Recent cross-section measurements of neutron-induced reactions of importance for background estimates in $0\nu\beta\beta$ searches

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&
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OUTLINE

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

II. $^{74,76}Ge(n,\gamma)^{75,77}Ge$, $^{76}Ge(n,2n)^{75}Ge$, $^{76}Ge(n,p)^{76}Ga$ and $^{74,76}Ge(n,n'\gamma)^{74,76}Ge$

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

IV. $^{136}Xe(n,\gamma)^{137}Xe$, $^{136}Xe(n,2n)^{135}Xe$ and $^{136}Xe(n,n'\gamma)^{136}Xe$

V. Future Experiments

Neutron energy range : 0.4 MeV to 14.8 MeV

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

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

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

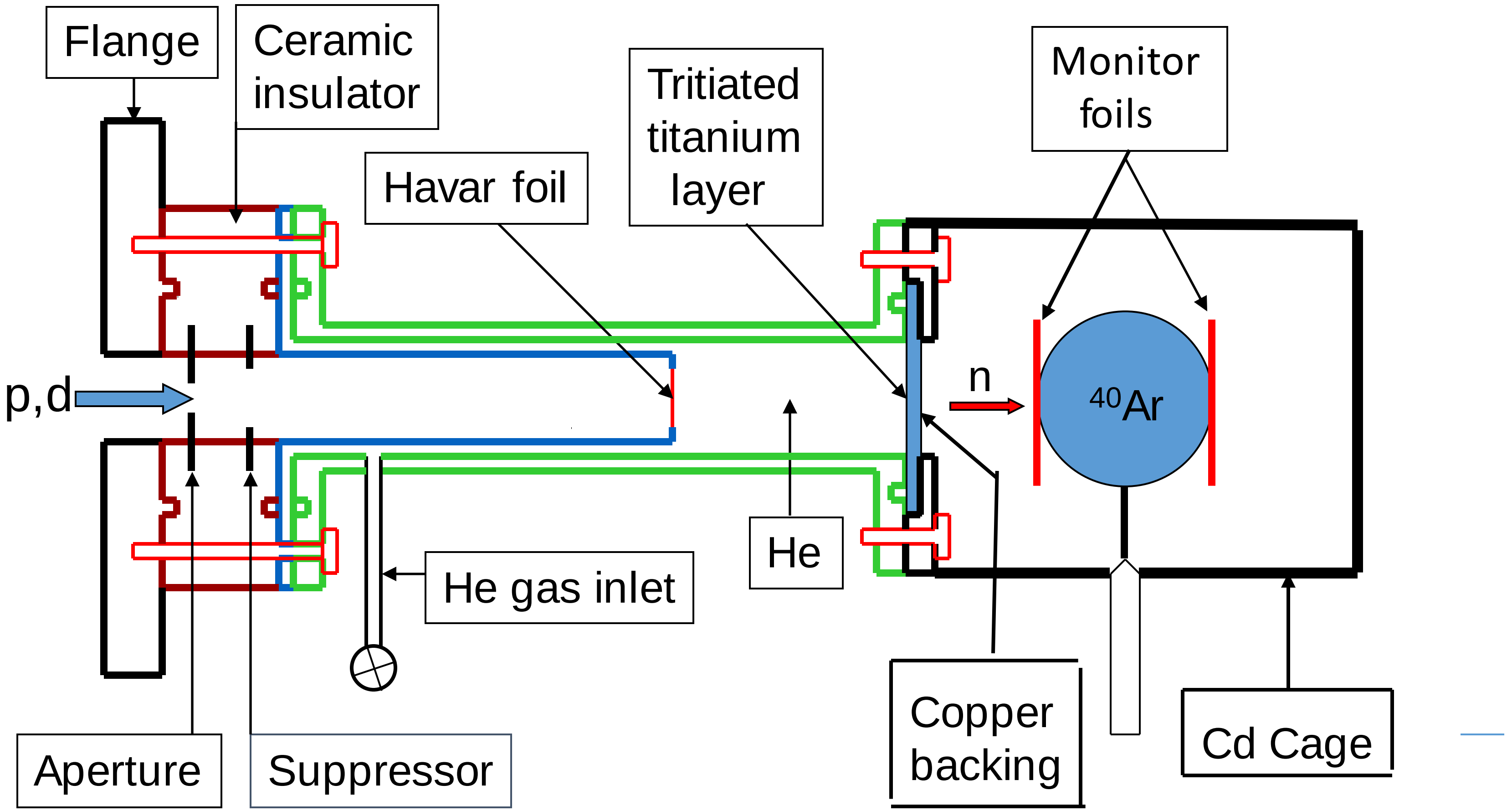
The spontaneous fission neutrons, basically from ^{238}U, are mainly below 3 MeV

Neutron Source Reactions

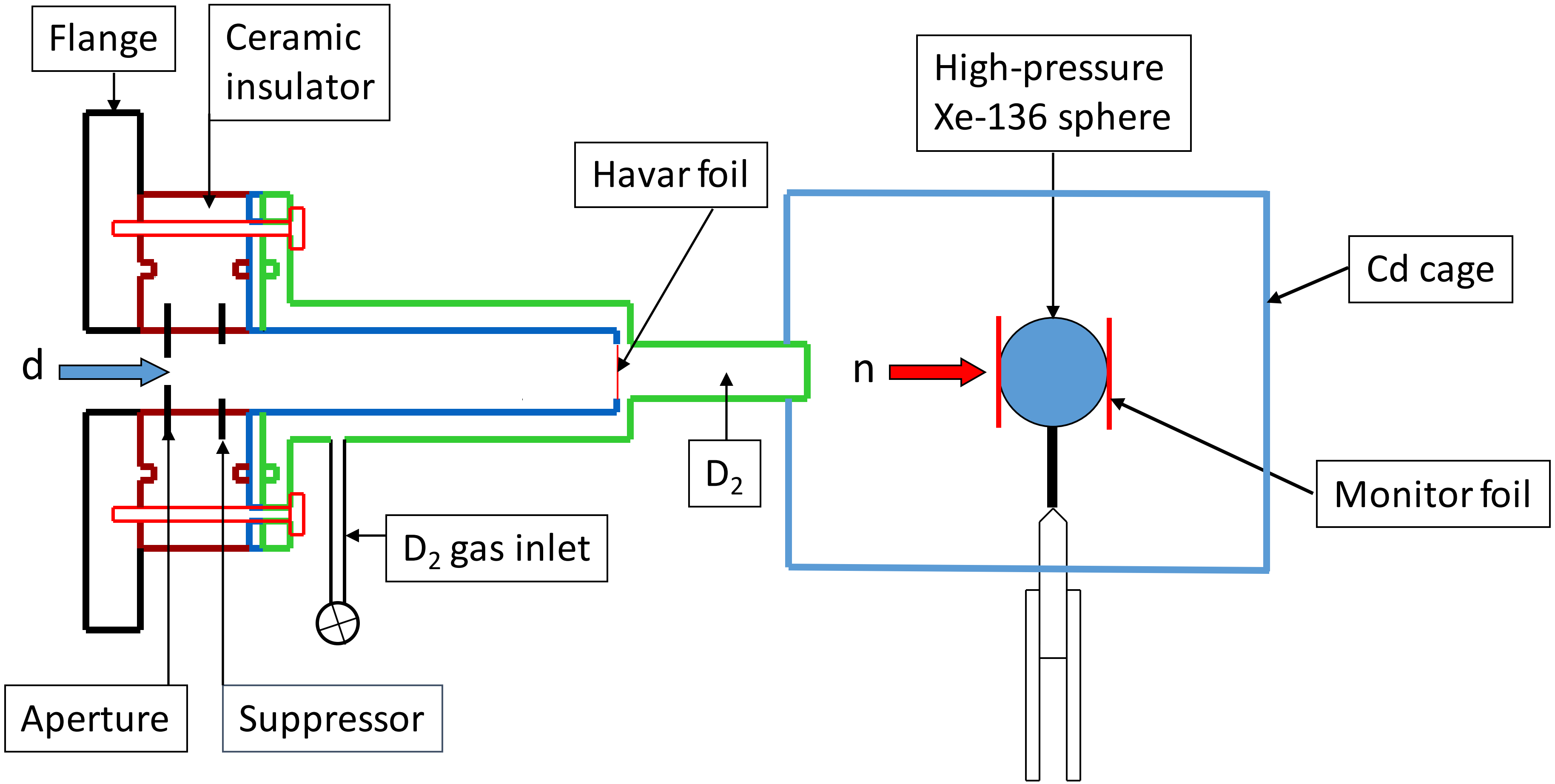
$^{3}H(p,n)^{3}He$	0.4 - 3.6 MeV
$^{7}Li(p,n)^{7}Be$	0.58 MeV
$^{2}H(d,n)^{3}He$	4.2 - 7.6 MeV
$^{3}H(d,n)^{4}He$	14.8 MeV

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

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



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


Flange
Ceramic insulator
High-pressure Xe-136 sphere
Havar foil
Cd cage
d
n
D2
Monitor foil
D2 gas inlet
Aperture
Suppressor

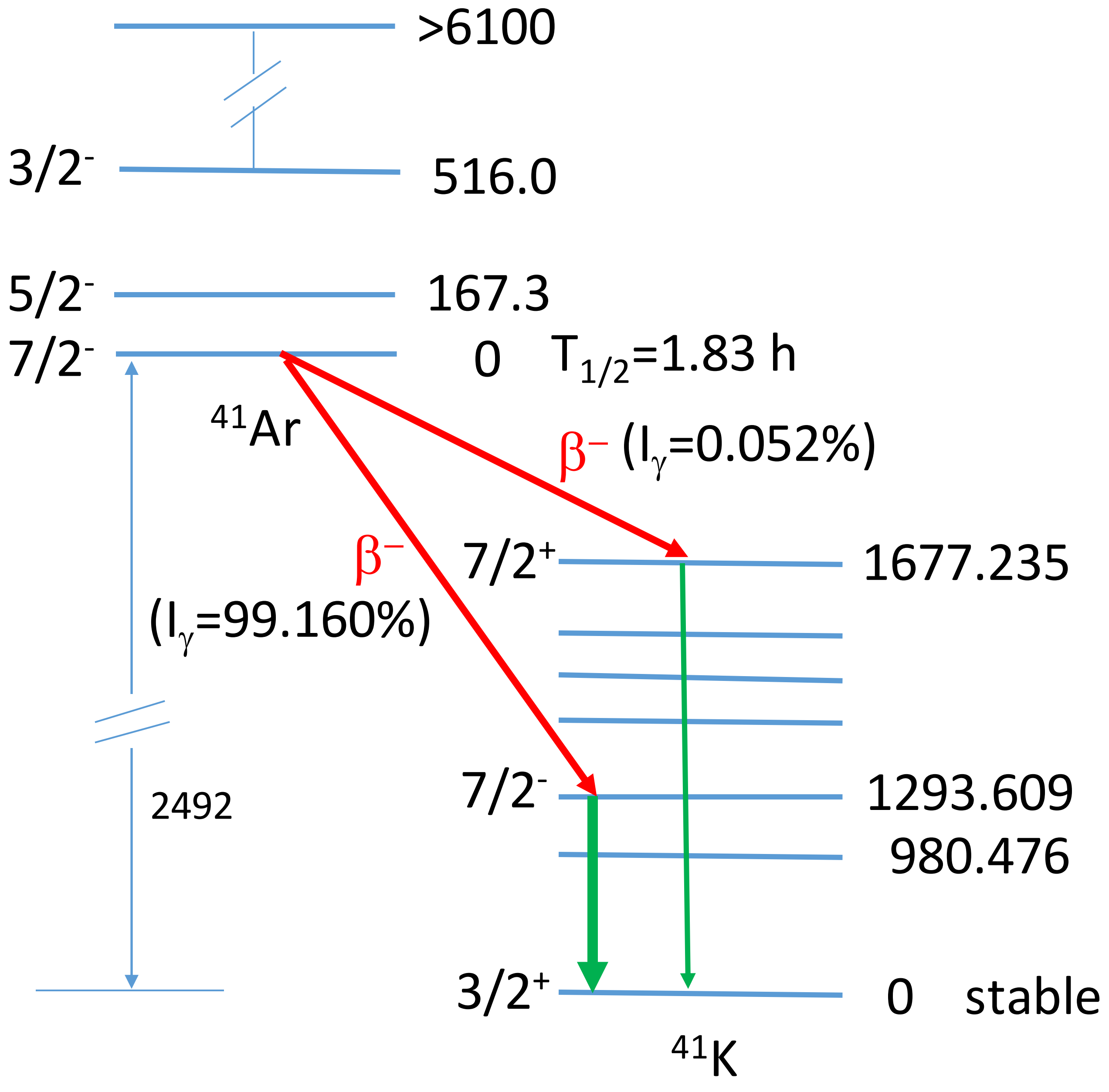
I. $^{40}Ar(n,\gamma)^{41}Ar$ and $^{40}Ar(n,p)^{39}Ar$

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

2. DUNE: Deep Underground Neutrino Experiment @ SURF
(former Homestake gold mine in SD)

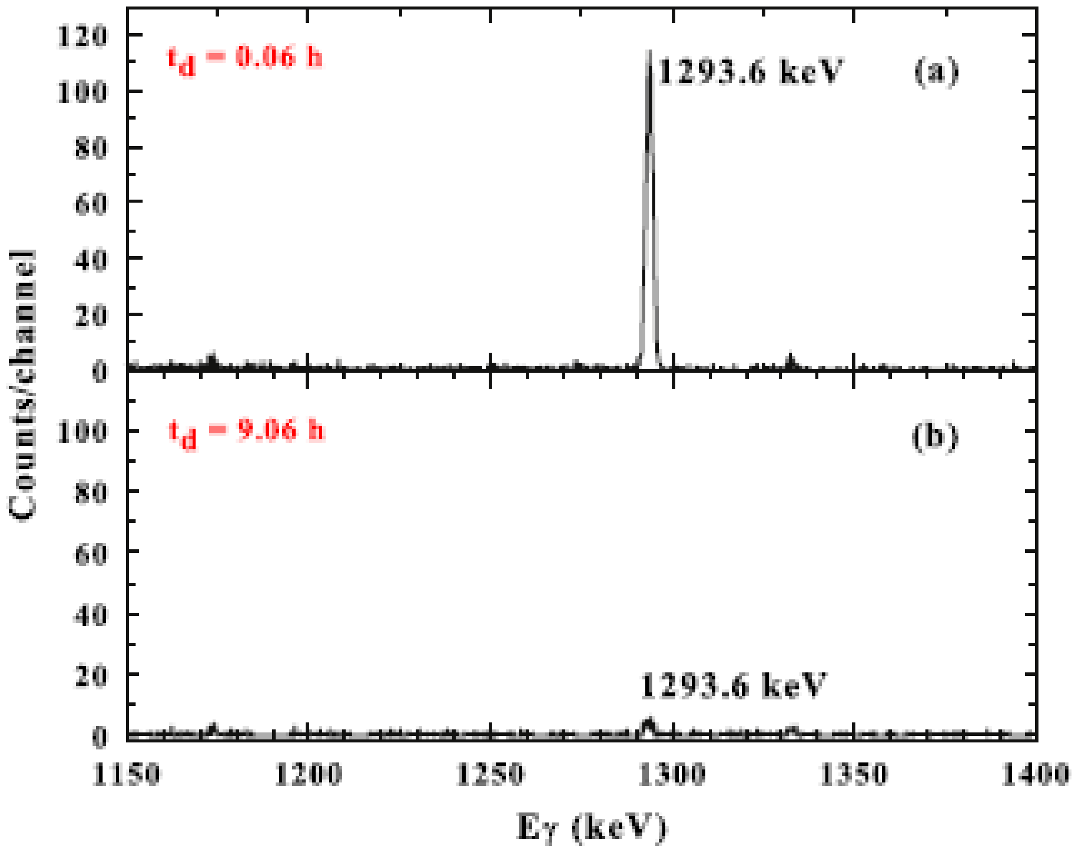
GERDA:
GERmanium
Detector
Array

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

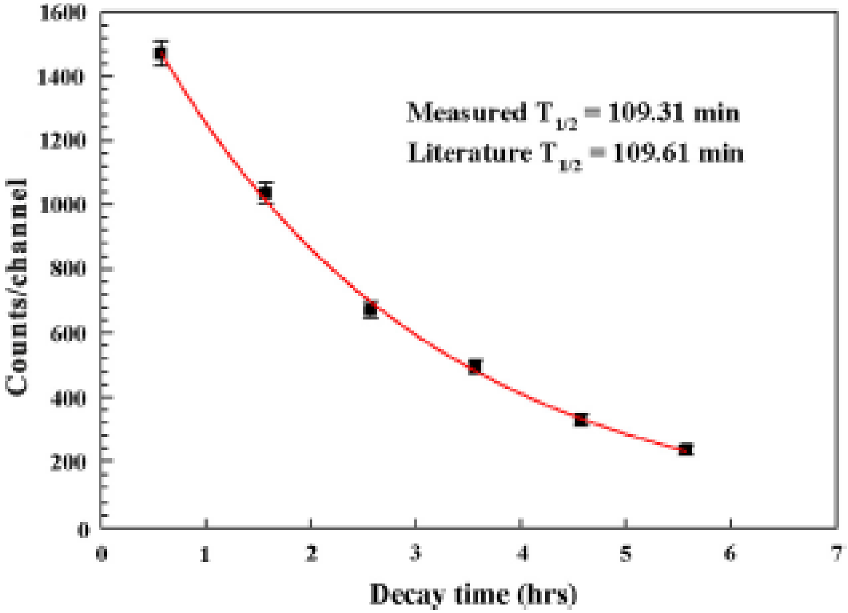


^{76}Ge: 0νββ Q-value: 2039 keV


CANBERRA



t_d = 0.06 h
1293.6 keV
(a)
t_d = 9.06 h
(b)
1293.6 keV
Counts/channel
Eγ (keV)



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

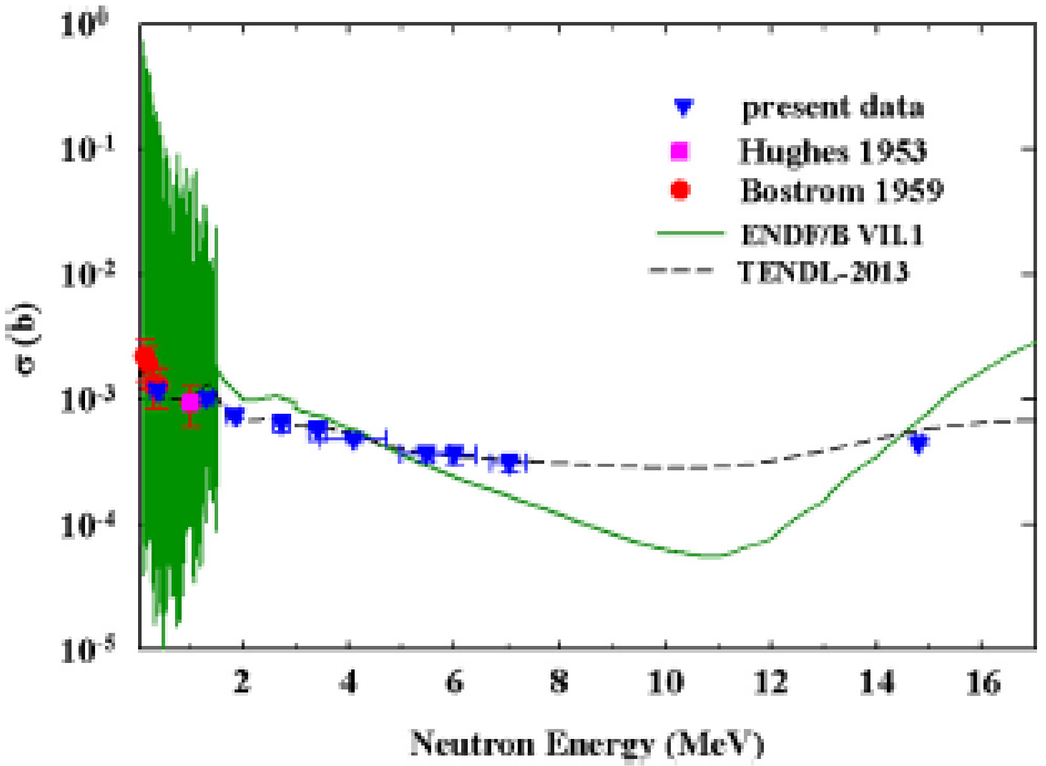
Indium and gold monitor foils for neutron flux determination

