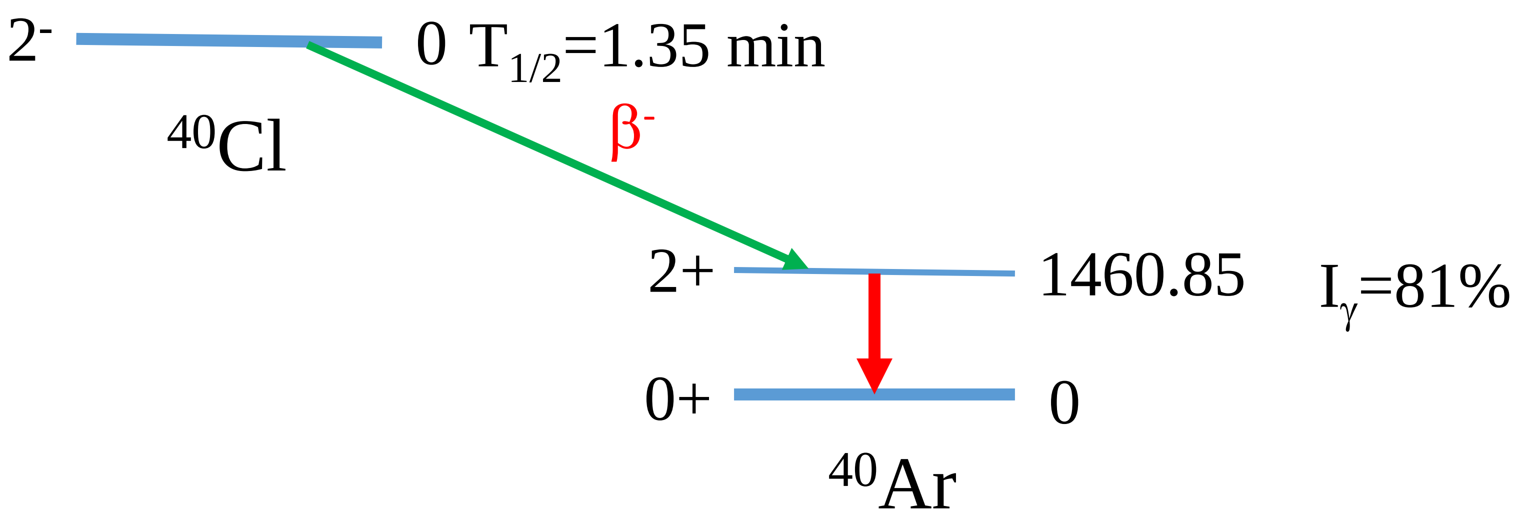
^{63,65}Cu(n,2n) ^{62,64}Cu: not done yet

