Calculation and Mitigation of Neutron-Induced Backgrounds in Rare Event Search Experiments

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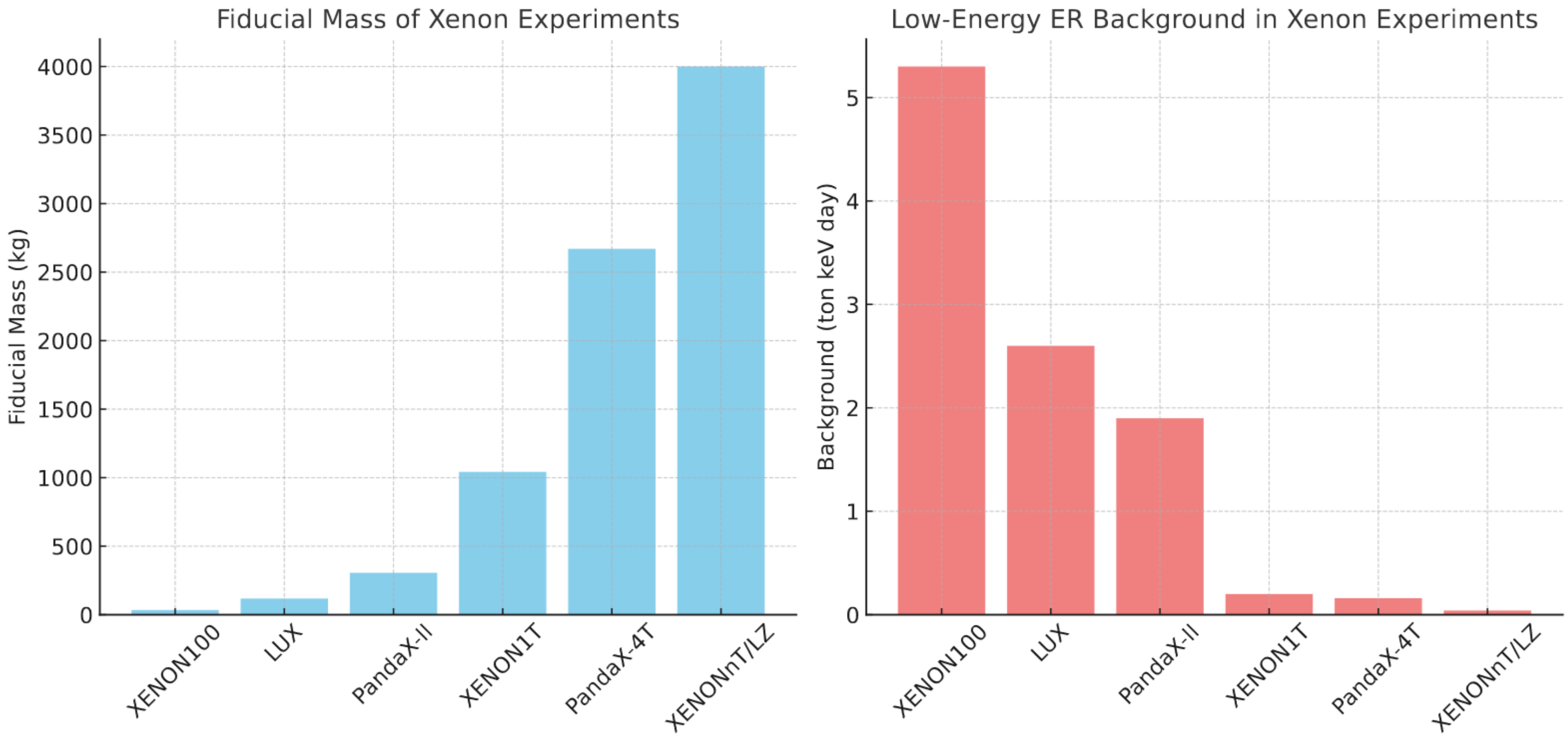
Low Radioactivity Techniques (LRT2024) 04/Oct/2024