Activation formula

$$\phi_n = \frac{A_m \lambda_m}{N_m \sigma_m \epsilon_m I_{\gamma m} (1 - e^{-\lambda_m t_i}) e^{-\lambda_m t_d} (1 - e^{-\lambda_m t_m})},$$

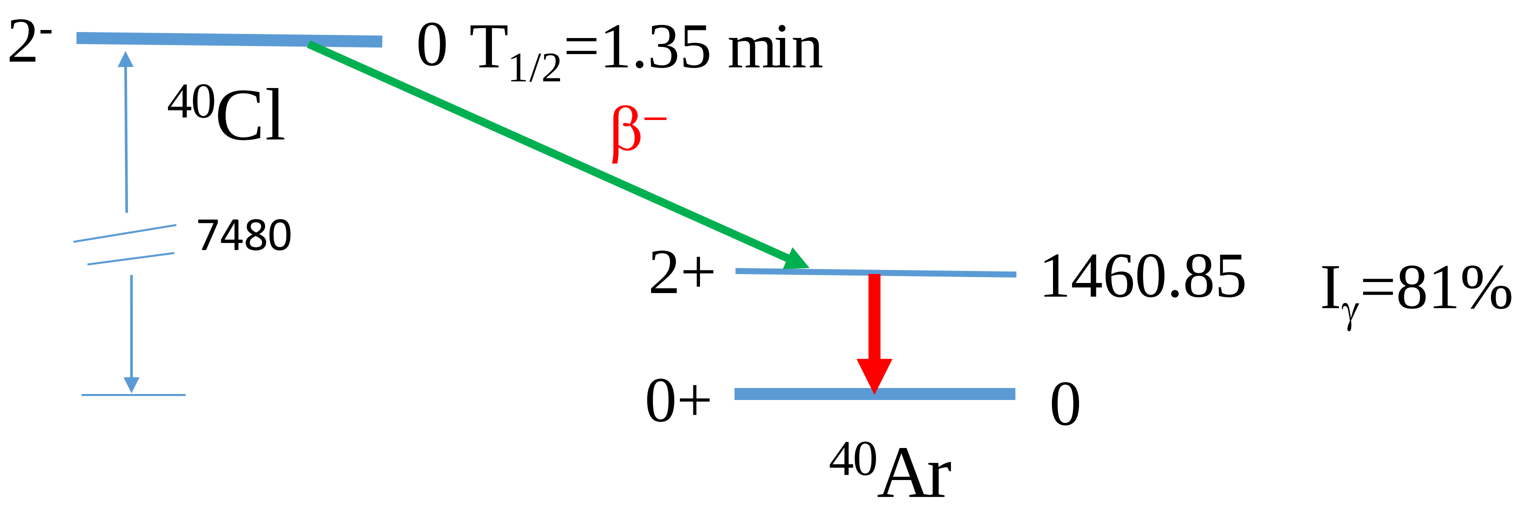
$$\sigma_{Ar} = \frac{A_{Ar} \lambda_{Ar}}{N_{Ar} \phi_n \epsilon_{Ar} I_{\gamma Ar} (1 - e^{-\lambda_{Ar} t_i}) e^{-\lambda_{Ar} t_d} (1 - e^{-\lambda_{Ar} t_m})}$$

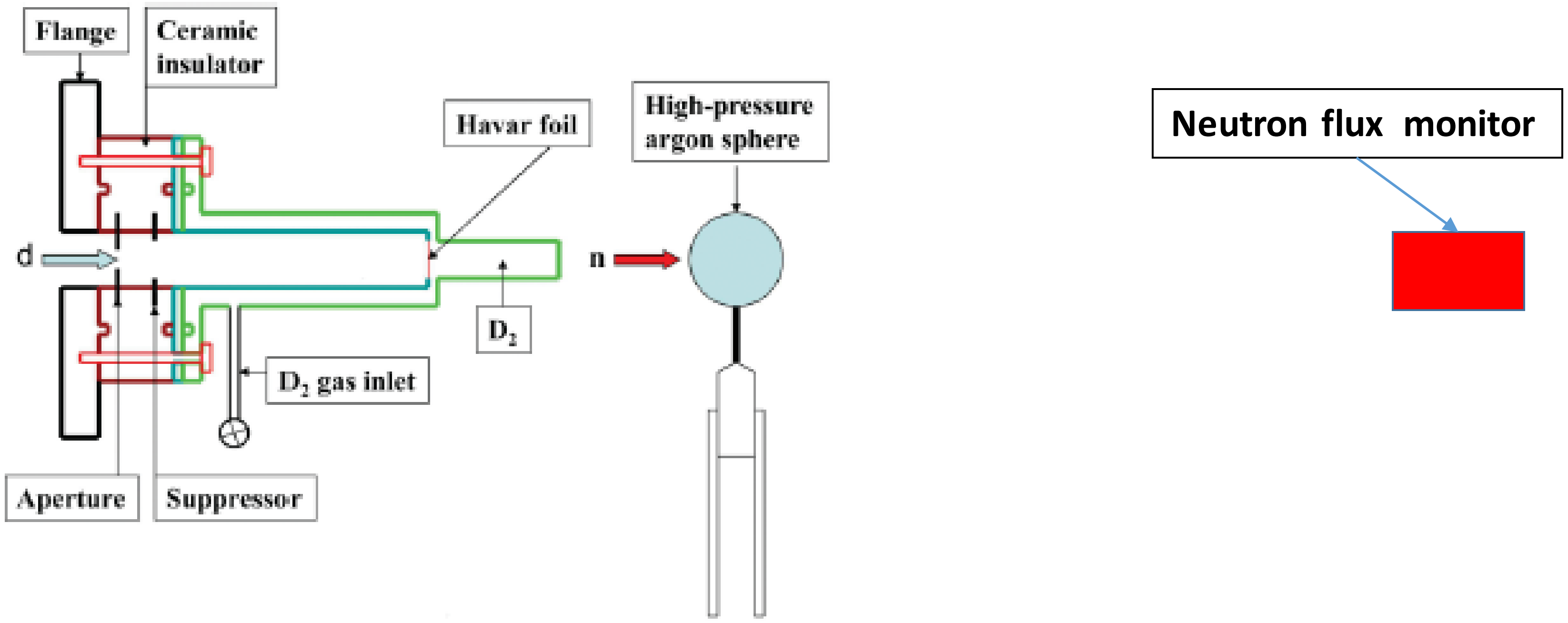
$^{40}Ar(n,\gamma)^{41}Ar$



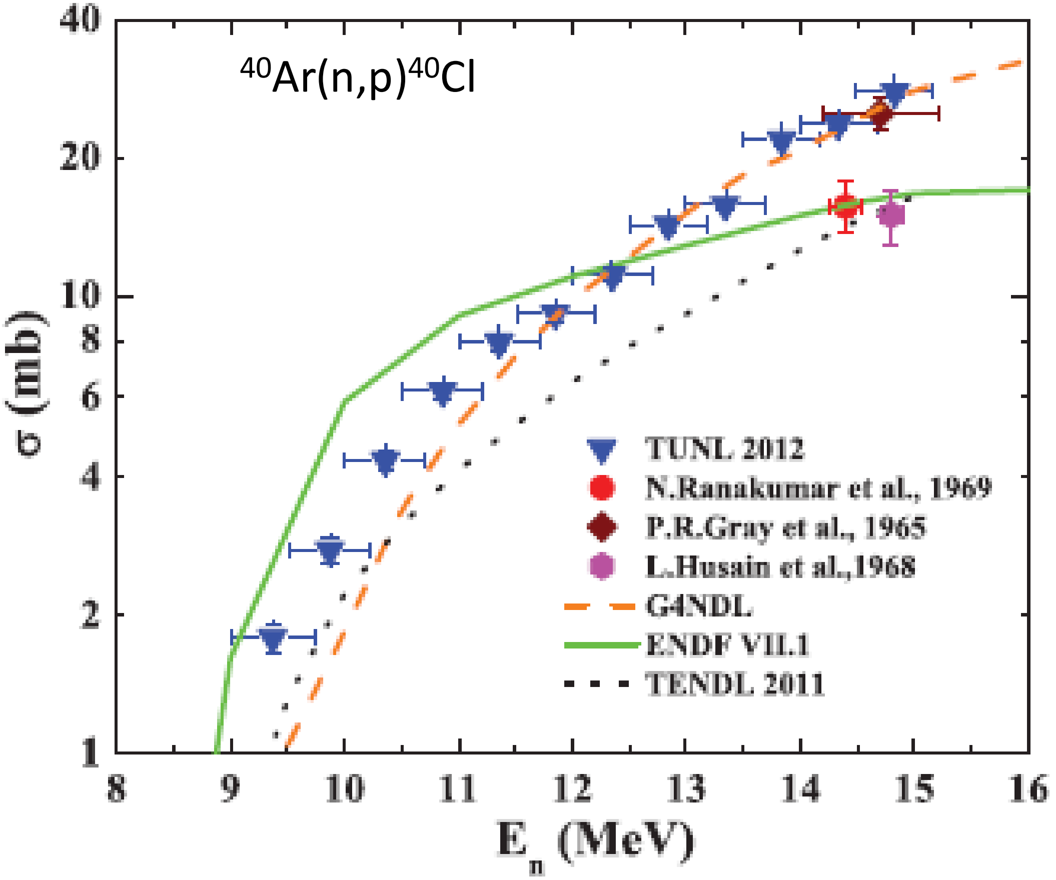
$^{40}Ar(n,p)^{40}Cl$

Q= –6.7 MeV





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



$^{40}Ar(n,p)^{40}Cl$
TUNL 2012
N.Ranakumar et al., 1969
P.R.Gray et al., 1965
L.Husain et al.,1968
G4NDL
ENDF VII.1
TENDL 2011
σ (mb)
E_n (MeV)

II. $^{74,76}Ge(n,\gamma)^{75,77}Ge$, $^{76}Ge(n,2n)^{75}Ge$, $^{76}Ge(n,p)^{76}Ga$ and $^{74,76}Ge(n,n'\gamma)^{74,76}Ge$