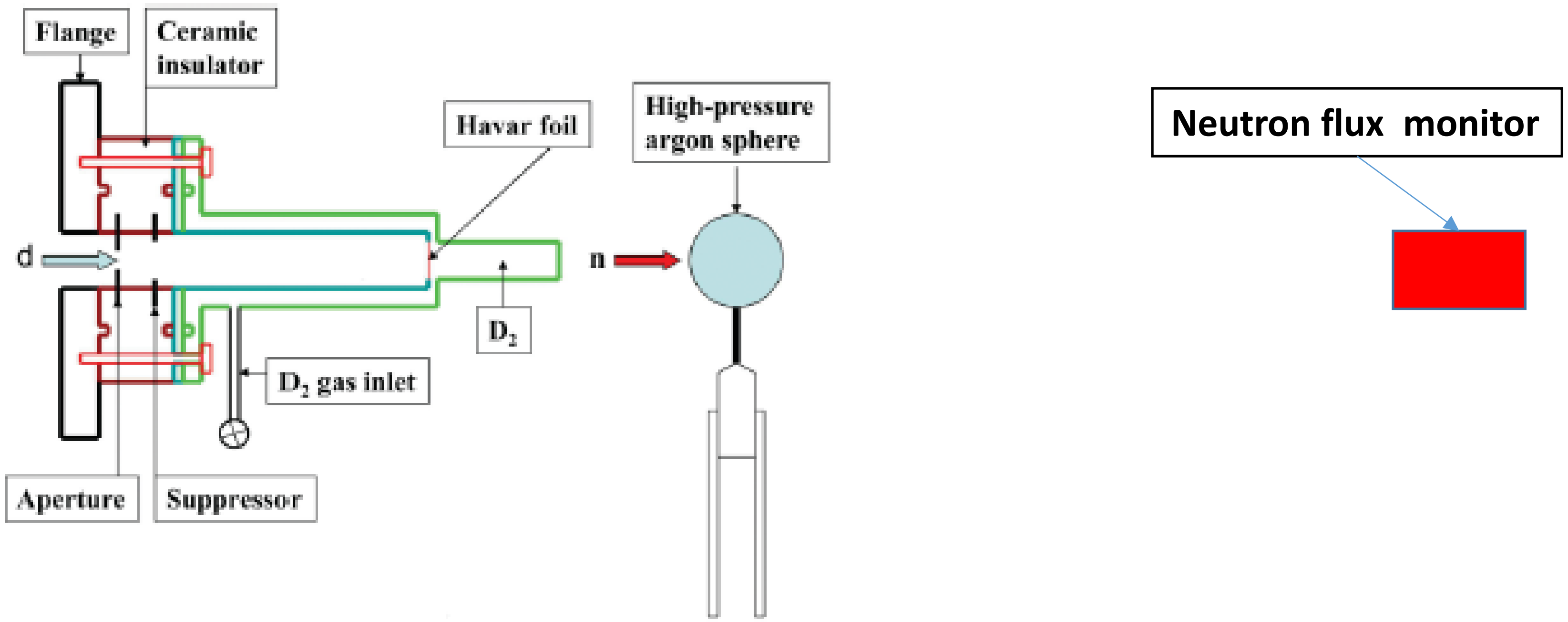
More Distant Future

Obtain (n,γ) data between 8 and 12 MeV

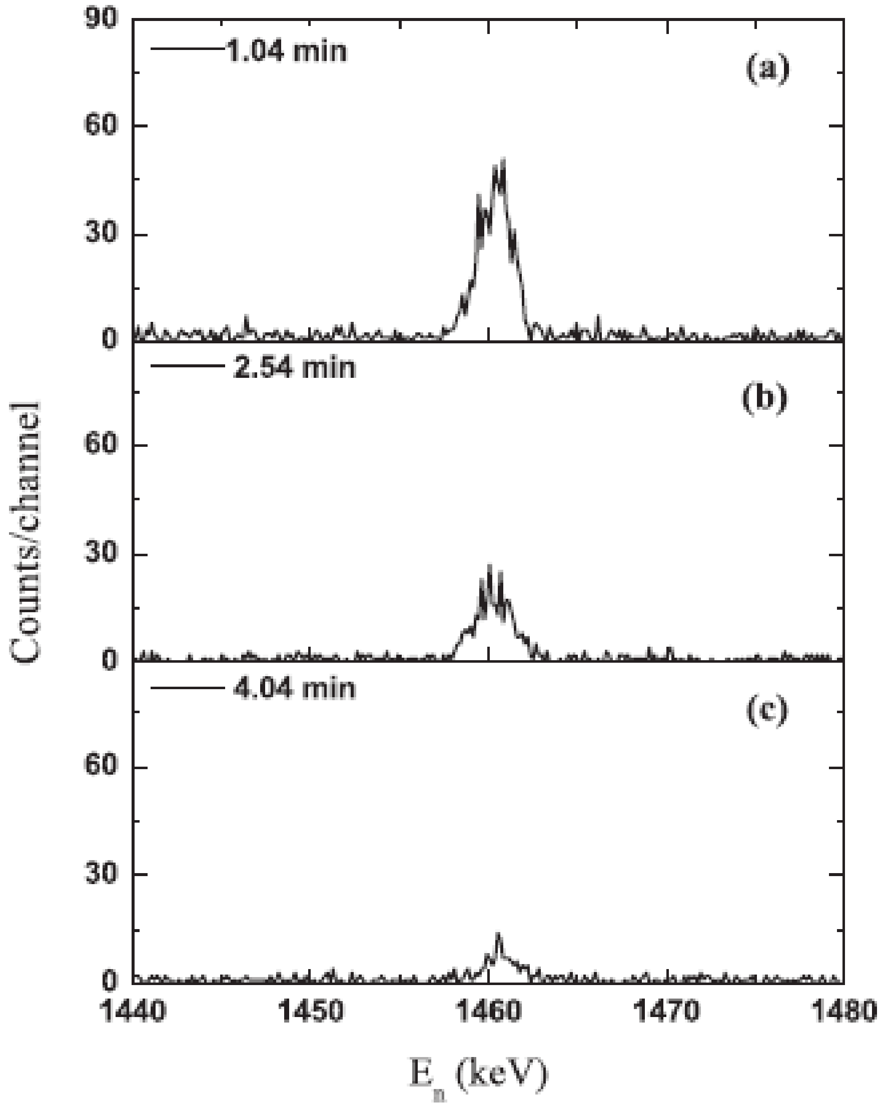
$^{40}Ar(n,p)^{40}Cl$

Q= –6.7 MeV

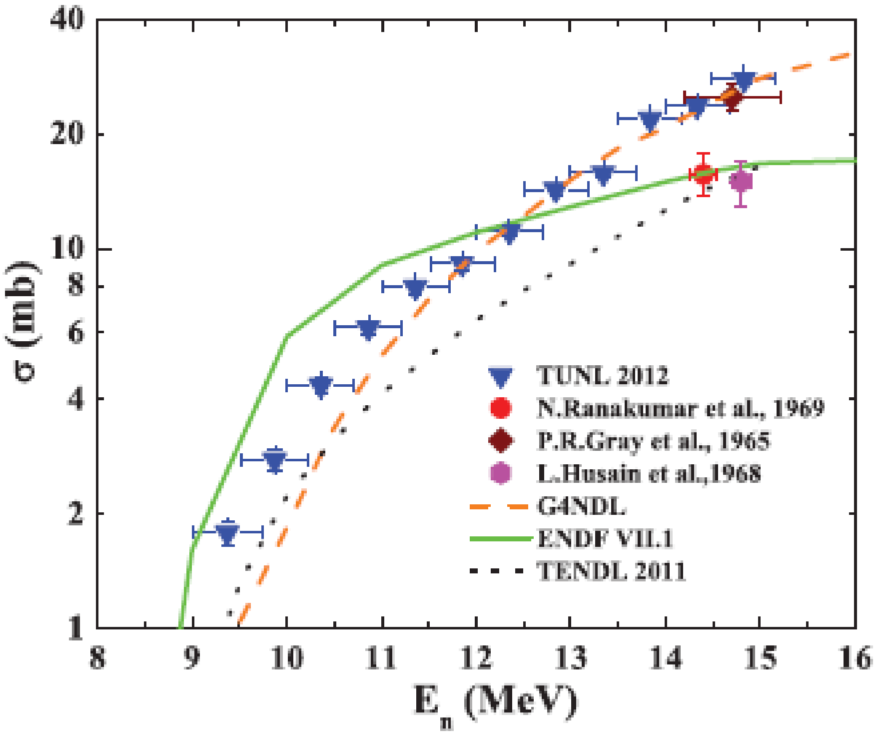