Signal vs Background


Fiducial Mass of Xenon Experiments
Fiducial Mass (kg)
0
500
1000
1500
2000
2500
3000
3500
4000
XENON100
LUX
PandaX-II
XENON1T
PandaX-4T
XENONnT/LZ
Low-Energy ER Background in Xenon Experiments
Background (ton keV day)
0
1
2
3
4
5
XENON100
LUX
PandaX-II
XENON1T
PandaX-4T
XENONnT/LZ

WIMP Direct detection - backgrounds

Backgrounds:

- *β : ER*
- *γ : ER*

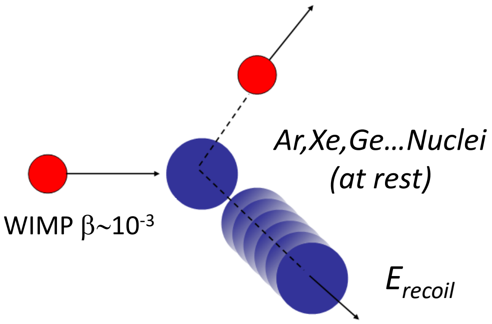
} > 10^{10} times the signal

- *α : higher energy depositions but degraded surface α and **(α,n)** reaction*
- *μ : materials activation above/under – ground. **Fast neutrons***

Mitigation strategies:

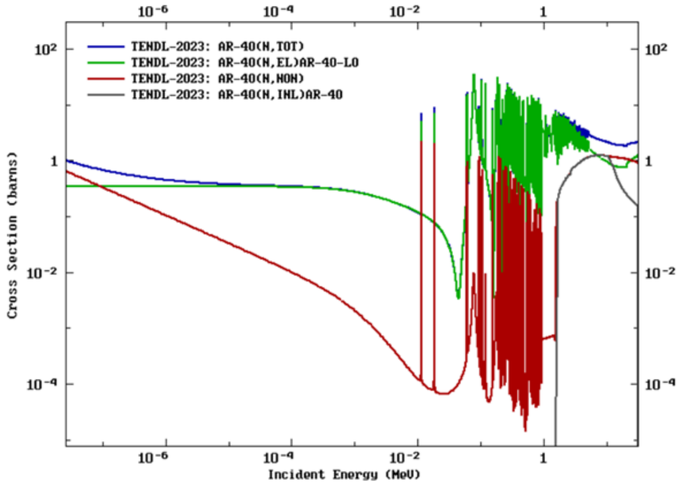
- ➢ Shielding (active+passive), Fiducial volume, ER discrimination techniques, materials radiopurity
- ➢ Surface treatment, Rn daughter (Pb-210 Po-210) polishing, material radiopurity
- ➢ Deep UG labs, active Muon Veto

WIMP Direct detection: neutrons



- *neutrons can produce nuclear recoil in the WIMP search region of interest*

→ ***Potential irreducible background***



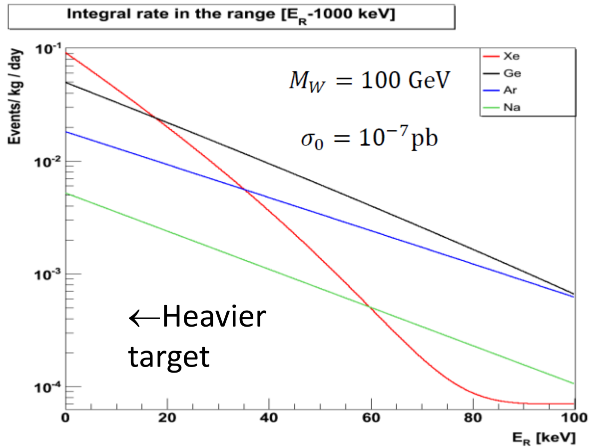
$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} e^{-\frac{E_R}{E_0 r}} F^2(q)$$

- $R_0 = \frac{2}{\sqrt{\pi}} \frac{N_A \rho_\chi}{A \cdot m_\chi} \sigma_0 v_0$
- $\sigma_0 = \sigma_n \frac{A^2}{m_n^2} \left(\frac{m_\chi m_N}{m_\chi + m_N} \right)^2$