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

Q=2039 keV

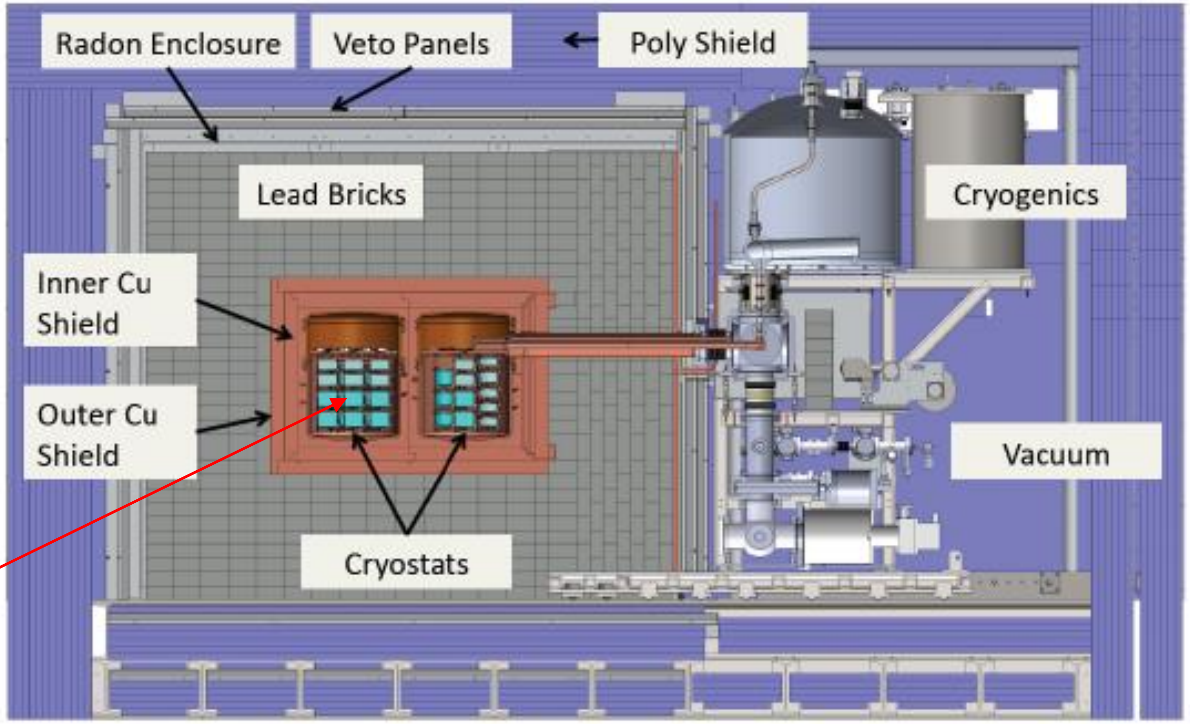
86% ^{76}Ge and 14% ^{74}Ge

GERDA:
GERmanium
Detector
Array

@ Gran Sasso

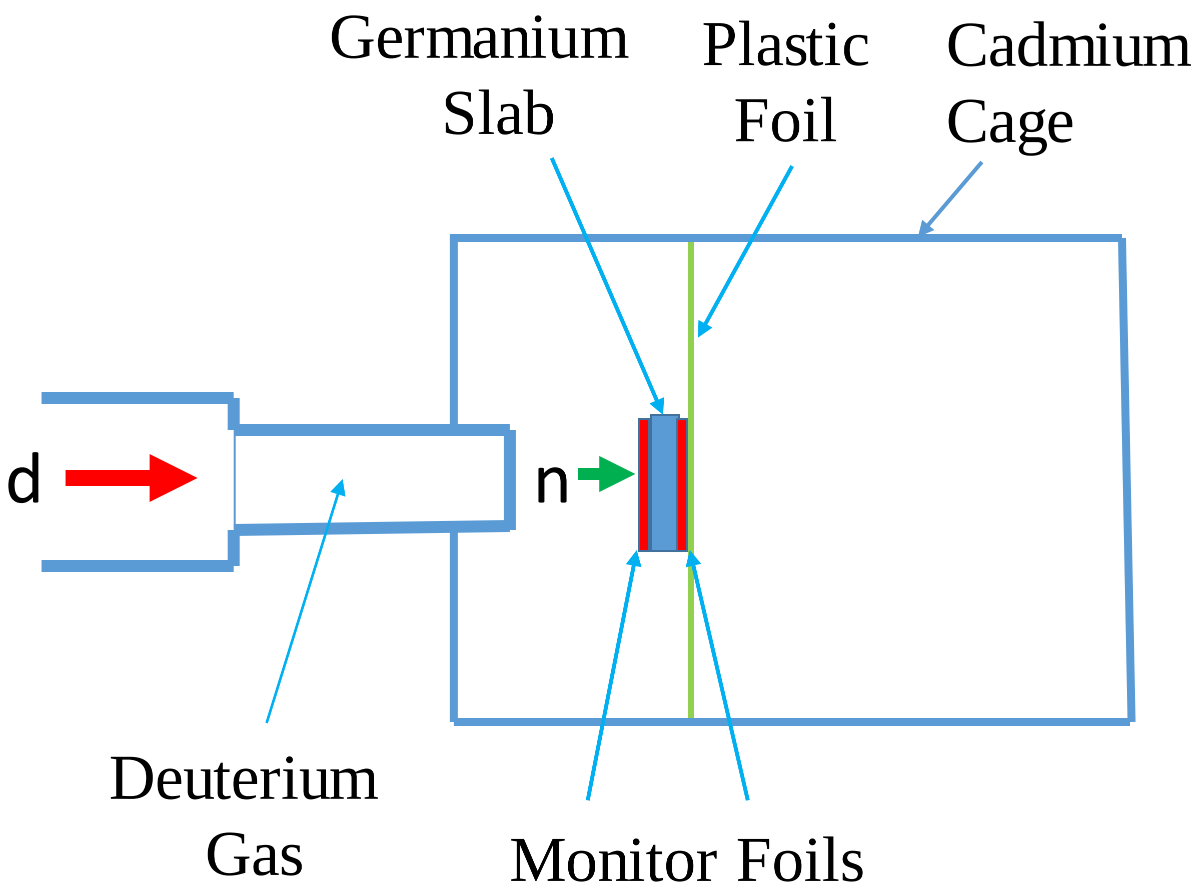
LAr

Enriched
HPGe
Detectors

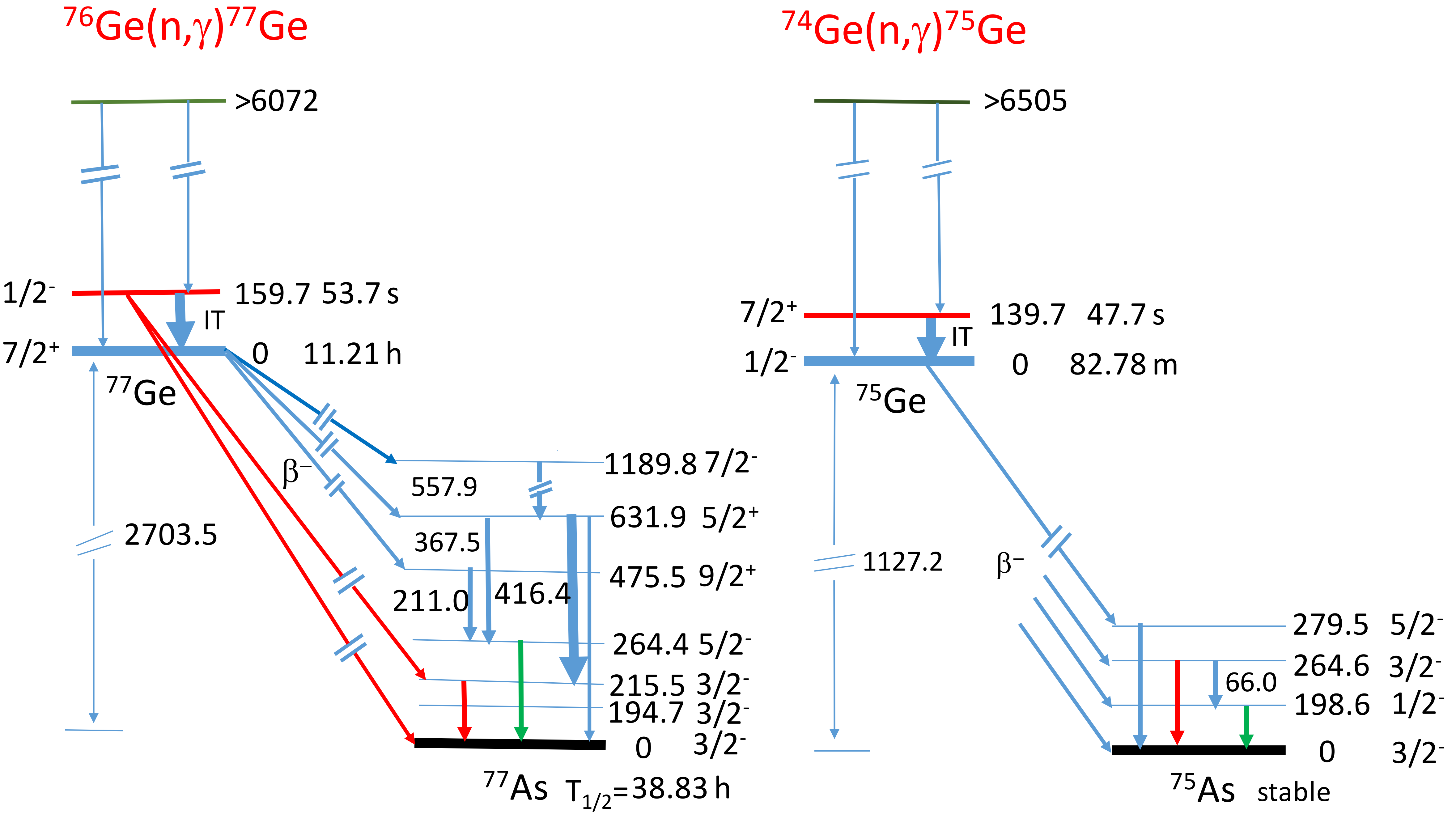


Enriched
HPGe
Detectors

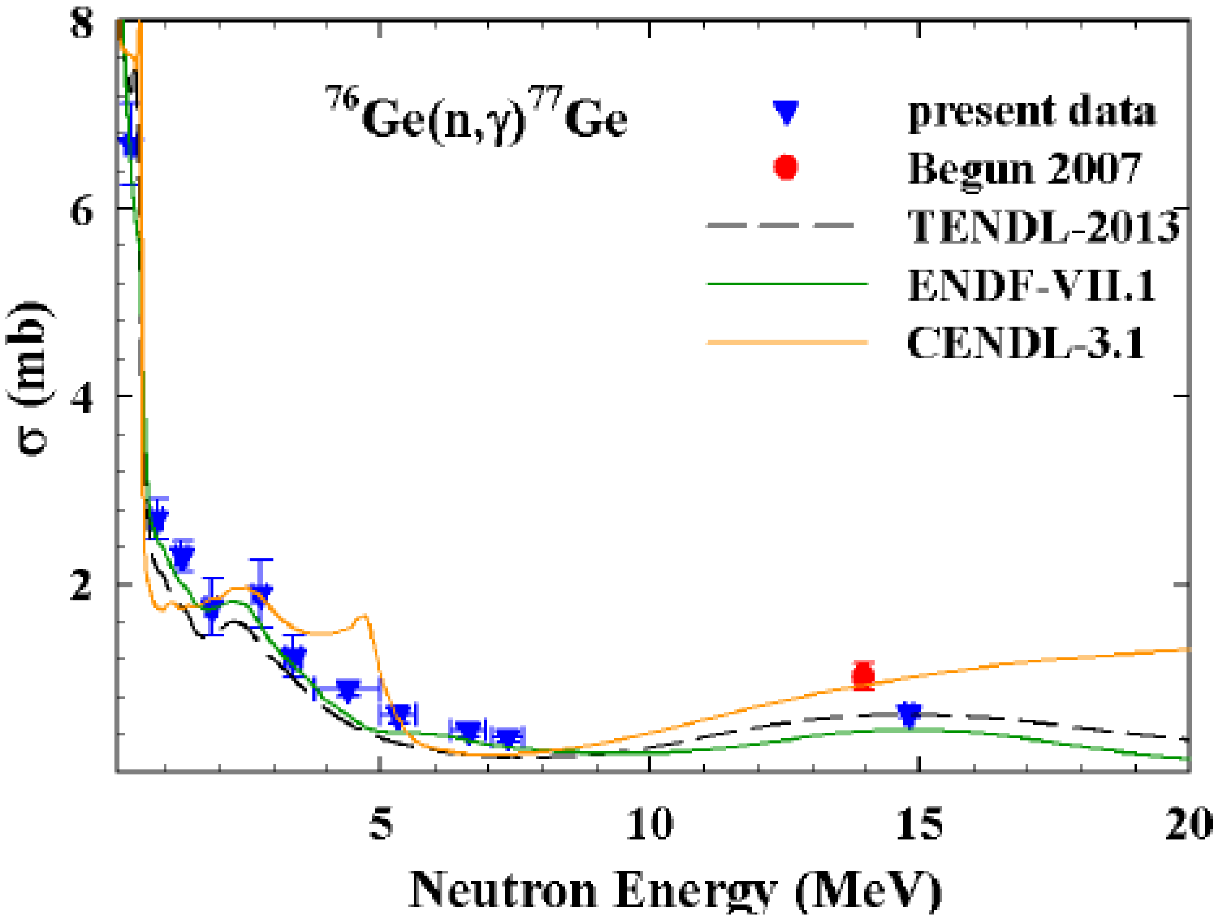
MAJORANA DEMONSTRATOR @ SURF



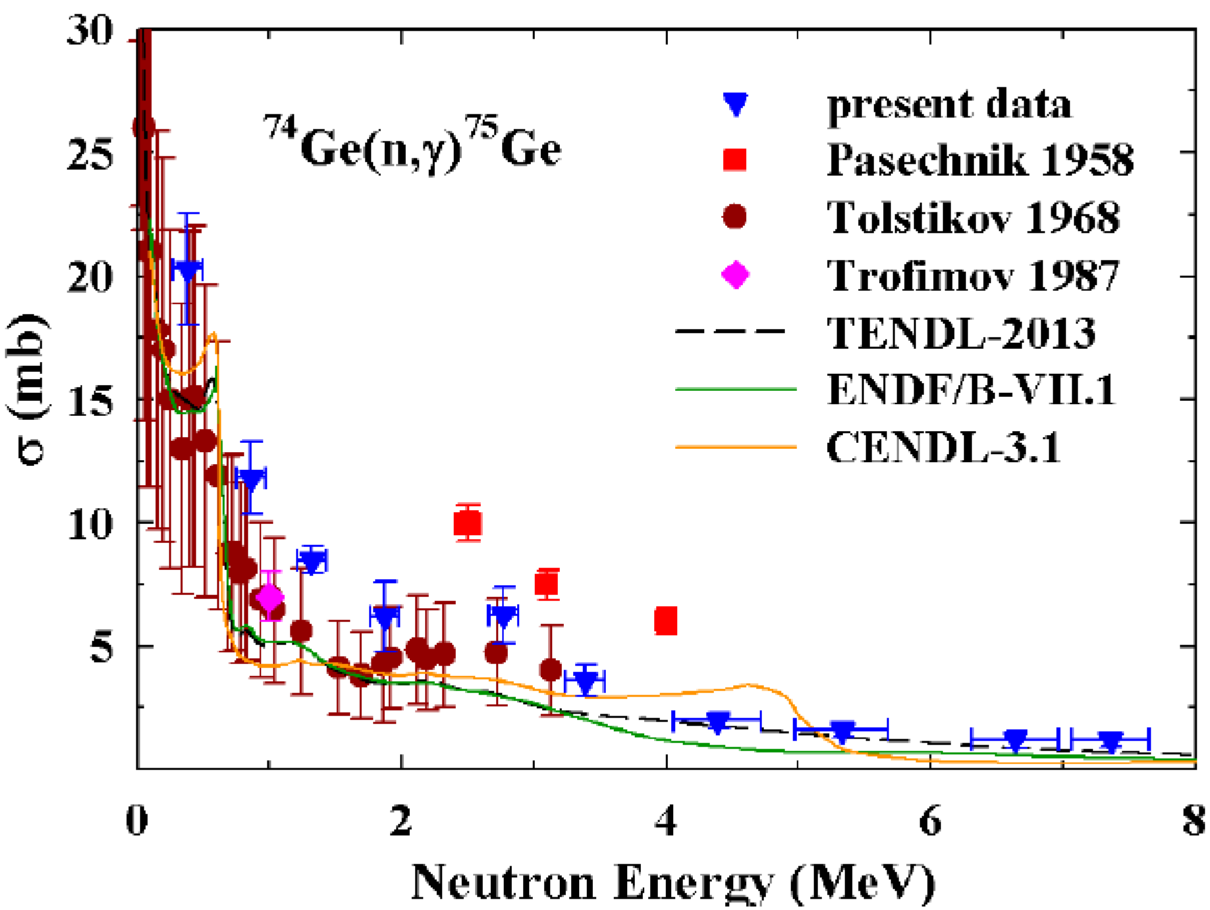
10 mm x 10 mm x 2 mm slabs of GERDA and MAJORANA Germanium



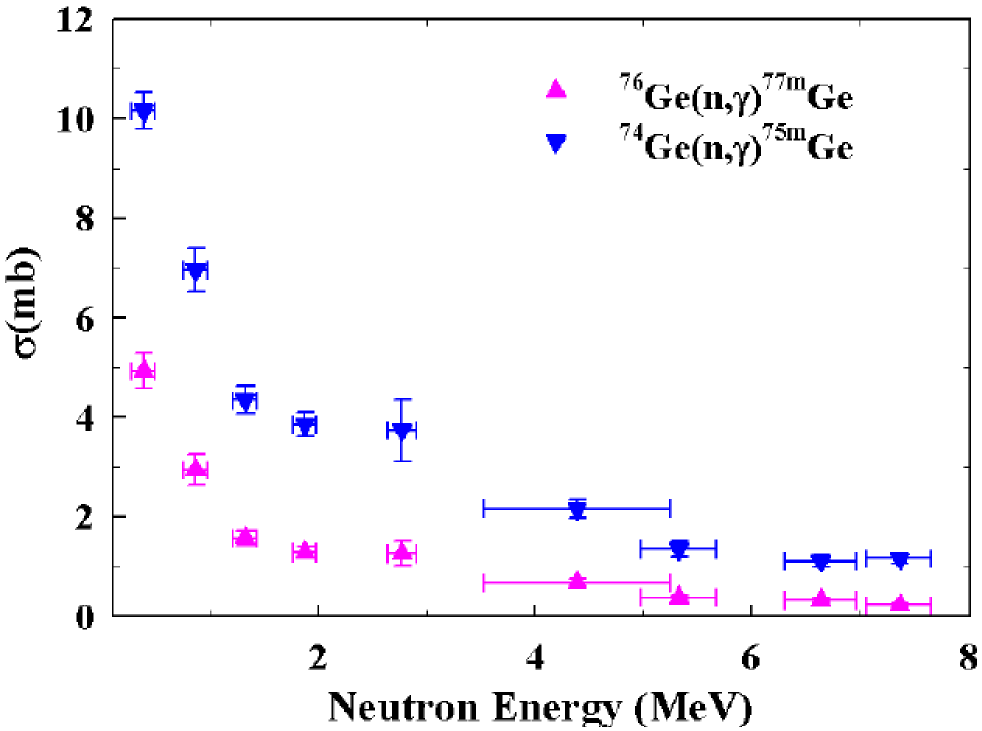
76Ge(n,γ)77Ge
>6072
1/2-
159.7 53.7 s
IT
7/2+
0 11.21 h
77Ge
2703.5
β−
1189.8 7/2-
557.9
631.9 5/2+
367.5
475.5 9/2+
211.0
416.4
264.4 5/2-
215.5 3/2-
194.7 3/2-
0 3/2-
77As T1/2=38.83 h
74Ge(n,γ)75Ge
>6505
7/2+
139.7 47.7 s
IT
1/2-
0 82.78 m
75Ge
1127.2
β−
279.5 5/2-
264.6 3/2-
66.0
198.6 1/2-
0 3/2-
75As stable



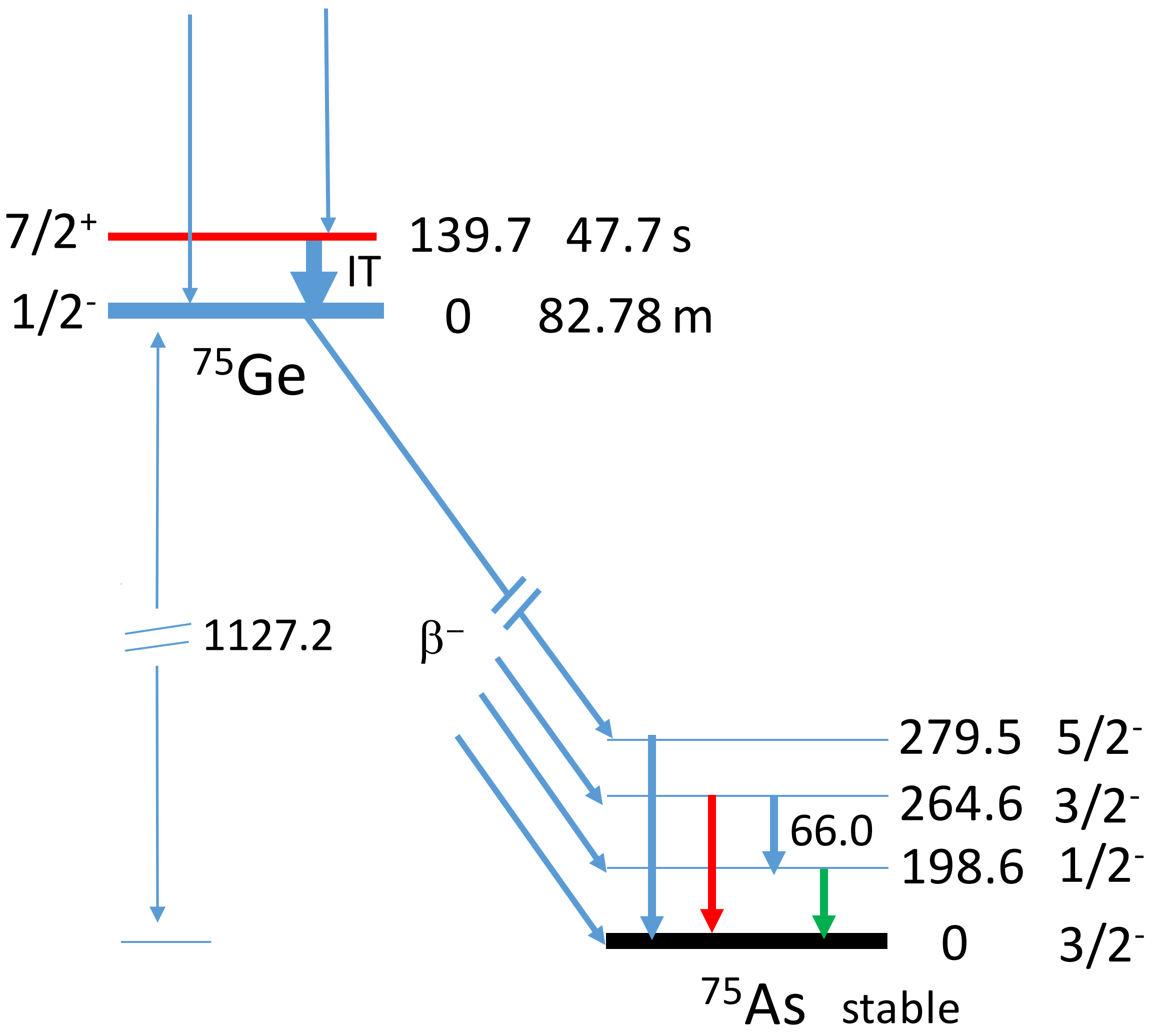
^{76}Ge(n,γ)^{77}Ge
present data
Begun 2007
TENDL-2013
ENDF-VII.1
CENDL-3.1
σ (mb)
Neutron Energy (MeV)



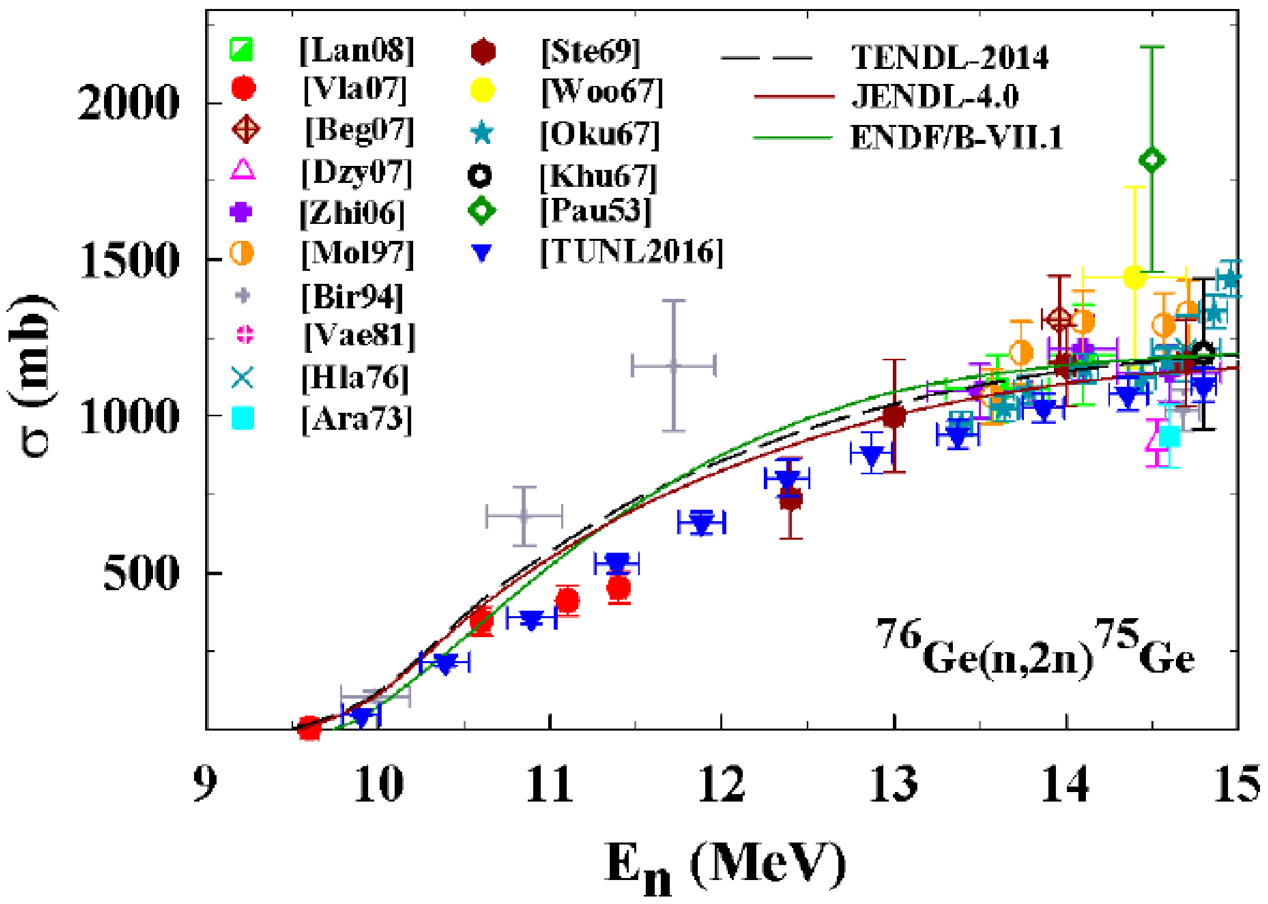
^{74}Ge(n,γ)^{75}Ge
present data
Pasechnik 1958
Tolstikov 1968
Trofimov 1987
TENDL-2013
ENDF/B-VII.1
CENDL-3.1
σ (mb)
Neutron Energy (MeV)