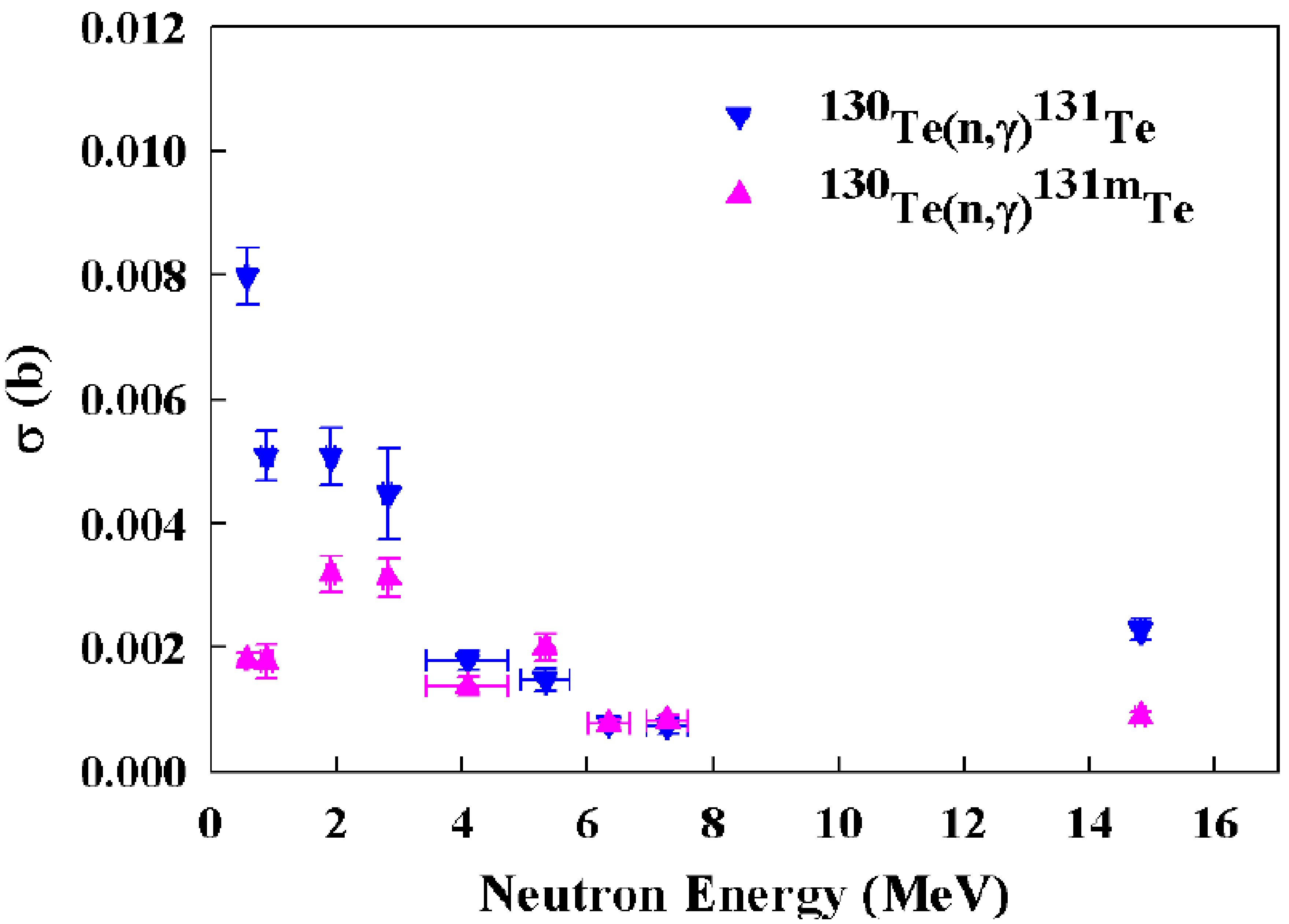
Half-life time too short for using monitor foils: used instead TOF and calibrated neutron monitor detector



1.04 min
(a)
2.54 min
(b)
4.04 min
(c)
Counts/channel
90
60
30
0
1440
1450
1460
1470
1480
E_n (keV)



C. Bhatia, S.W. Finch, M.E. Gooden and W.Tornow, Phys. Rev. C **86**, 041602(R) (2012)



0.012
0.010
0.008
0.006
0.004
0.002
0.000
σ (b)
0
2
4
6
8
10
12
14
16
Neutron Energy (MeV)
130Te(n,γ)131Te
130Te(n,γ)131mTe