Particle physics

Detector

DM halo



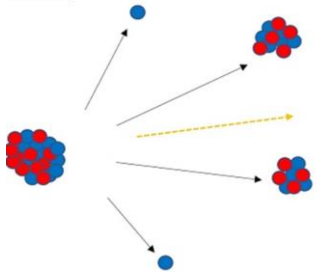
Neutrons and neutrino physics

- Inverse beta decay in SNO+: The combination of the prompt neutron signal with the delayed capture can mimic events relevant for the anti-neutrino analysis.
- $0\nu\beta\beta$: Gammas produced by neutron capture can fall in the region $Q_{\beta\beta}$
- Low energy studies in DUNE: Potential source of background for supernova and solar neutrino studies

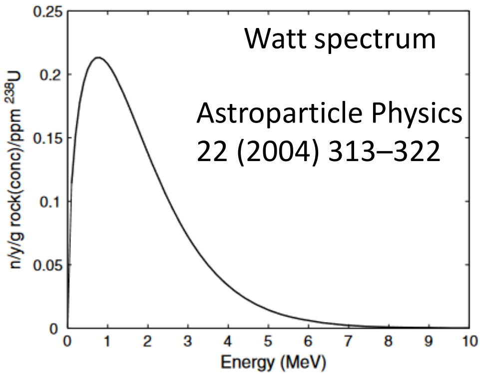
Neutrons production

Main processes contributing to neutron production:

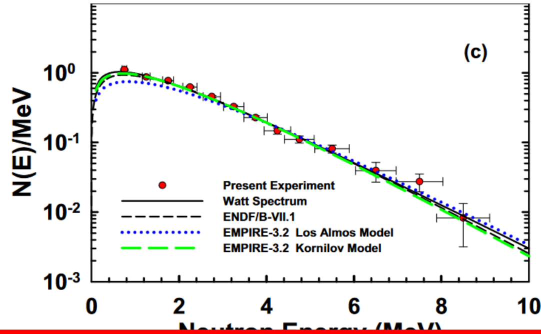
- **Spallation** reactions from muons in the detector material and the rock
- **Spontaneous fission**: mainly from ^{238}U, probability of about $5x10^{-7}$/chain (Generally dominates for high Z materials)



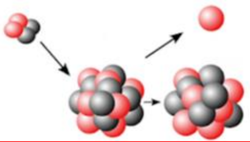
0.52 neutrons/year/g /ppm(^{238}U)
2.4 ± 0.2 n/fission



PHYSICAL REVIEW C 92, 014609 (2015)

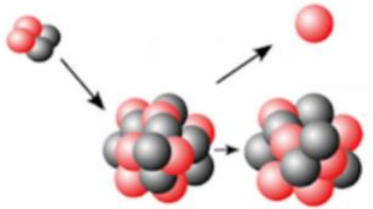


- **(α, n)** reactions: Generally is dominant source for low Z-materials (probability $>10^{-4}$ / α-decay)



- Depends on the alpha energy and on the target
- Wide spectrum in energy

Neutron yield calculation



$$Y_i(E_\alpha) = \frac{\eta_i}{\eta} \int_0^{E_\alpha} \frac{\sigma^i_{(\alpha,Xn)}(E)}{\varepsilon(E)} dE$$

E_α is the initial energy of the α particle;
η_i is the number density of nuclide i;
η is the number density of the material;
$\sigma^i(\alpha,Xn)(E)$ is the neutron production x-sec for the nuclide i
$\varepsilon(E) = -\frac{dE}{dx}$ is the stopping power of the material

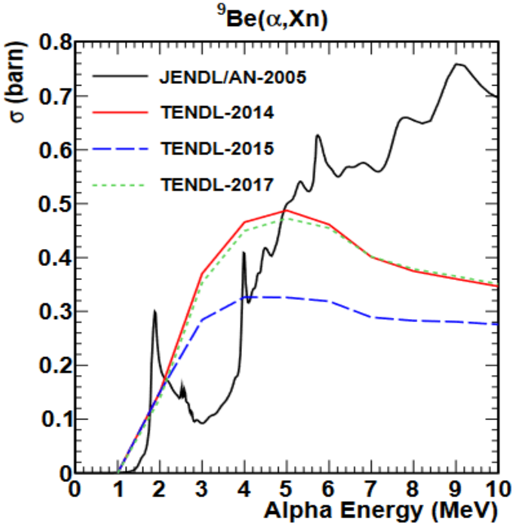
- Codes (SOURCES4C, NeuCBOT, SaG4n)
- Libraries (JENDL, TENDL…)