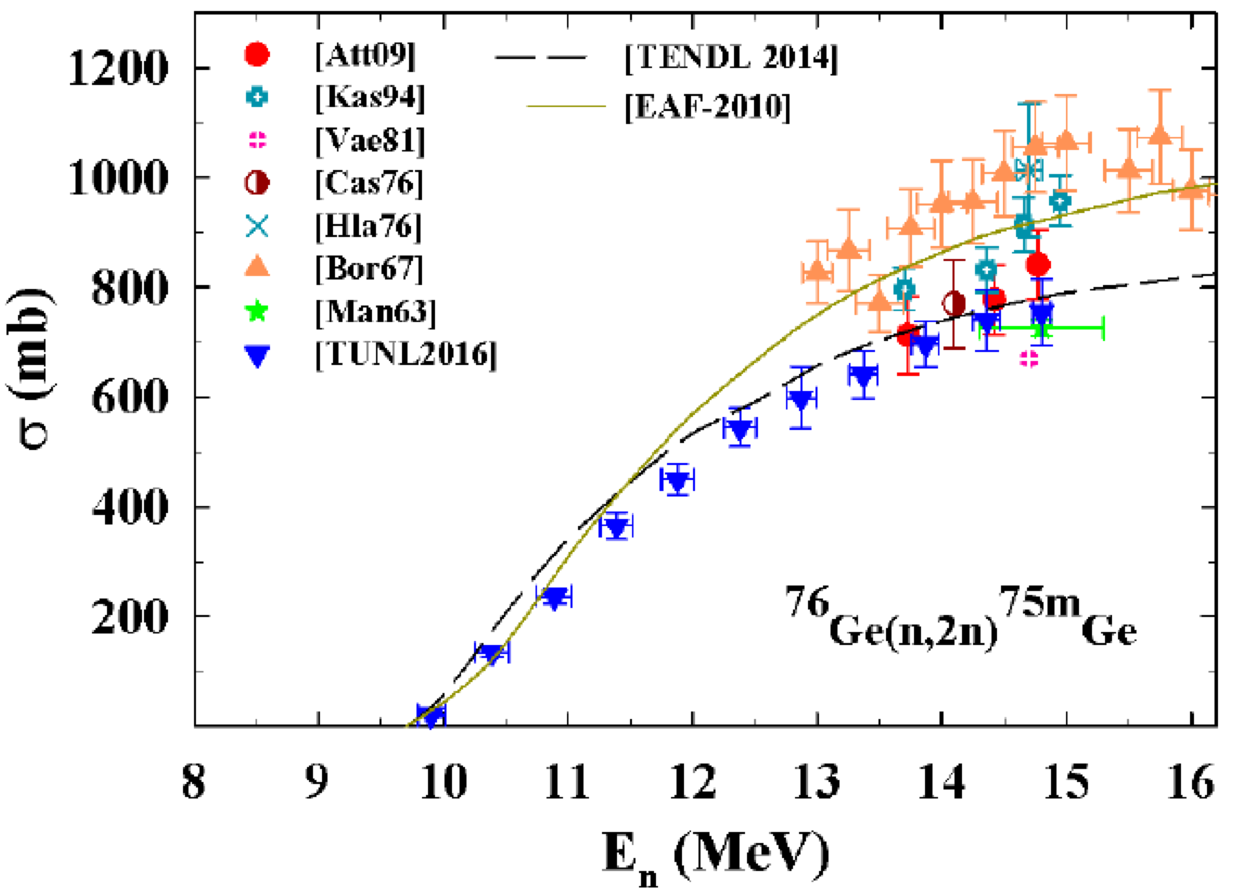

σ(mb)
Neutron Energy (MeV)
^{76}Ge(n,γ)^{77m}Ge
^{74}Ge(n,γ)^{75m}Ge
0
2
4
6
8
10
12
2
4
6
8

$^{76}Ge(n,2n)^{75}Ge$



$^{76}Ge(n,2n)^{75}Ge$

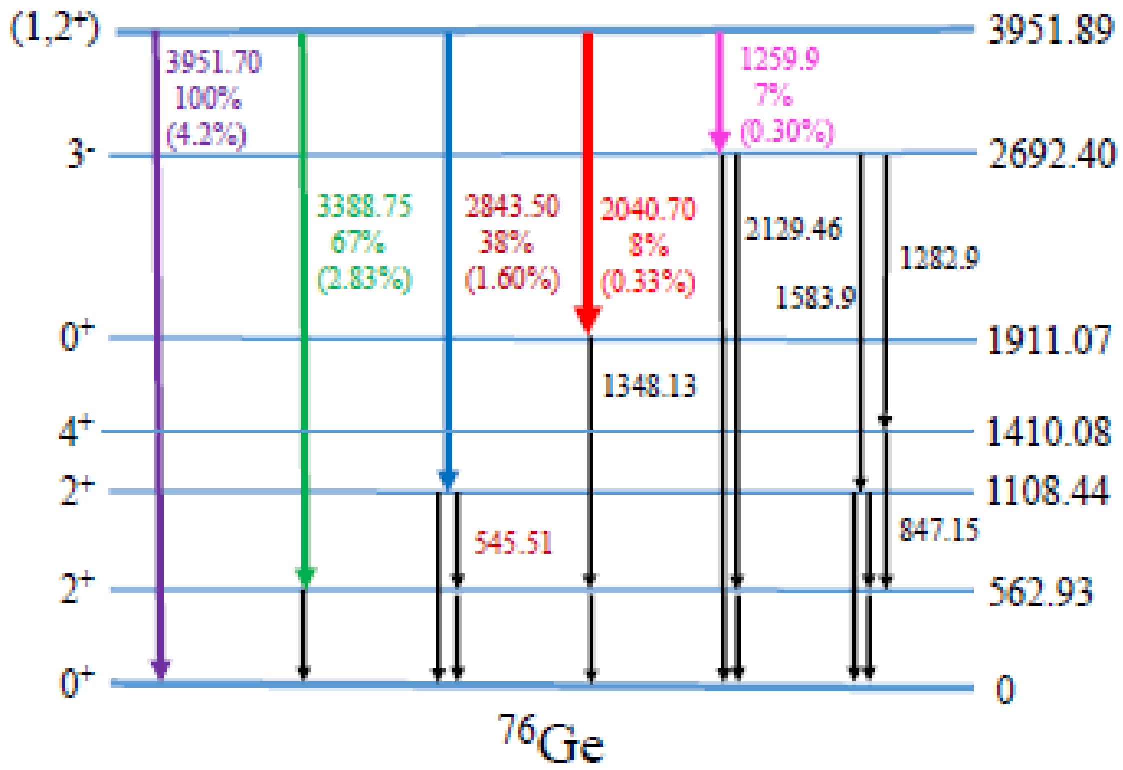




$^{76}Ge(n,p)^{76}Ga$

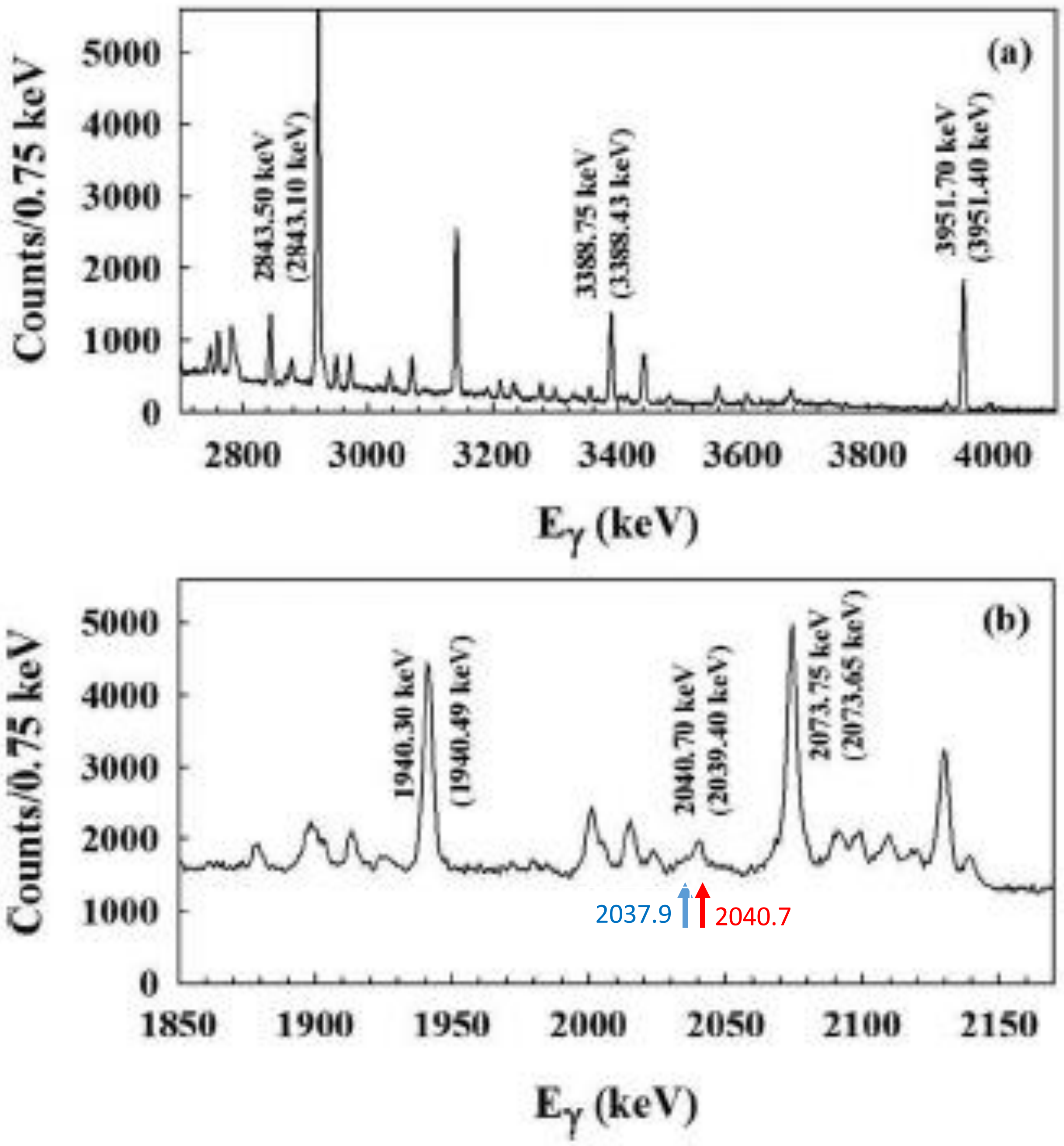
$Q=-6.134$ MeV $T_{1/2}=32.6$ s

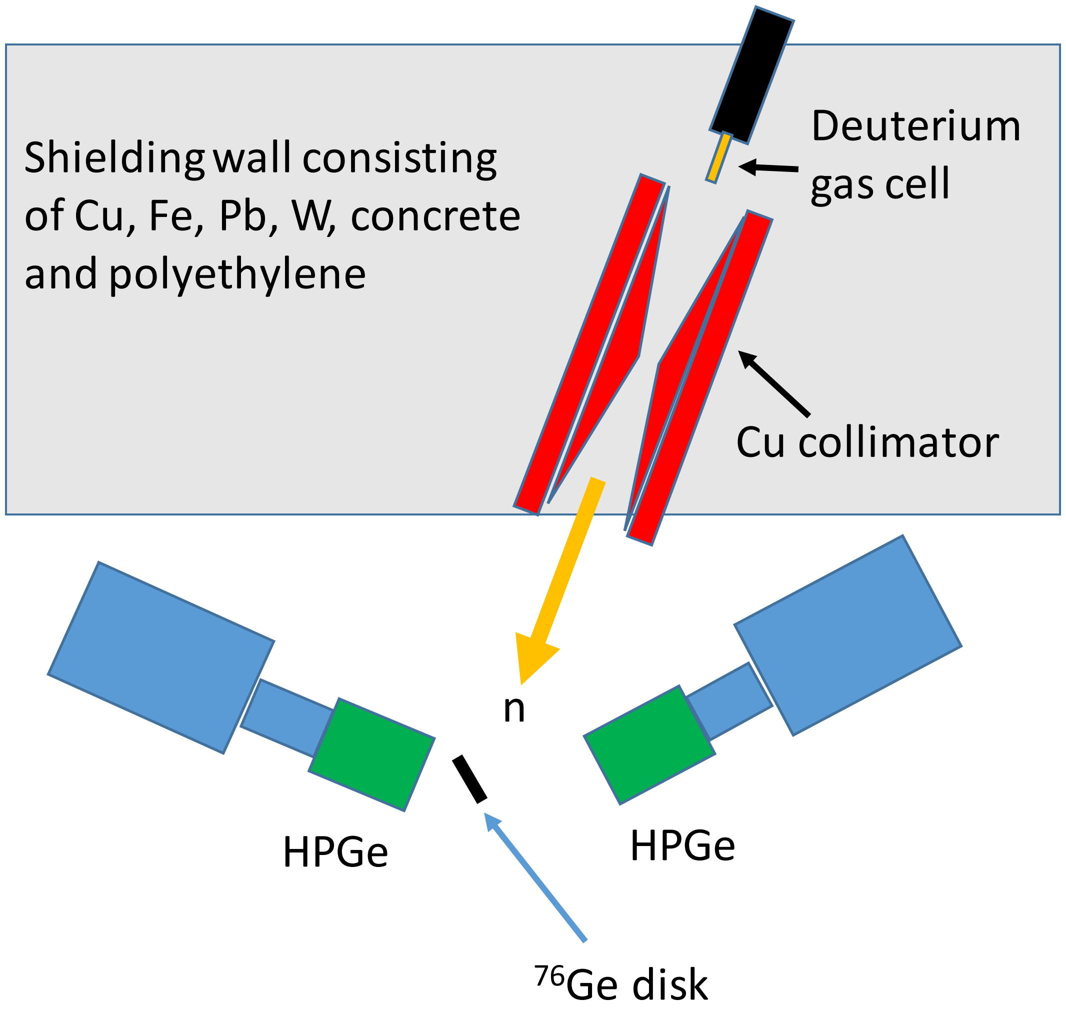
D.C. Camp and B.F. Foster, Nucl. Phys. A **177**, 401 (1971)



2039.0

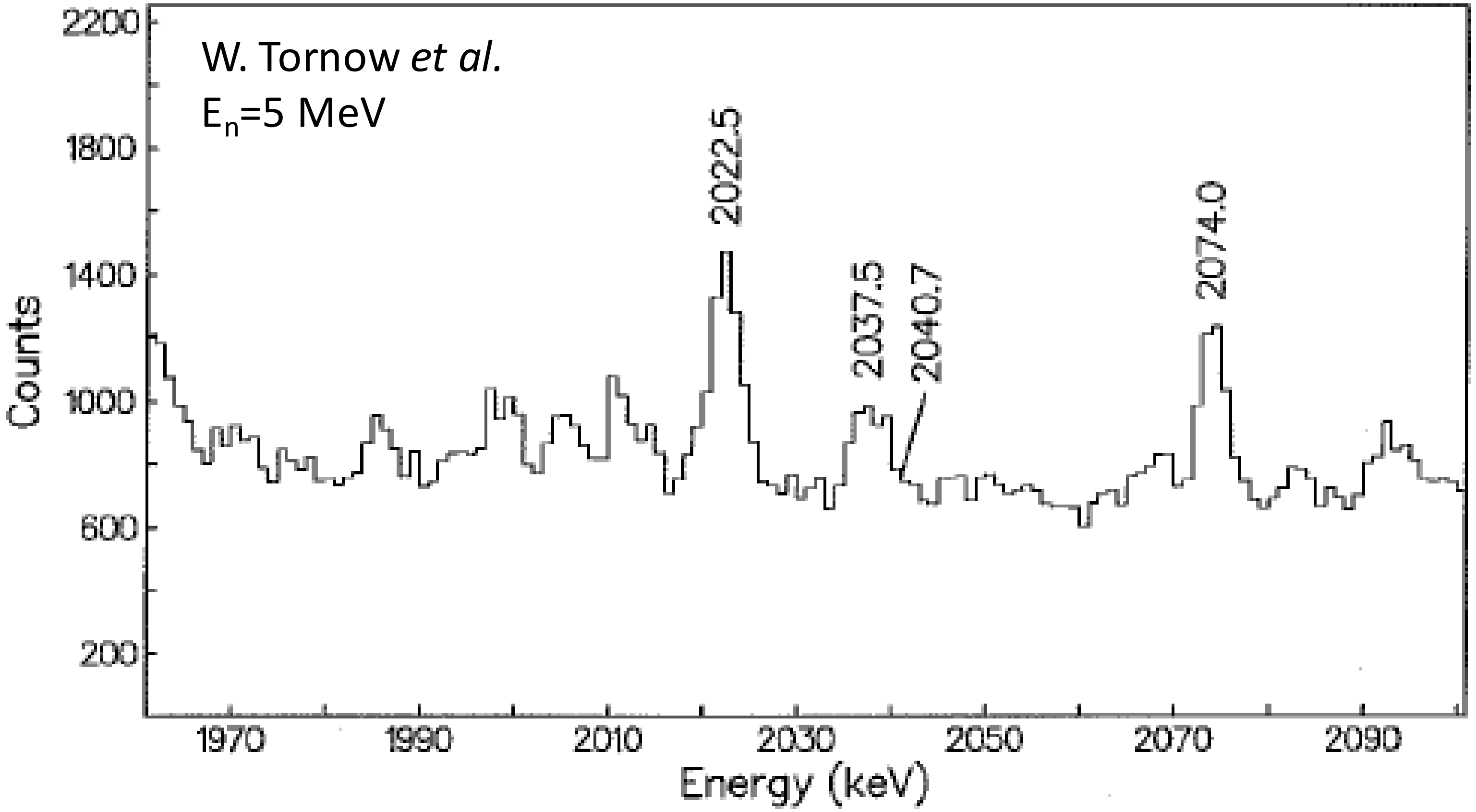
$^{76}Ge(n,p)^{76}Ga$


(a)
2843.50 keV
(2843.10 keV)
3388.75 keV
(3388.43 keV)
3951.70 keV
(3951.40 keV)
Counts/0.75 keV
Eγ (keV)
(b)
1940.30 keV
(1940.49 keV)
2040.70 keV
(2039.40 keV)
2073.75 keV
(2073.65 keV)
2037.9
2040.7
Counts/0.75 keV
Eγ (keV)



$^{74,76}Ge(n,n'\gamma)^{74,76}Ge$

$^{76}Ge(n,n'\gamma)^{76}Ge$



$0\nu\beta\beta$ Q-value 2039.0 keV

C. Rouki *et al*. (including A.J. Koning and A.J.M. Plompen) PRC **88,** 054613 (2013)
B.P. Crider *et al*. (Kentucky group) PRC **92**, 034310 (2015)

More important: 2037.5 keV γ-ray; origin not clear yet, Crider *et al*.: 3147.4 keV to 1108.4 keV (2039 .0 keV)
NNDC: 3577.0 keV to 1539.5 keV (2037.5 keV)

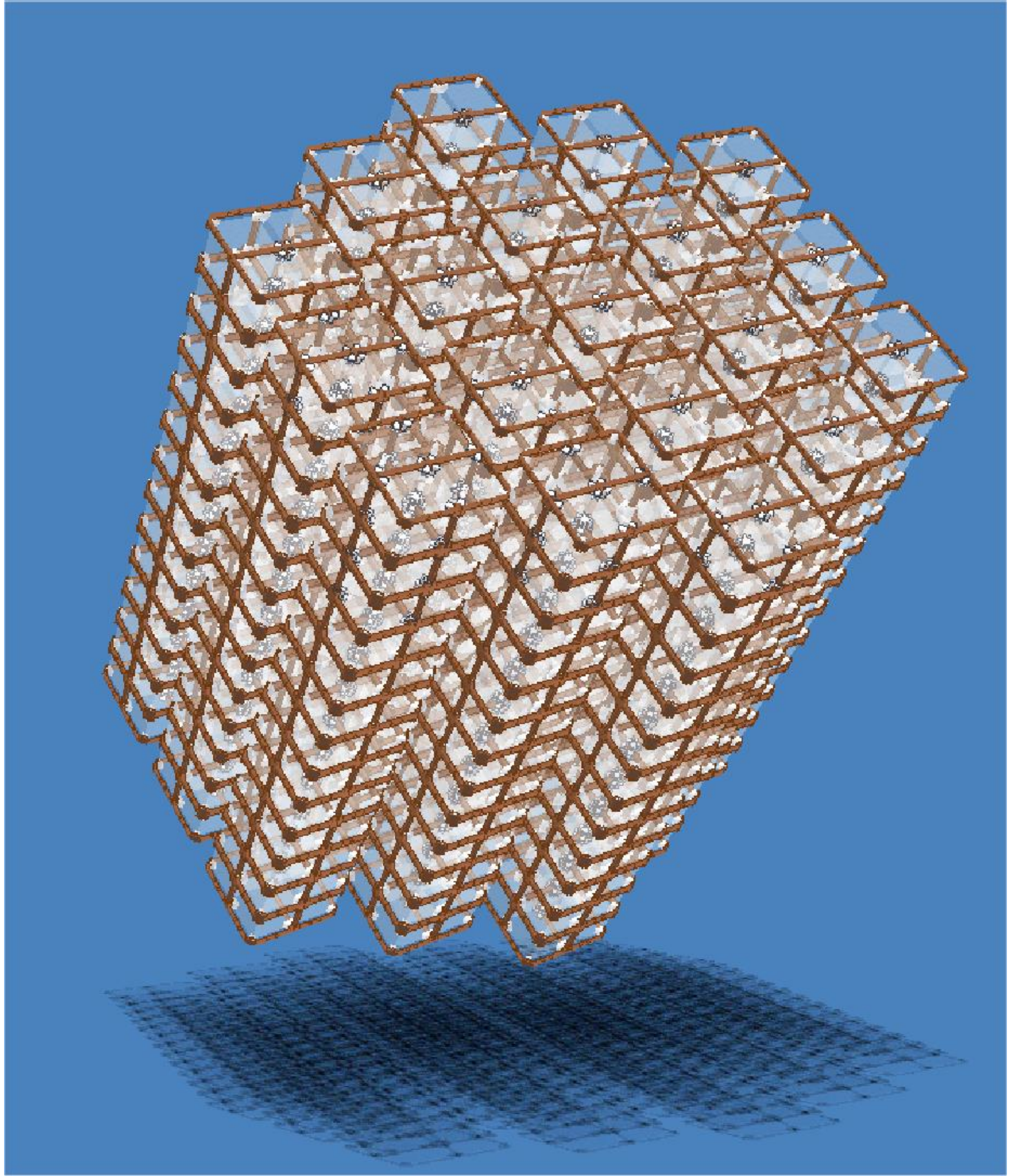
In addition: 2037.9 keV γ-ray from $^{76}Ge(n,\gamma)^{77}Ge$ capture

III. $^{128,130}Te(n,\gamma)^{129,131}Te$ and $^{128,130}Te(n,2n)^{127,129}Te$

1. CUORE: Cryogenic Underground Observatory for Rare Events @ LNGS
2. SNO+: Sudbury Neutrino Observatory @ Creighton mine in Sudbury, Ontario, Canada

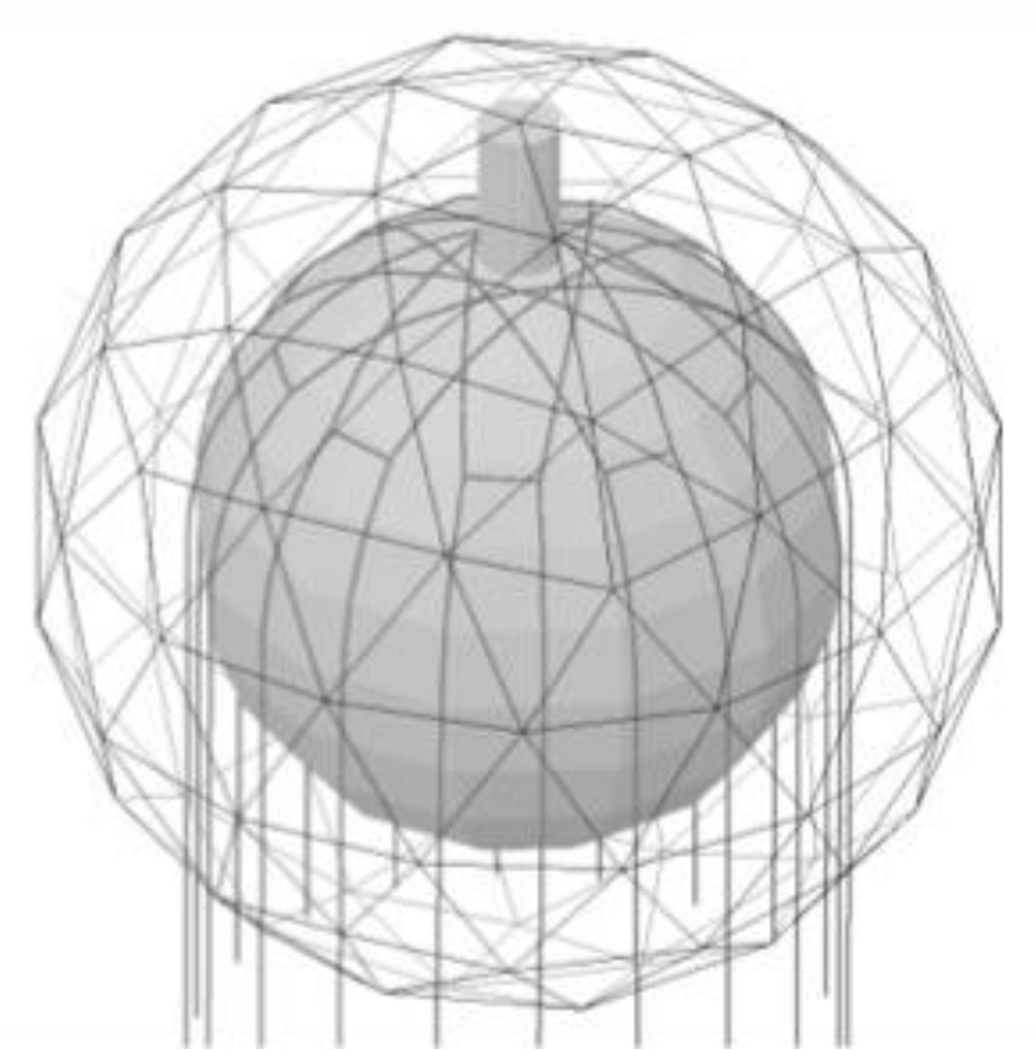
$0\nu\beta\beta$ of ^{128}Te and ^{130}Te Q=867 keV and 2528 keV

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



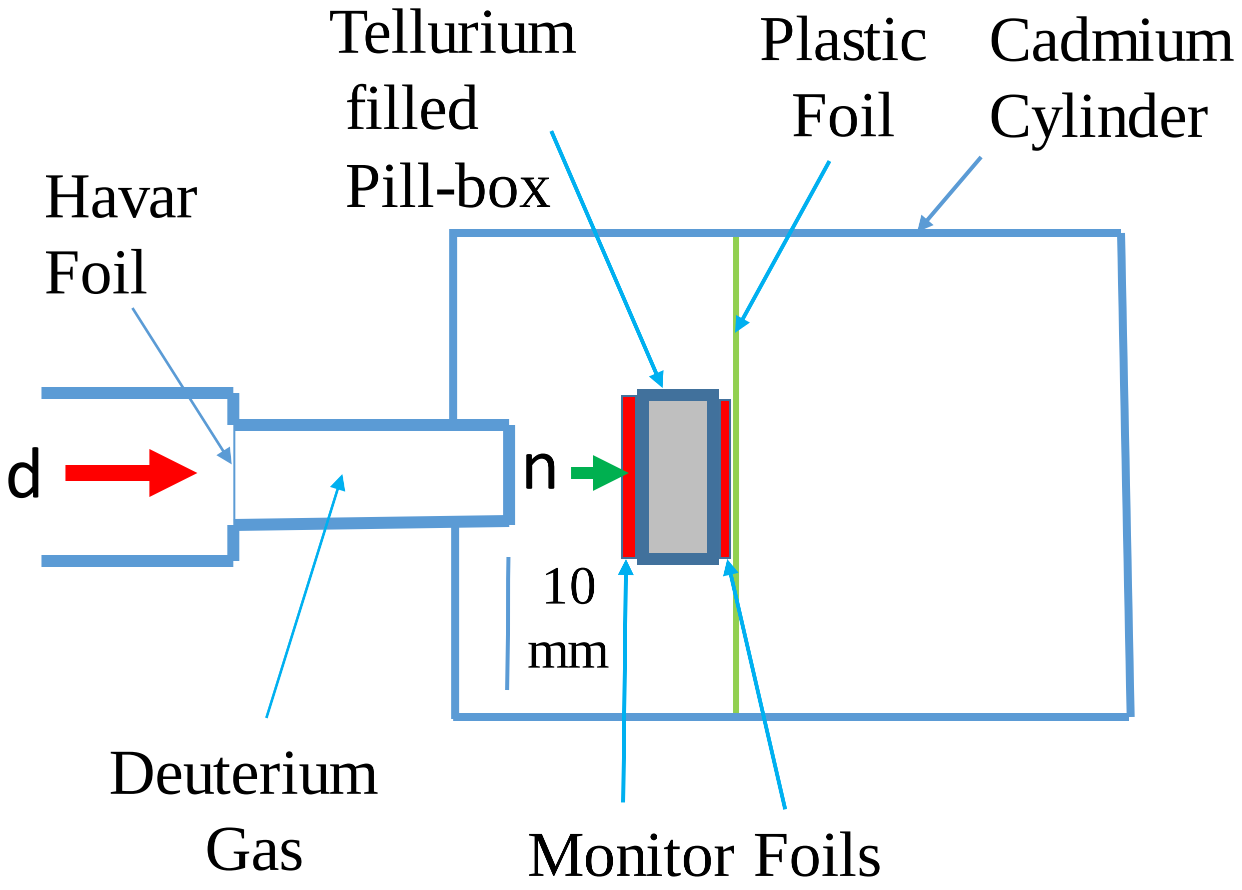
CUORE

988 750 g TeO_2 bolometers

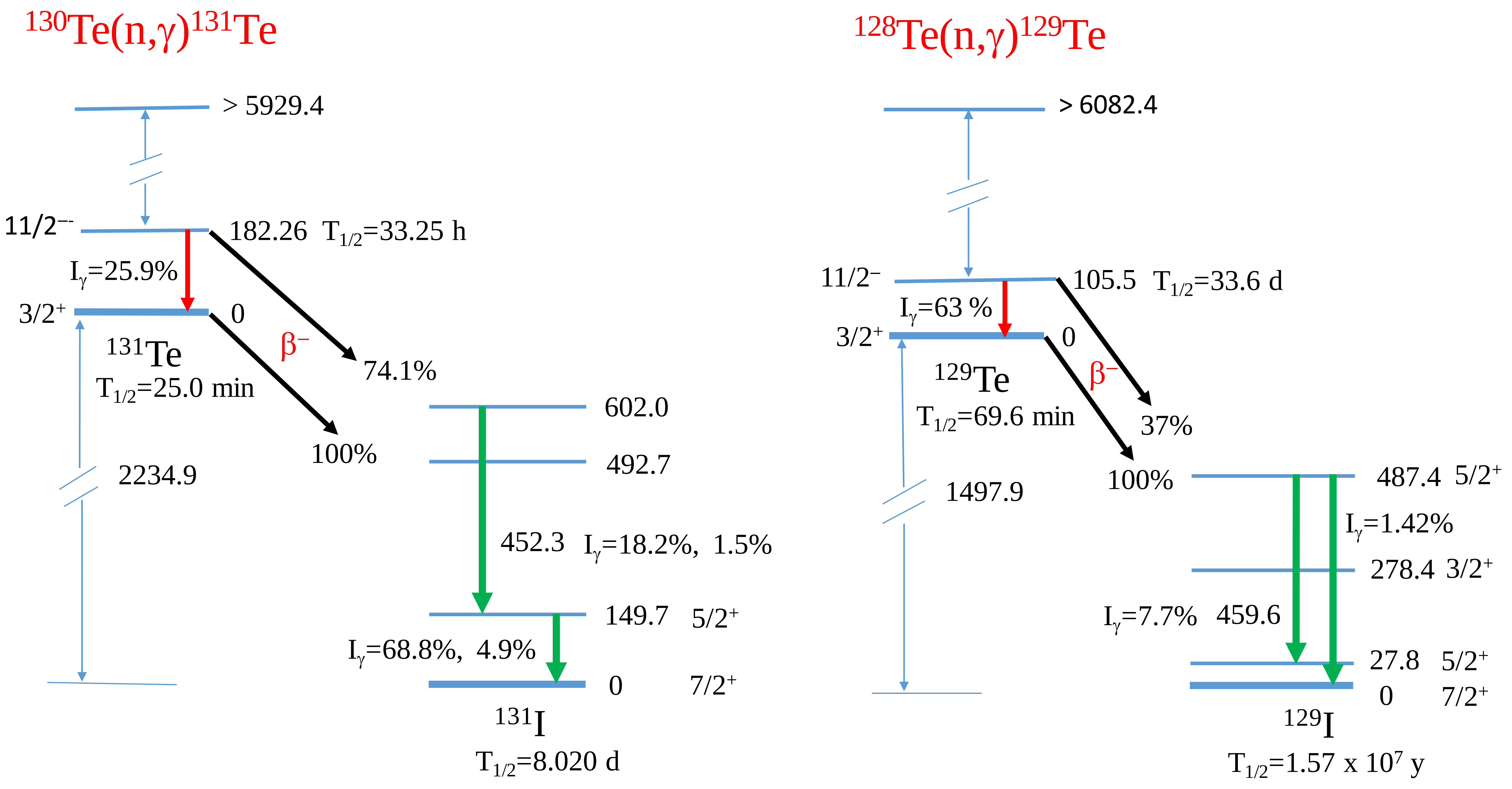


SNO+

Tellurium loaded
Liquid Scintillator

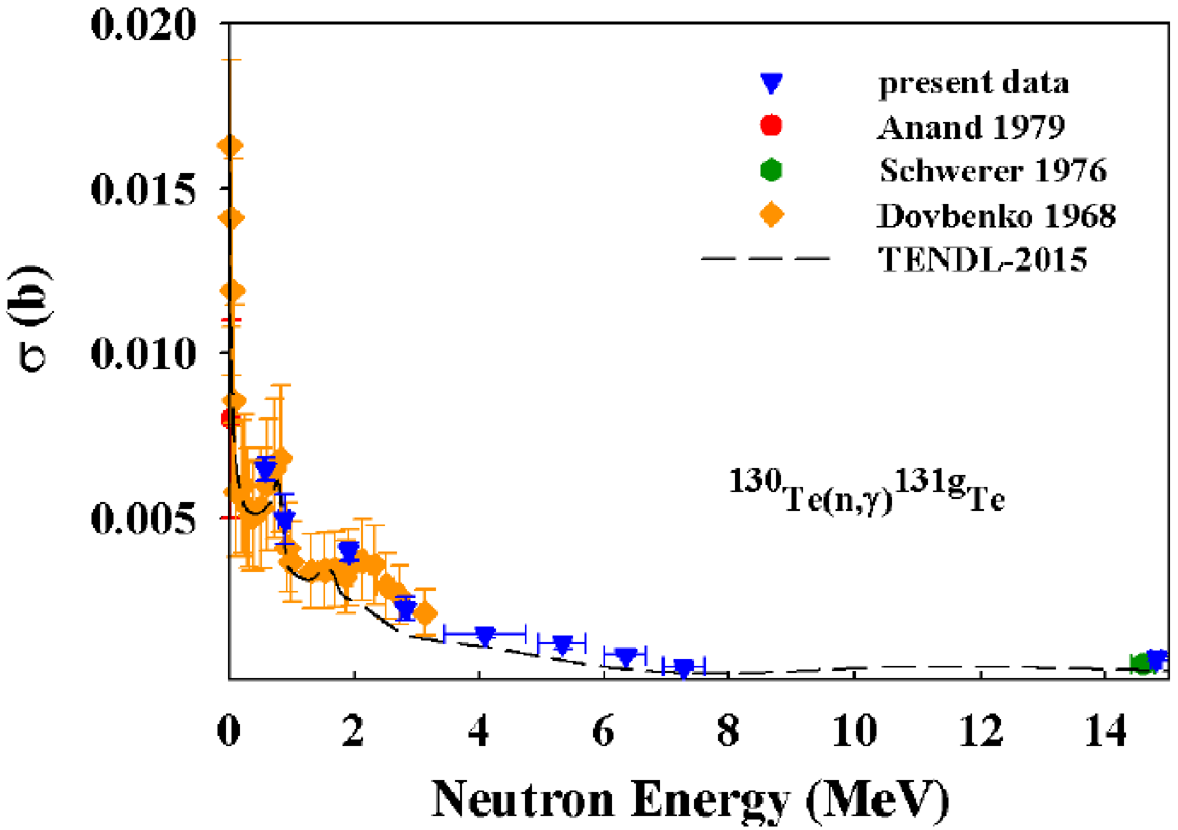


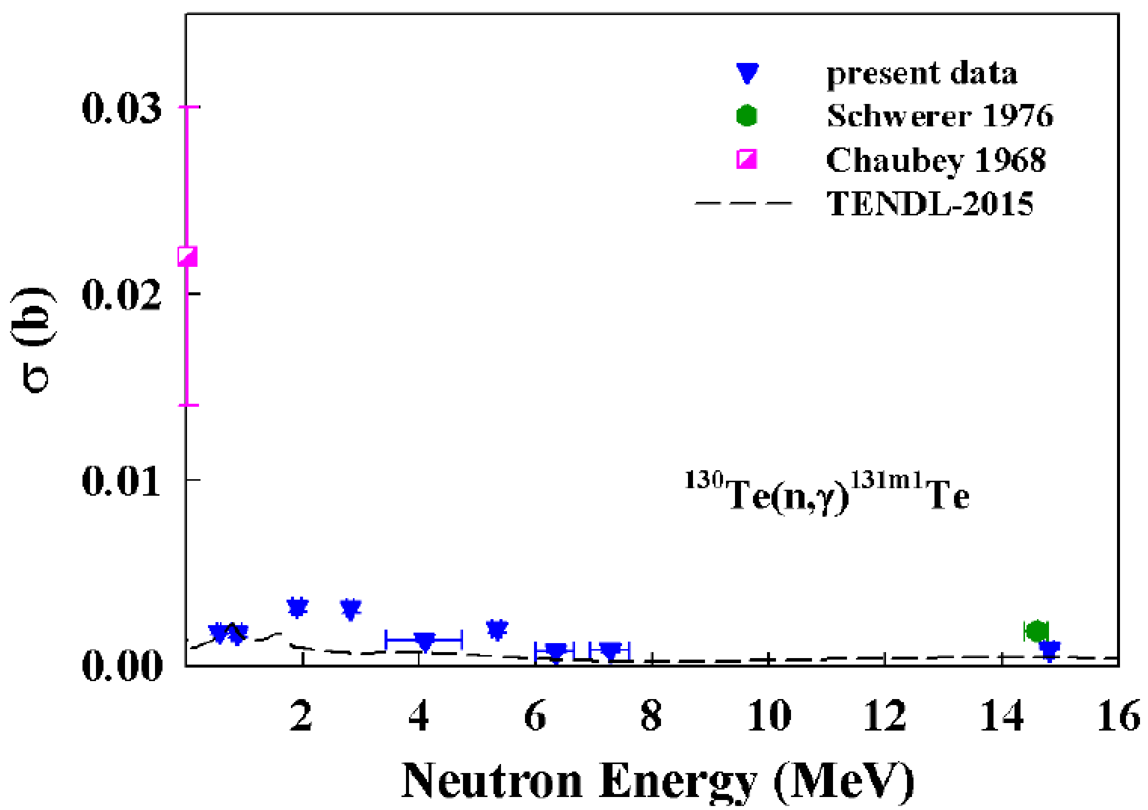
Tellurium
filled
Pill-box
Plastic
Foil
Cadmium
Cylinder
Havar
Foil
d
n
10
mm
Deuterium
Gas
Monitor Foils