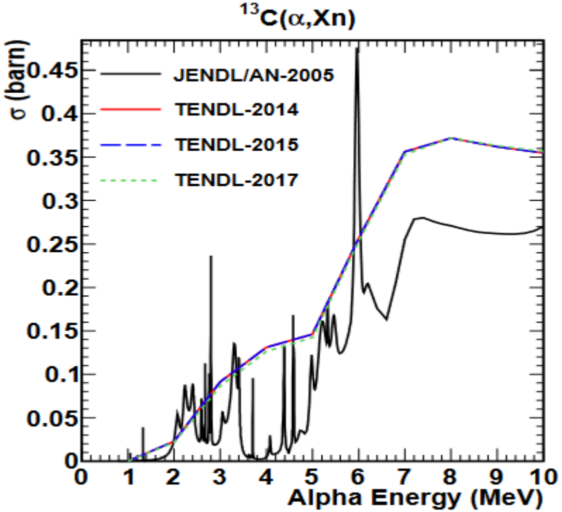
SaG4n: Simple and versatile tool provided to the community SaG4n (http://win.ciemat.es/SaG4n/)
"Neutron production induced by α-decay with Geant4", Nucl. Instrum. Methods A 960, 163659 (2020)

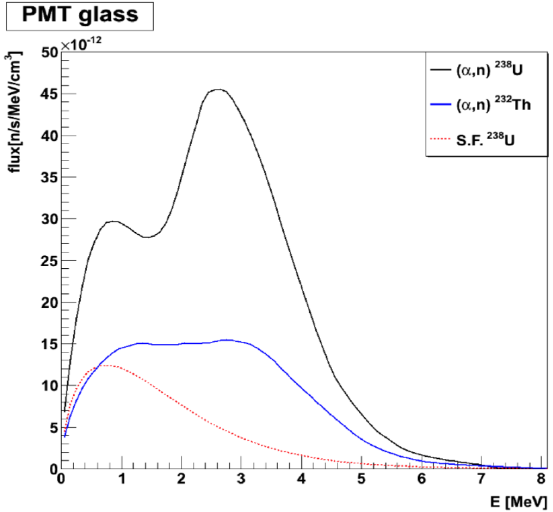
- Exploiting evaluated libraries (JENDL)
- Detailed geometries (actual geometry and border effects)
- Neutron transport, precise tracking
- Biasing techniques

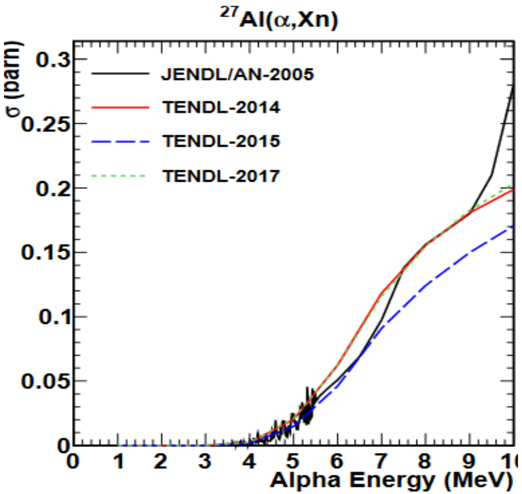
Very challenging task

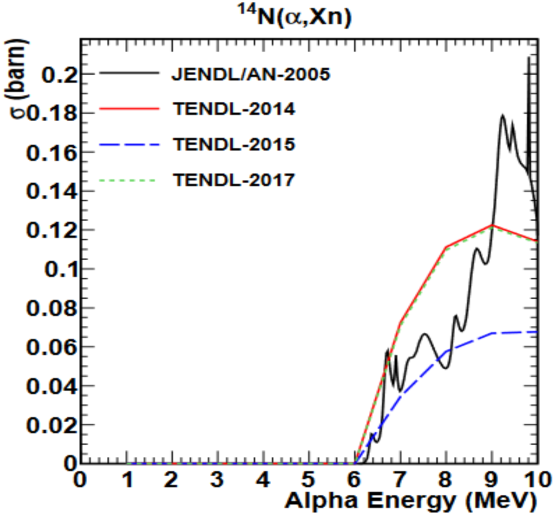
- Missing experimental data (truly evaluated cross-sections)
- Discrepancies between exp. results (differences in the setups or the corrections applied)
- Uncertainty on the theoretical models used to evaluate the (α, n) reactions
- Missing data for the correlated γ-ray emission