130Te(n,γ)131Te
128Te(n,γ)129Te
> 5929.4
11/2−
182.26 T1/2=33.25 h
Iγ=25.9%
3/2+
0
131Te
T1/2=25.0 min
β−
74.1%
100%
2234.9
602.0
492.7
452.3 Iγ=18.2%, 1.5%
149.7 5/2+
Iγ=68.8%, 4.9%
0 7/2+
131I
T1/2=8.020 d
> 6082.4
11/2−
105.5 T1/2=33.6 d
Iγ=63 %
3/2+
0
129Te
T1/2=69.6 min
β−
37%
100%
1497.9
487.4 5/2+
Iγ=1.42%
278.4 3/2+
Iγ=7.7% 459.6
27.8 5/2+
0 7/2+
129I
T1/2=1.57 x 10^7 y

$^{130}Te(n,\gamma)^{131}Te$



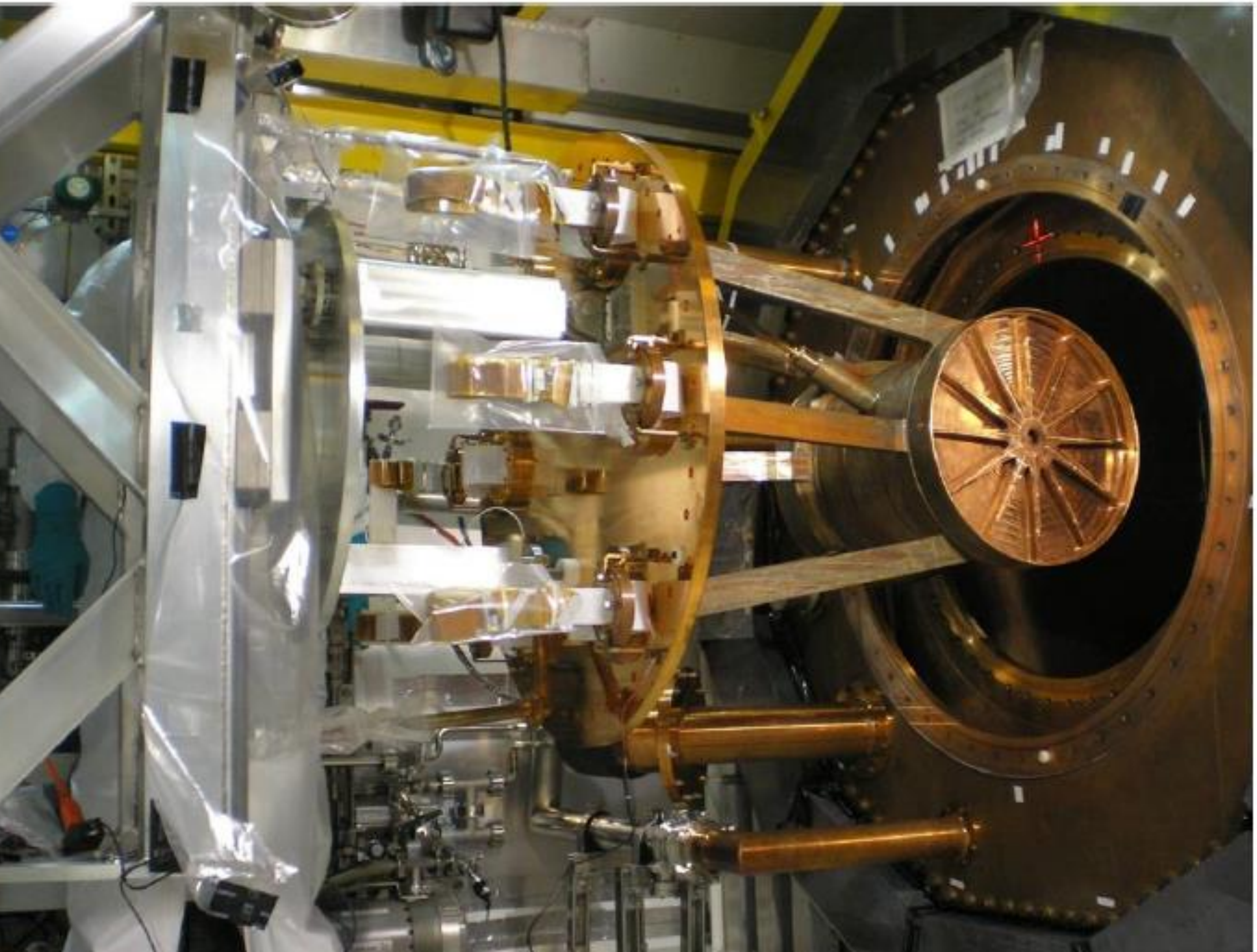


IV. $^{136}Xe(n,\gamma)^{137}Xe$, $^{136}Xe(n,2n)^{135}Xe$ and $^{136}Xe(n,n'\gamma)^{136}Xe$

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

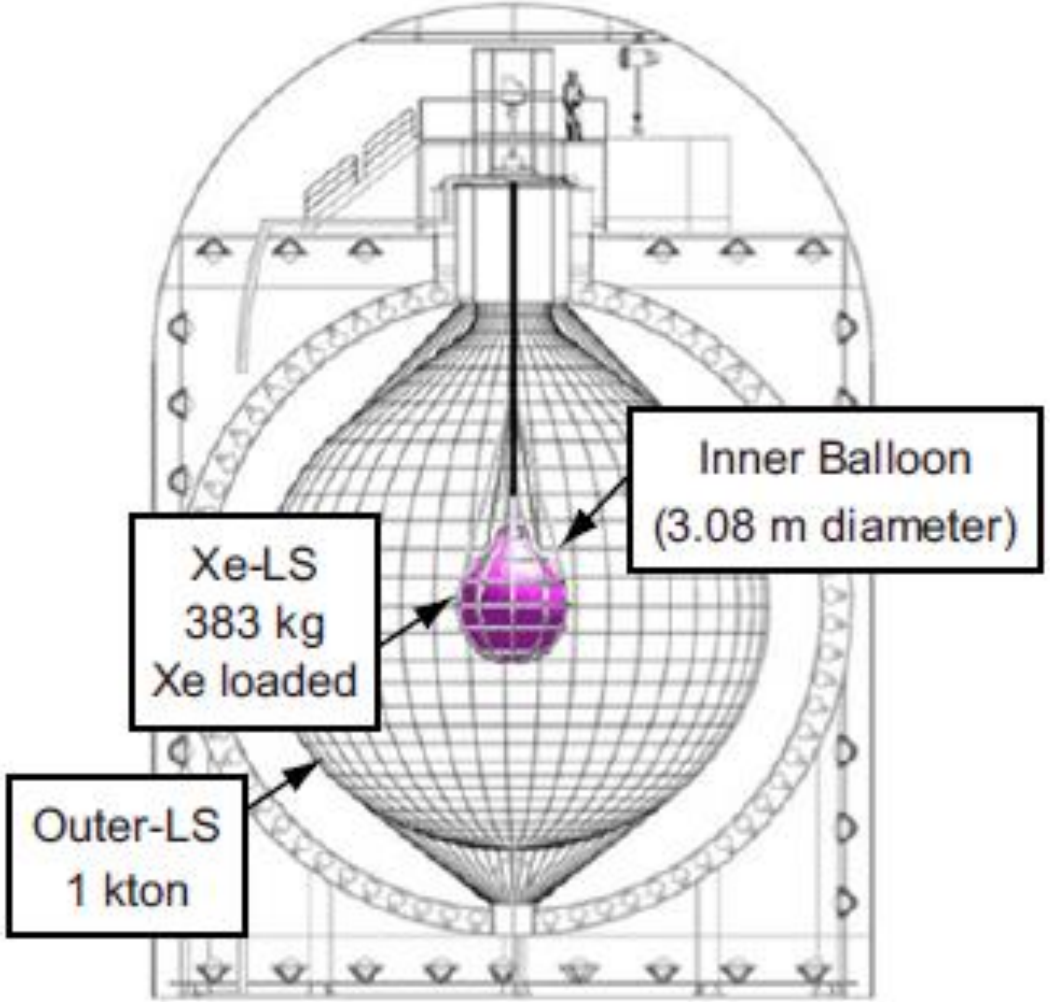


EXO-200

Xenon-based Time-Projection – Chamber

FV: 76.3 kg of ^{136}Xe

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

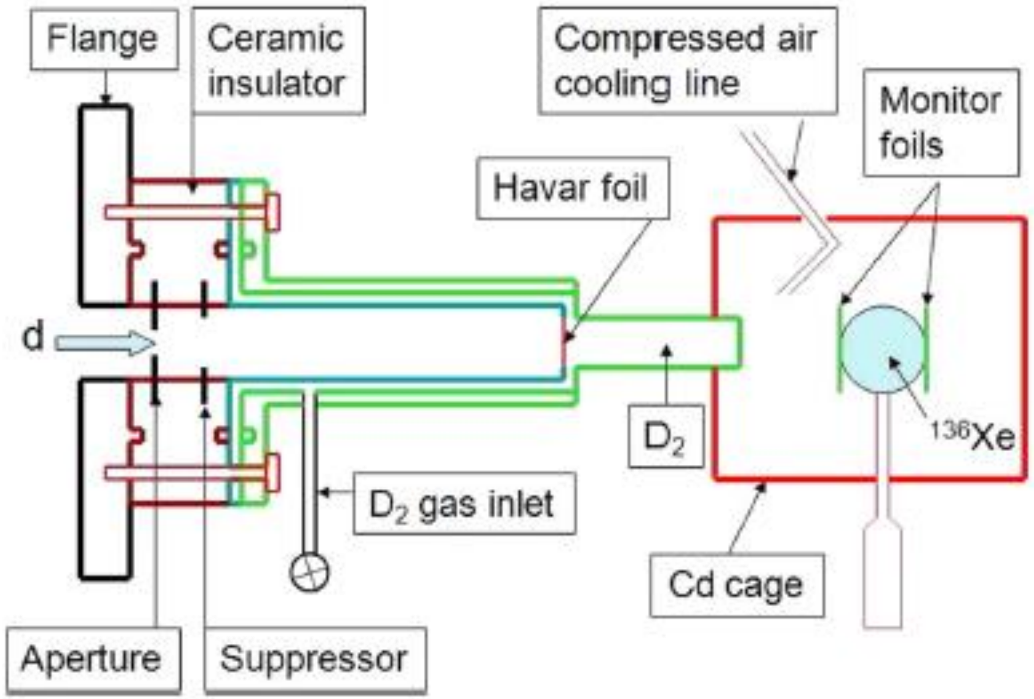


KamLAND-Zen

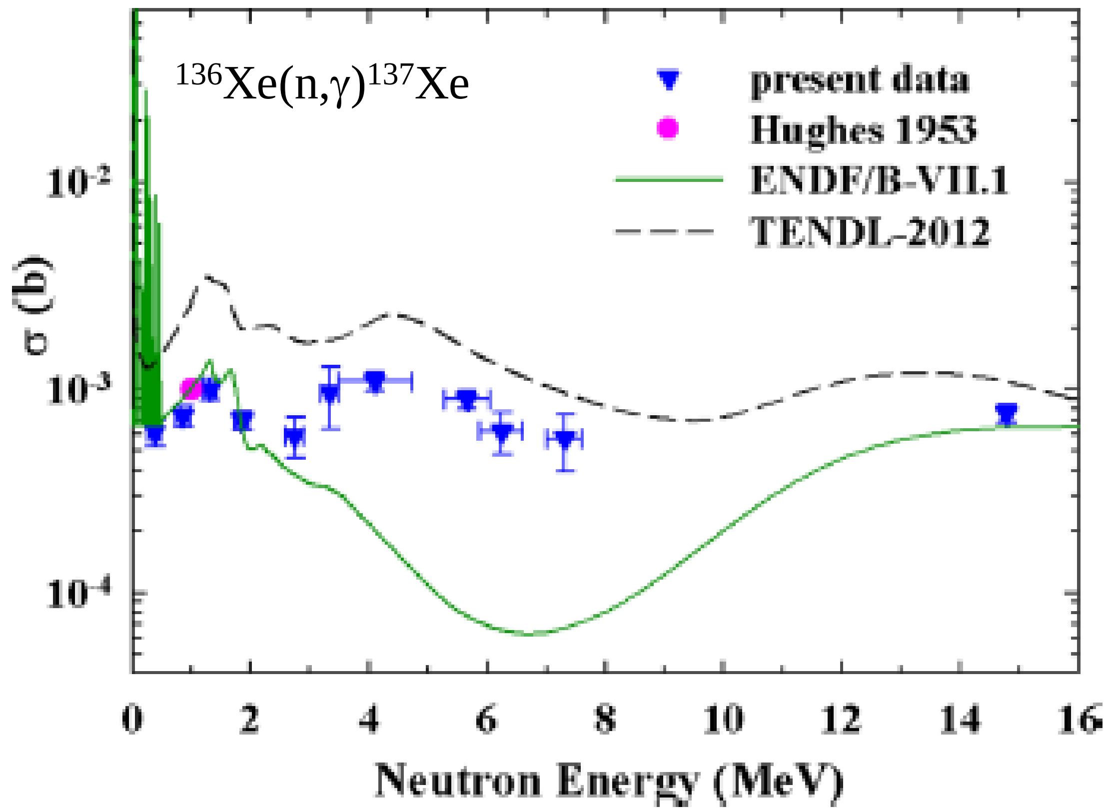
Xenon-loaded Liquid Scintillator

FV: 179 kg of ^{136}Xe

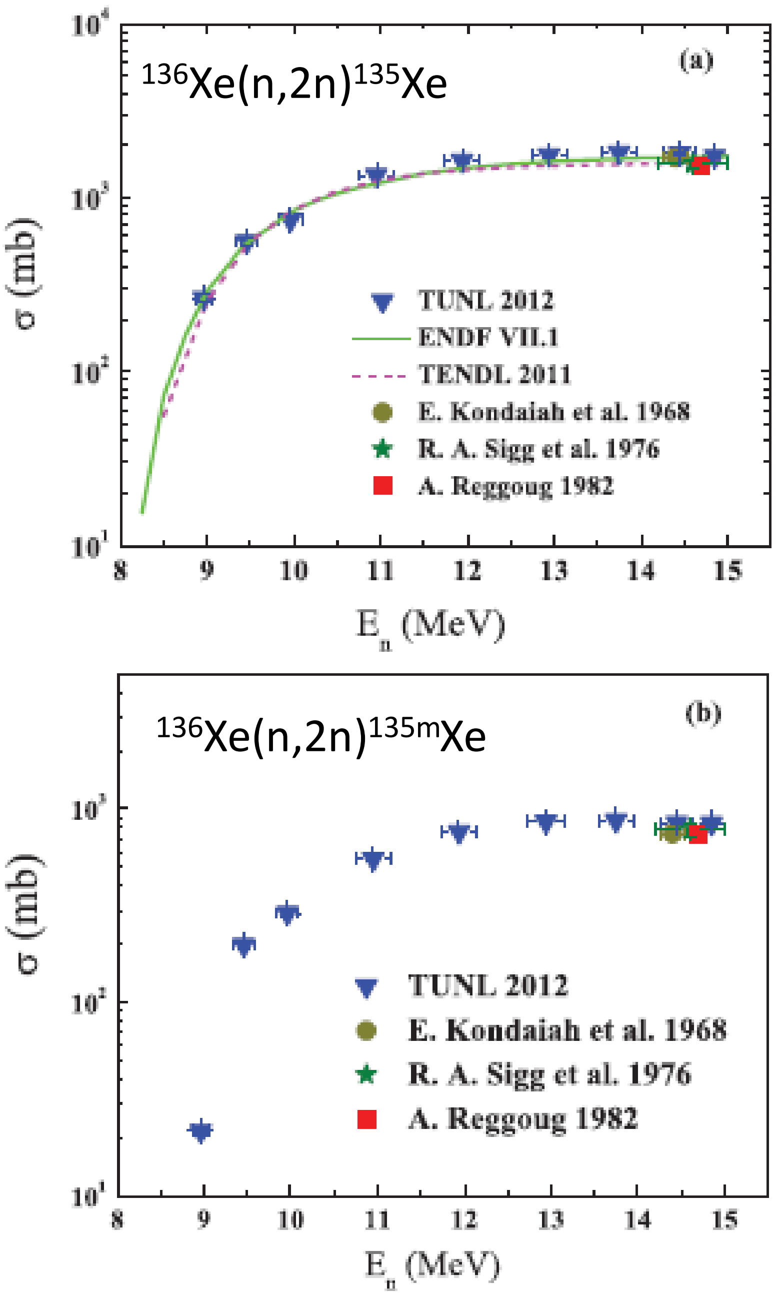
Kamioka Mine, Japan


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

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

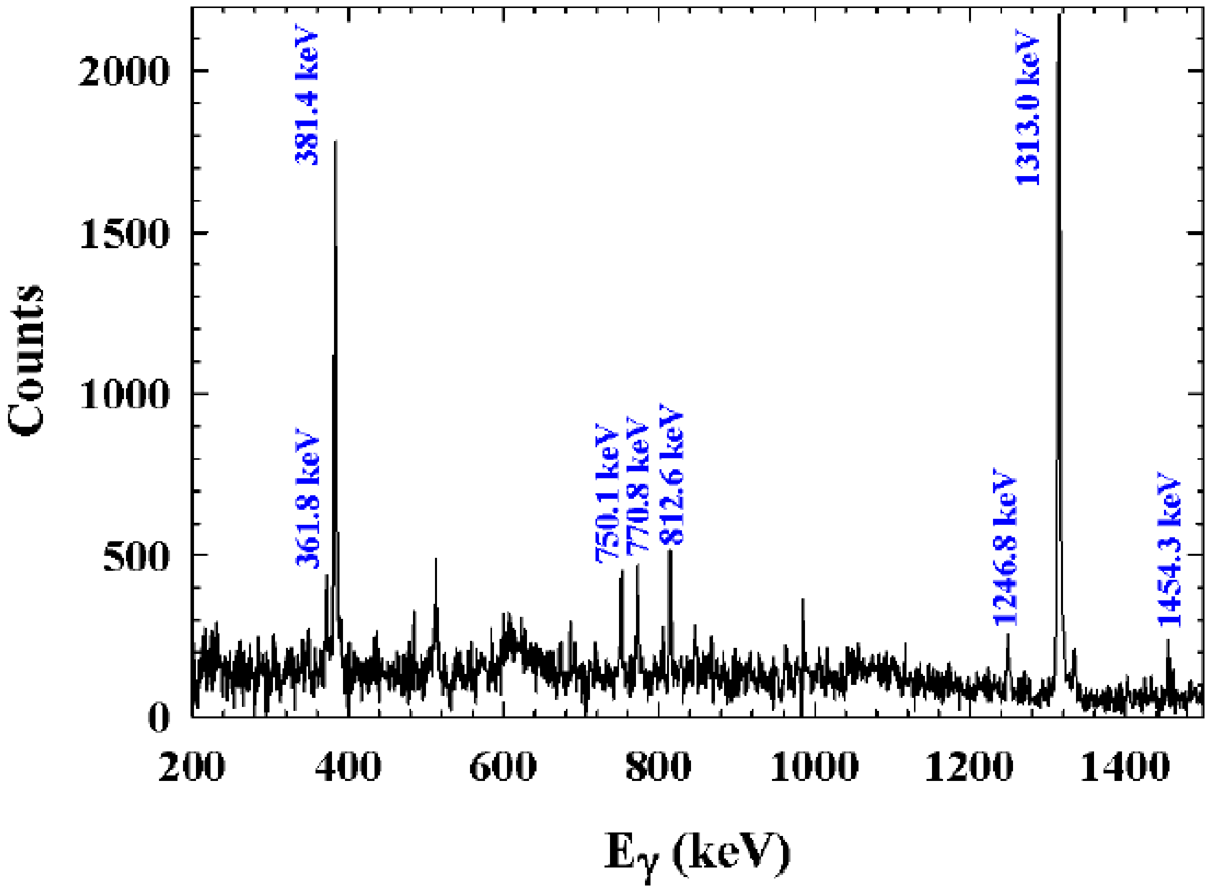


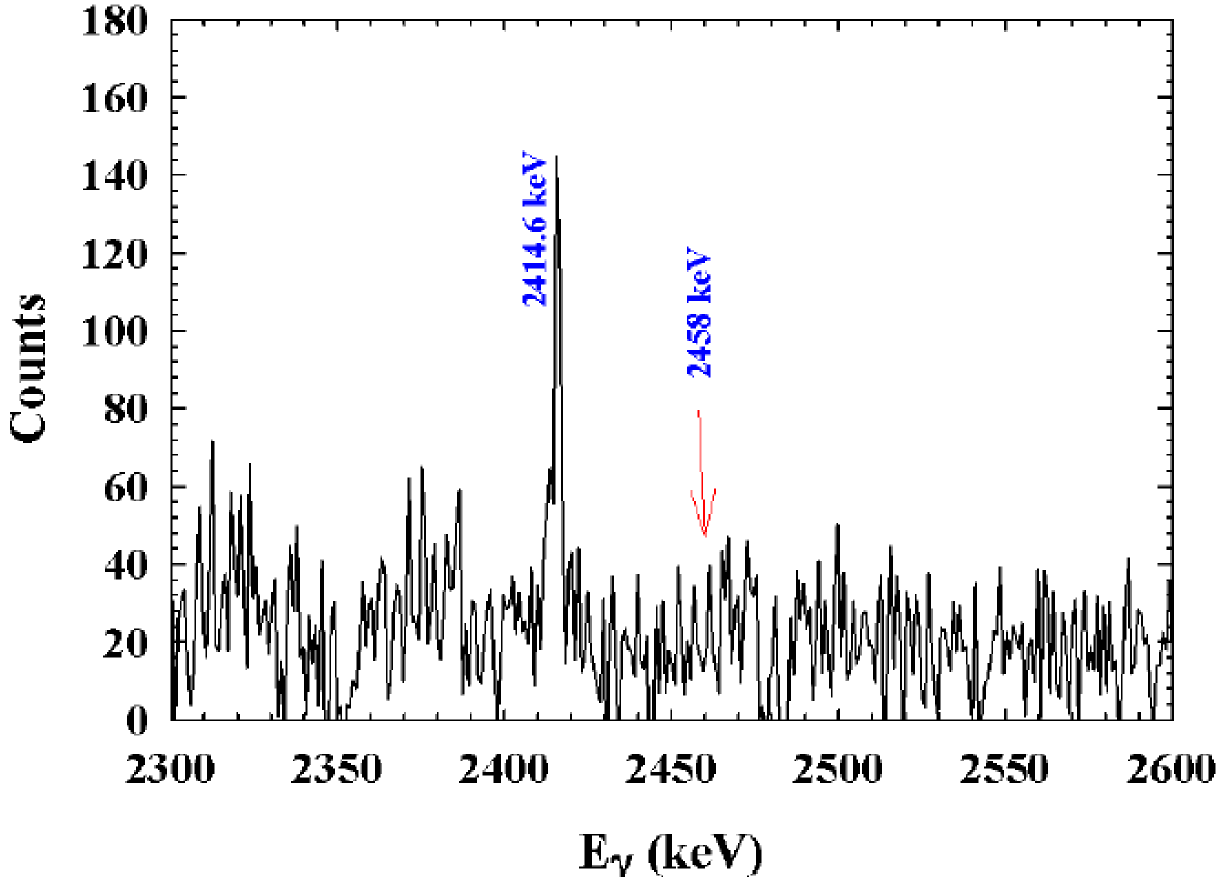
$^{136}Xe(n,2n)^{135}Xe$



$^{136}Xe(n,n'\gamma)^{136}Xe$

E_n=5 MeV





^{40}Ar

^{40}Ar(n,p)^{40}Cl from 9 to 12 MeV	C. Bhatia, S.W. Finch, M.E. Gooden, and W. Tornow, PRC **86**, 041602(R) (2012)
^{40}Ar(n,γ)^{41}Ar form 0.4 to 14.8 MeV	M. Bhike, B. Fallin, and W. Tornow, Phys. Letts. B **736**, 361 (2014)

^{76}Ge

^{76}Ge(n,p)^{76}Ga at 19 MeV	W. Tornow. M. Bhike, B. Fallin, and Krishichayan, PRC **93,** 014614 (2016)
^{74,76}Ge(n,γ)^{75,77}Ge from 0.4 to 8 MeV	M. Bhike, B. Fallin, Krishichayan, and W. Tornow, PLB **741**, 150 (2015)
^{76}Ge(n,2n)^{75}Ge from 9 to 15 MeV	M. Bhike, Krishichayan, and W. Tornow, submitted to PRC
^{74,76}Ge(n,n'γ)^{74,76}Ge from 4 to 15 MeV	Analysis almost completed

^{130}Te

^{128,130}Te(n,γ)1^{29,131}Te from 0.4 to 8 MeV	Completed, ready for publication
^{128,129}Te(n,2n)^{127,129T}e from 9 to 15 MeV	Analysis almost completed

^{136}Xe

^{136}Xe(n,γ)^{137}Xe from 0.4 MeV to 15 MeV	M. Bhike and W. Tornow, PRC **89**, 031602(R) (2014)
^{136}Xe(n,2n)^{135}Xe from 9 to 15 MeV	C. Bhatia, S.W. Finch, M.E. Gooden, and W. Tornow, PRC **87**, 011601(R) (2013)
^{136}Xe(n,n'γ)^{136}Xe	Work ongoing

Future Experiments

$^{134}Xe(n,\gamma)^{135}Xe$

$^{134}Xe(n,2n)^{133}Xe$

$^{134}Xe(n,n'\gamma)^{134}Xe$ (just starting)

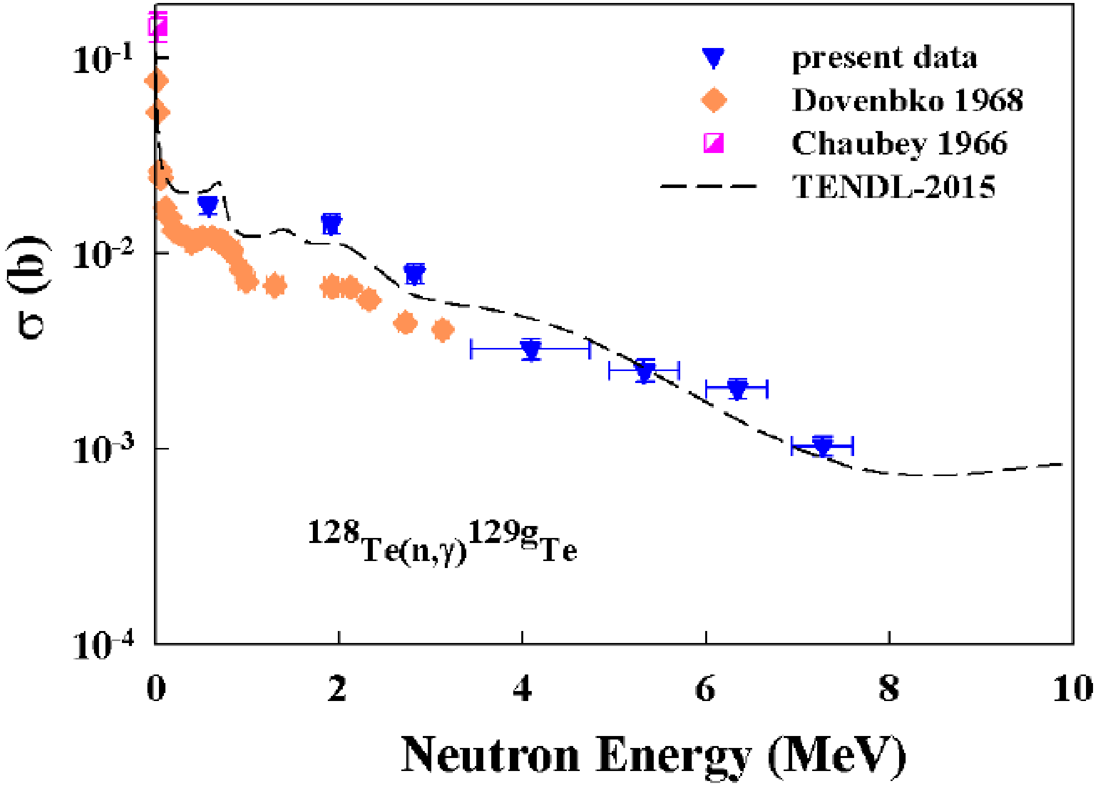
$^{128,130}Te(n,n'\gamma)^{128,130}Te$

$^{63,65}Cu(n,\gamma)^{64,66}Cu$ (halfway done done)

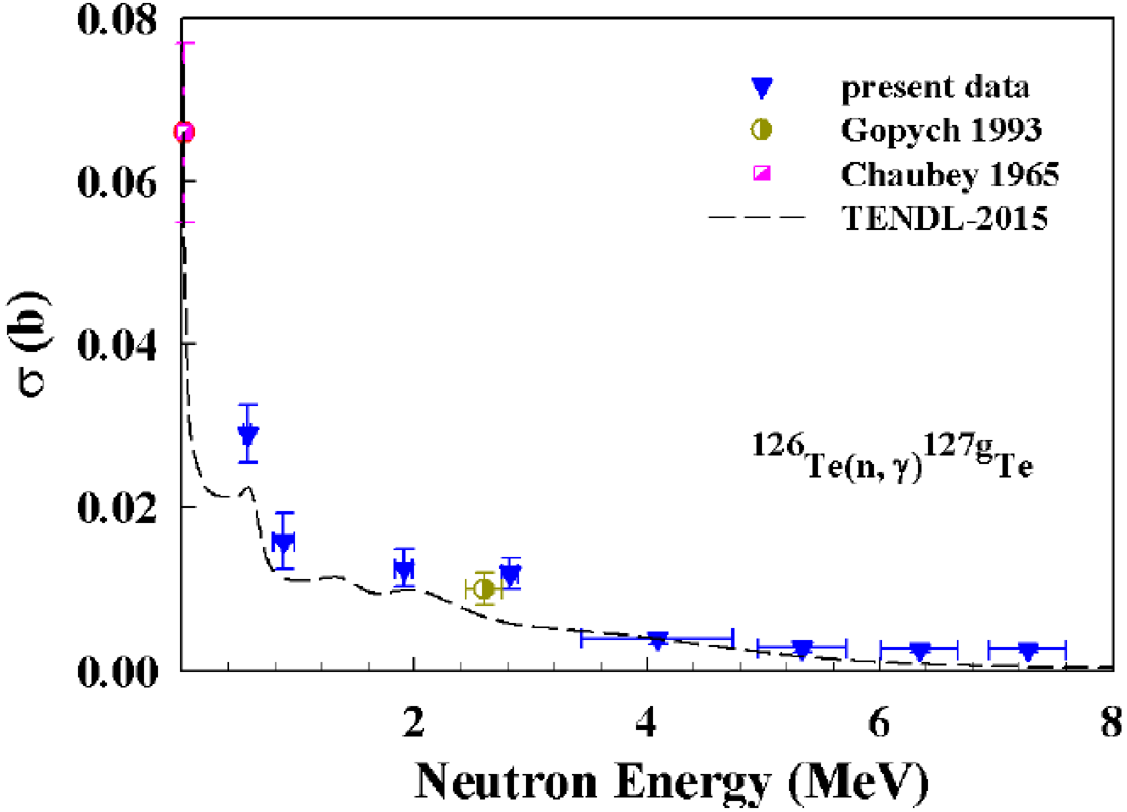
$^{63,65}Cu(n,2n)^{62,64}Cu$ (halfway done done)

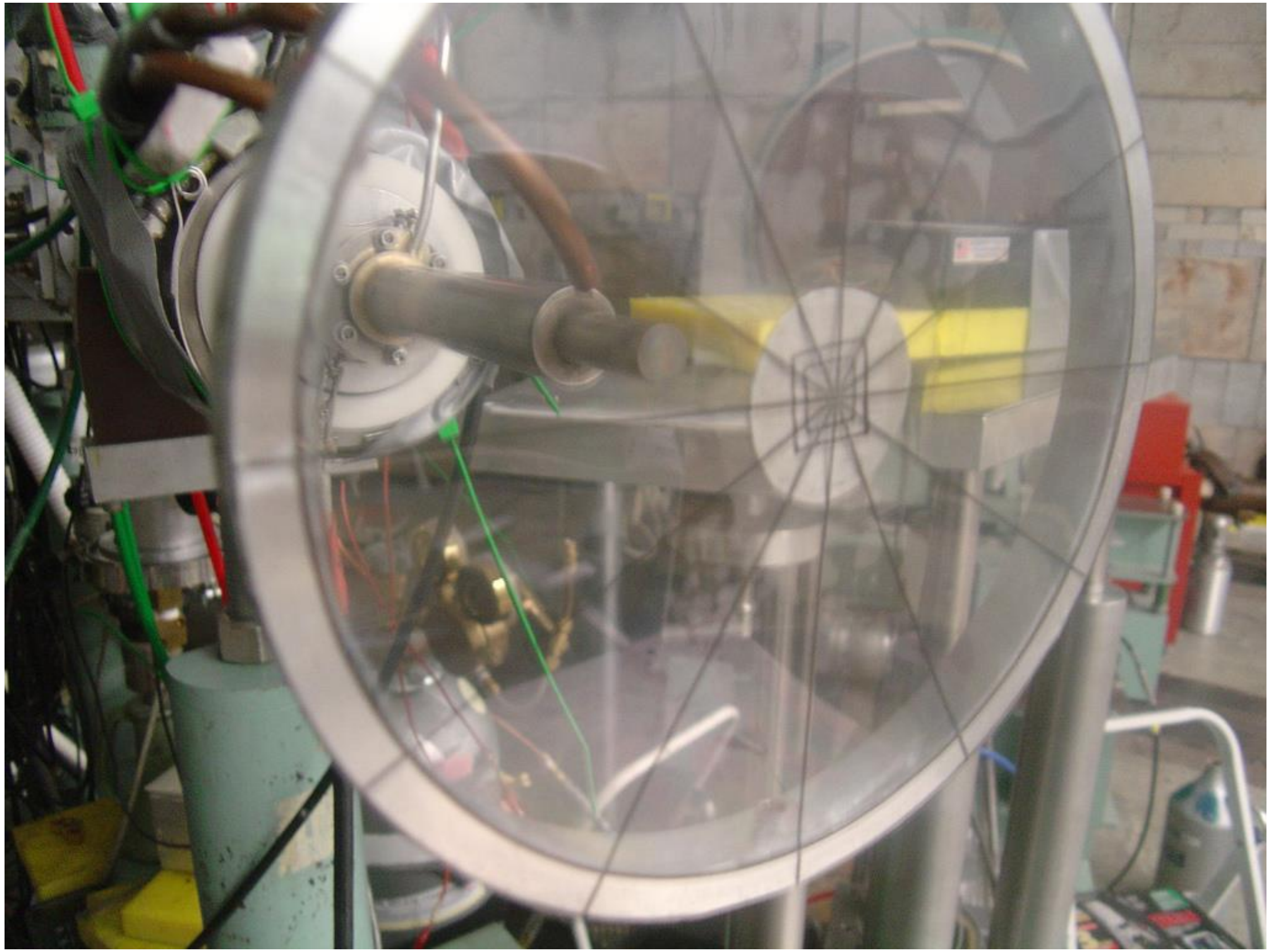
Thank you very much

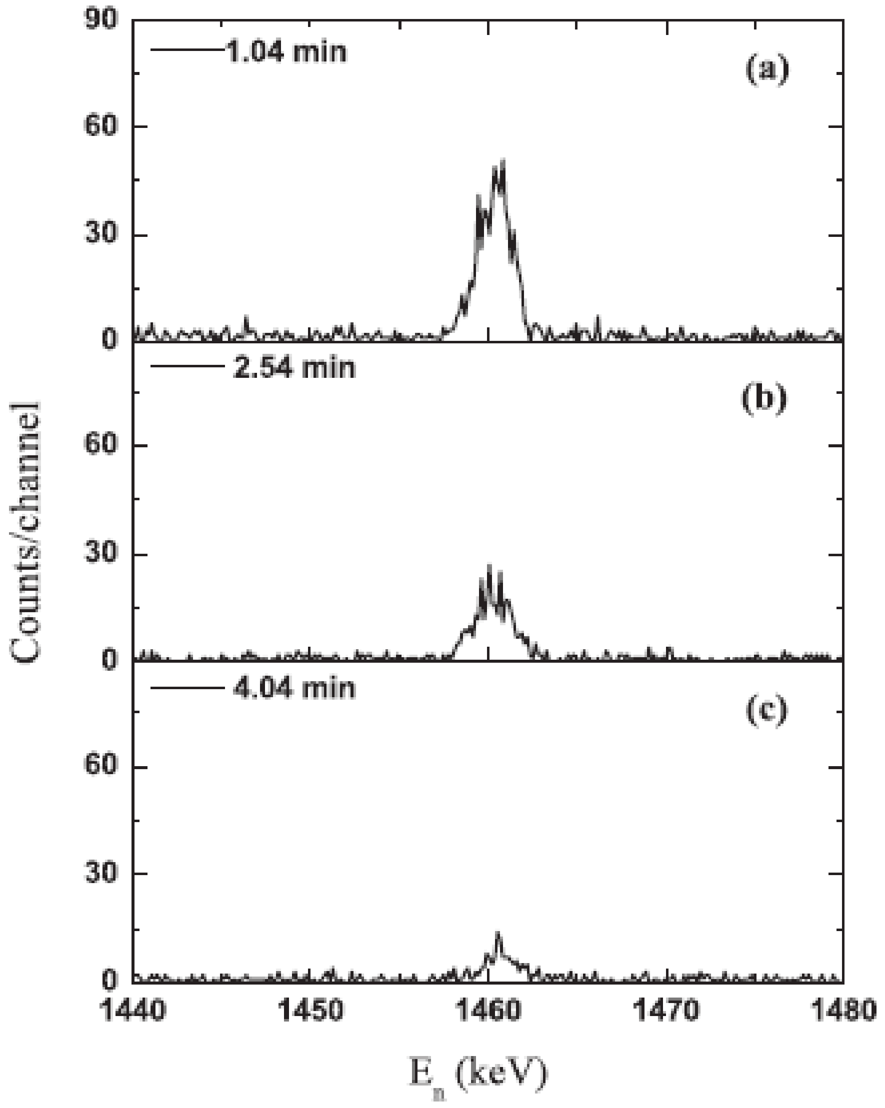
^{128}Te(n,γ)^{129}Te



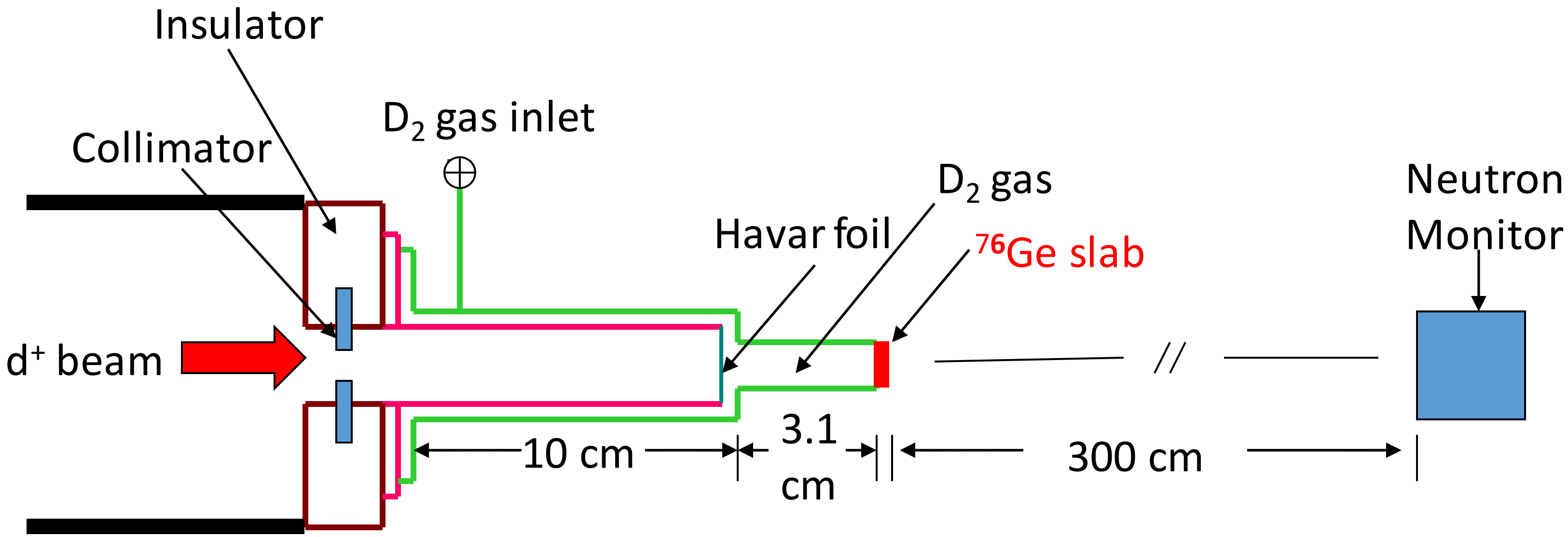
^{126}Te(n,γ)^{127}Te

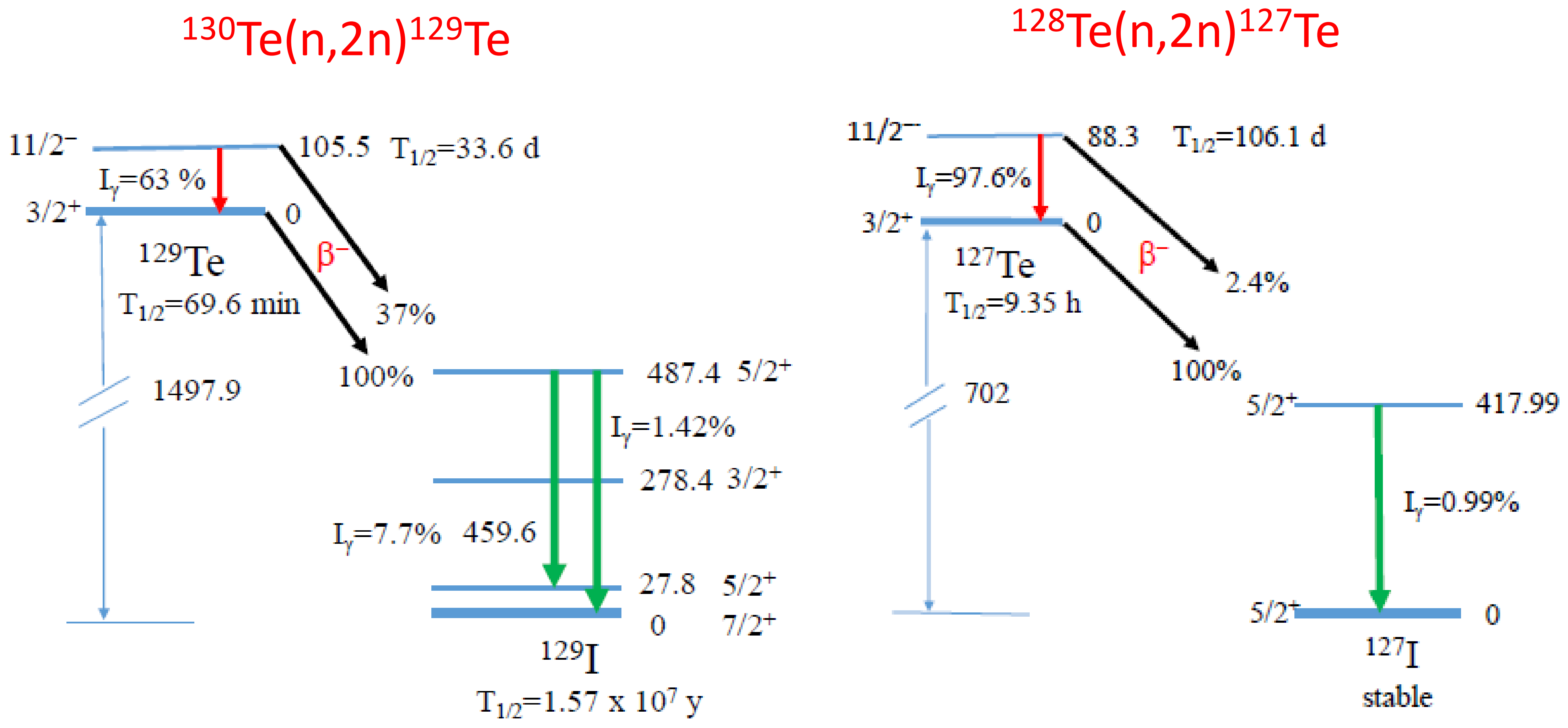




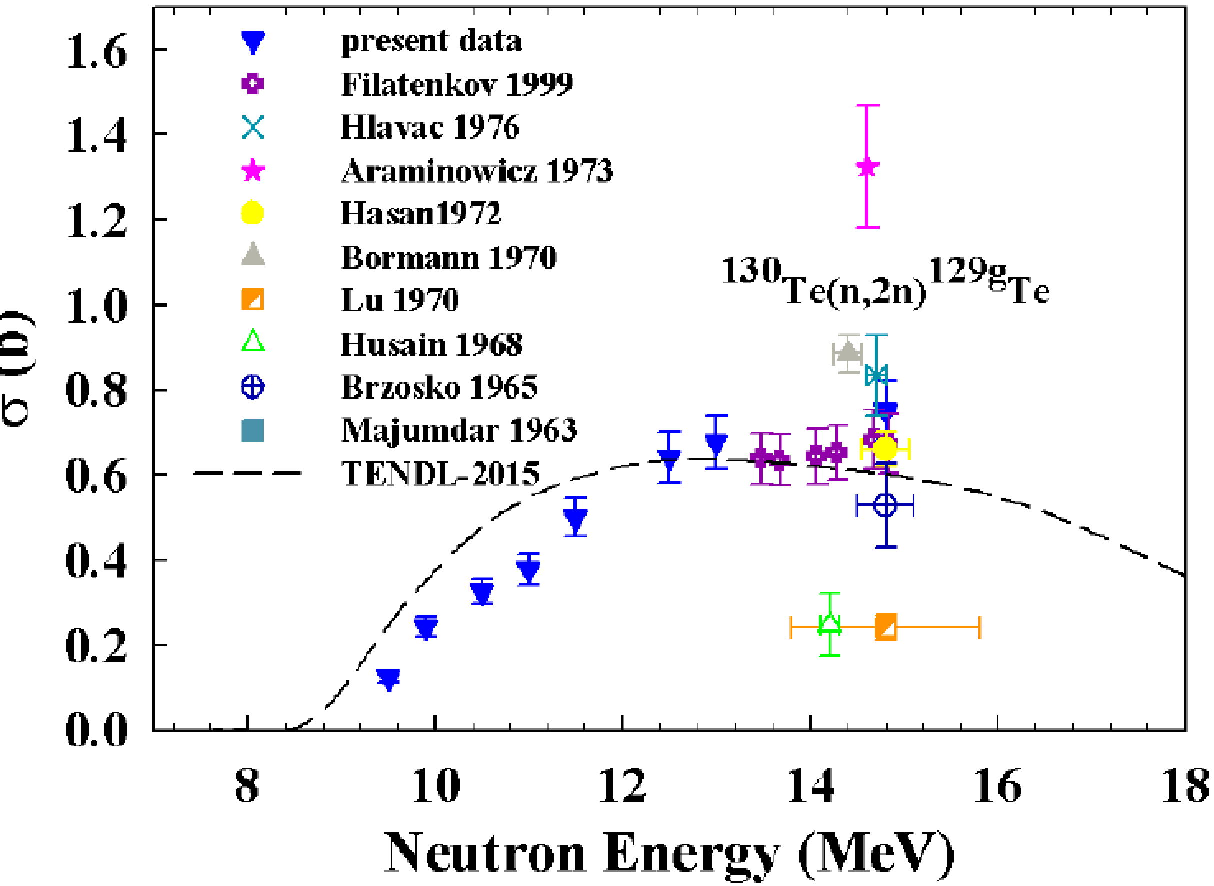


1.04 min
(a)
2.54 min
(b)
4.04 min
(c)
Counts/channel
90
60
30
0
1440
1450
1460
1470
1480
E_n (keV)

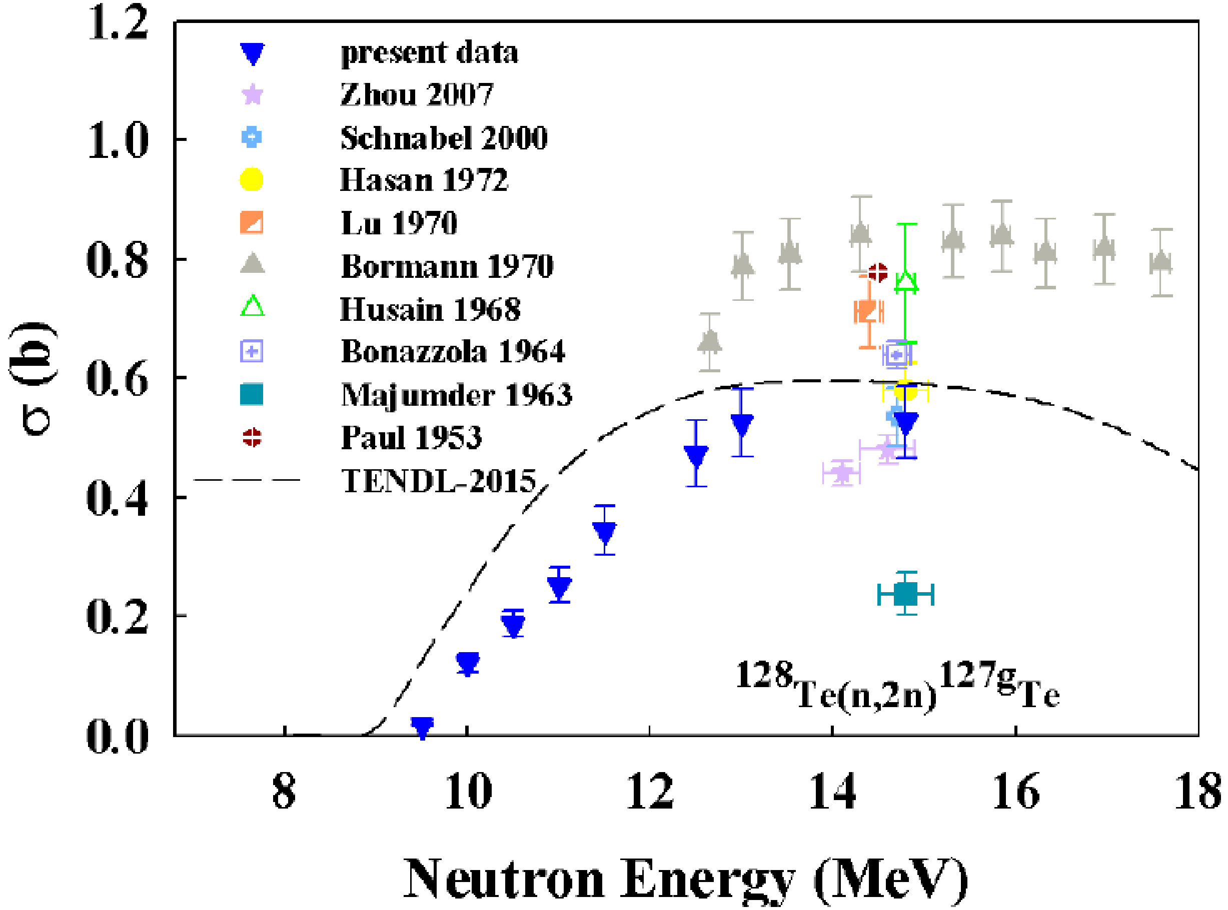

Insulator
Collimator
D_2 gas inlet
d⁺ beam
Havar foil
D_2 gas
^{76}Ge slab
Neutron Monitor
10 cm
3.1 cm
300 cm
//



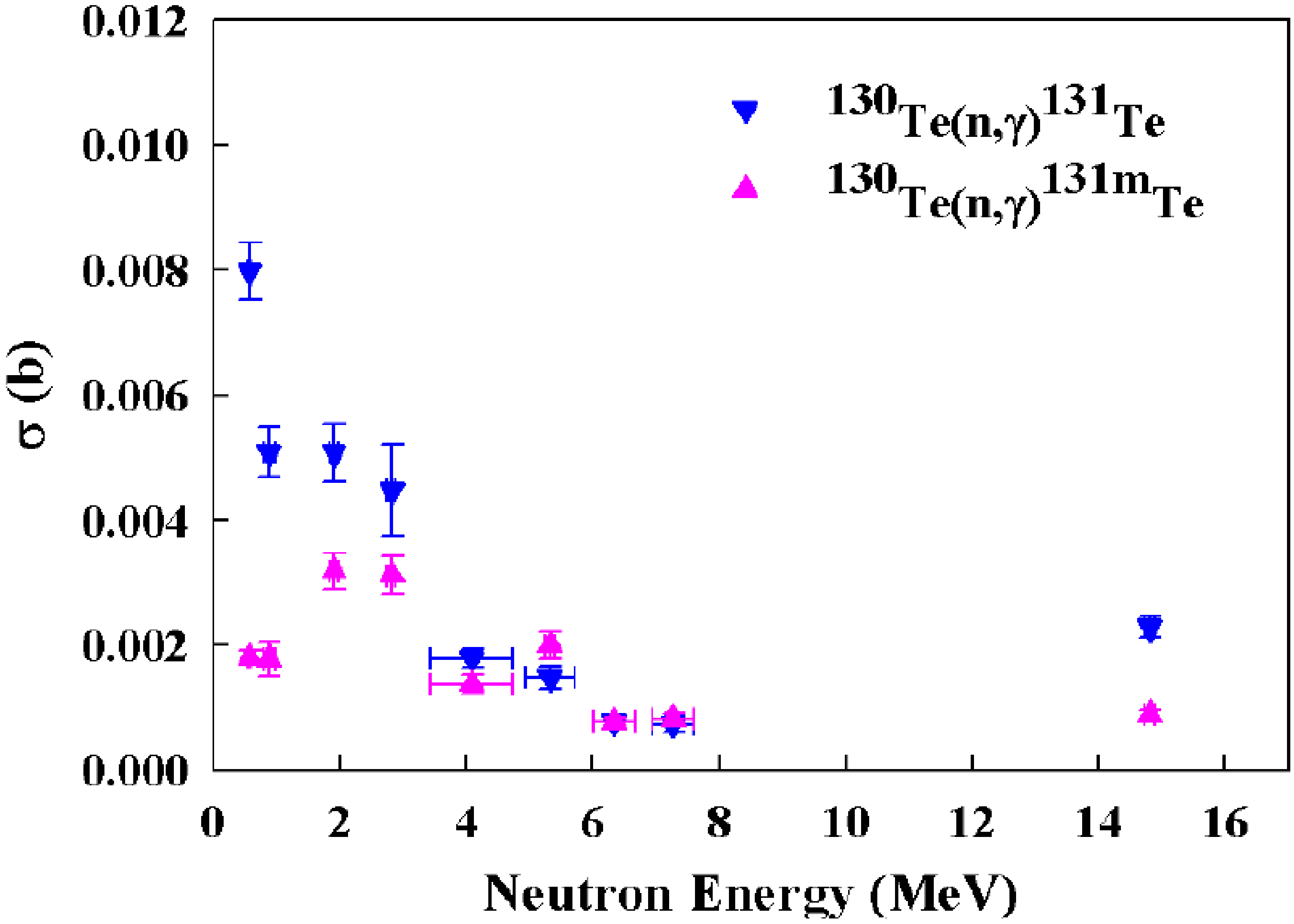
130Te(n,2n)129Te
11/2−
105.5
T1/2=33.6 d
Iγ=63 %
3/2+
0
129Te
T1/2=69.6 min
β−
37%
100%
1497.9
487.4 5/2+
Iγ=1.42%
278.4 3/2+
Iγ=7.7%
459.6
27.8 5/2+
0 7/2+
129I
T1/2=1.57 x 10^7 y
128Te(n,2n)127Te
11/2−
88.3
T1/2=106.1 d
Iγ=97.6%
3/2+
0
127Te
T1/2=9.35 h
β−
2.4%
100%
702
5/2+
417.99
Iγ=0.99%
5/2+
0
127I
stable



1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
σ (b)
8
10
12
14
16
18
Neutron Energy (MeV)
present data
Filatenkov 1999
Hlavac 1976
Araminowicz 1973
Hasan1972
Bormann 1970
Lu 1970
Husain 1968
Brzosko 1965
Majumdar 1963
TENDL-2015
130Te(n,2n)129gTe



1.2
1.0
0.8
0.6
0.4
0.2
0.0
σ (b)
8
10
12
14
16
18
Neutron Energy (MeV)
present data
Zhou 2007
Schnabel 2000
Hasan 1972
Lu 1970
Bormann 1970
Husain 1968
Bonazzola 1964
Majumder 1963
Paul 1953
TENDL-2015
128Te(n,2n)127gTe



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)
$^{130}Te(n,\gamma)^{131}Te$
$^{130}Te(n,\gamma)^{131m}Te$