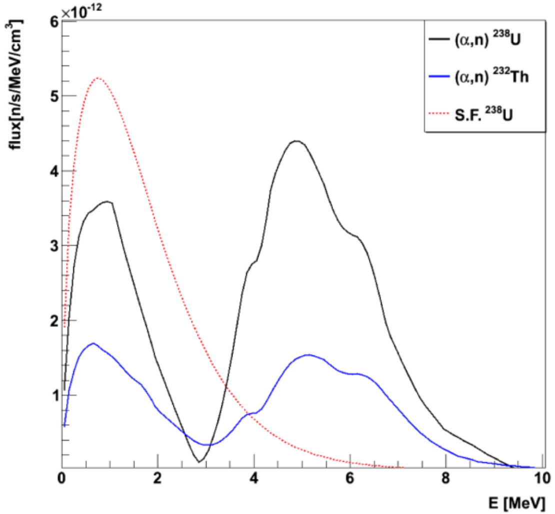

^{9}Be(α,Xn)
σ (barn)
JENDL/AN-2005
TENDL-2014
TENDL-2015
TENDL-2017
Alpha Energy (MeV)


^{13}C(α,Xn)
σ (barn)
JENDL/AN-2005
TENDL-2014
TENDL-2015
TENDL-2017
Alpha Energy (MeV)


PMT glass
×10^{-12}
flux[n/s/MeV/cm^3]
(α,n) ^{238}U
(α,n) ^{232}Th
S.F. ^{238}U
E [MeV]

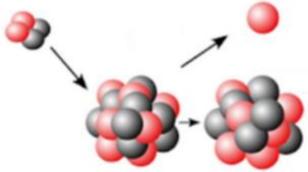

^{27}Al(α,Xn)
σ (barn)
JENDL/AN-2005
TENDL-2014
TENDL-2015
TENDL-2017
Alpha Energy (MeV)


^{14}N(α,Xn)
σ (barn)
JENDL/AN-2005
TENDL-2014
TENDL-2015
TENDL-2017
Alpha Energy (MeV)


×10^{-12}
flux[n/s/MeV/cm^3]
(α,n) ^{238}U
(α,n) ^{232}Th
S.F. ^{238}U
E [MeV]

(α,n) white paper

[2405.07952](https://arxiv.org/abs/2405.07952)



Multidisciplinar WG on (α,n) neutron yield studies

alphan@ciemat.es

Members of several DM experiments + Neutrino + Nuclear + IAEA:

- DarkSide-20k
- XENON
- LZ
- CRESST …

White paper on (α, n) neutron yield calculations

D. Cano-Ott,[1] S. Cebrián,[2] M. Gromov,[3,4] M. Harańczyk,[5] A. Kish,[6] H. Kluck,[7] V. A. Kudryavtsev,[8] I. Lazanu,[9] V. Lozza,[10,11] G. Luzón,[2] E. Mendoza,[1] M. Parvu,[9] V. Pesudo,[1] A. Pocar,[12] R. Santorelli,[1,a] M. Selvi,[13] S. Westerdale,[14] and G. Zuzel[5]

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(Dated: Tuesday 28th May, 2024- 00:28, Version: F1.0)

Understanding the radiogenic neutron production rate through the (α, n) reaction is essential in many fields of physics like dark matter searches, neutrino studies, nuclear astrophysics and medical physics. This white paper provides a review of the current landscape of (α, n) yields, neutron spectra and correlated γ-rays calculations, and describes the existing tools and the available cross sections. The uncertainties that contribute to (α, n) yield calculations are also discussed with plans for a program to improve the accuracy of these estimates. Novel ideas to measure (α, n) cross sections for a variety of materials of interest are presented. The goal of this study is to reduce the uncertainty in the expected sensitivity of next-generation physics experiments in the keV–MeV regime.

CONTENTS

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arXiv:2405.07952v2 [nucl-ex] 25 May 2024

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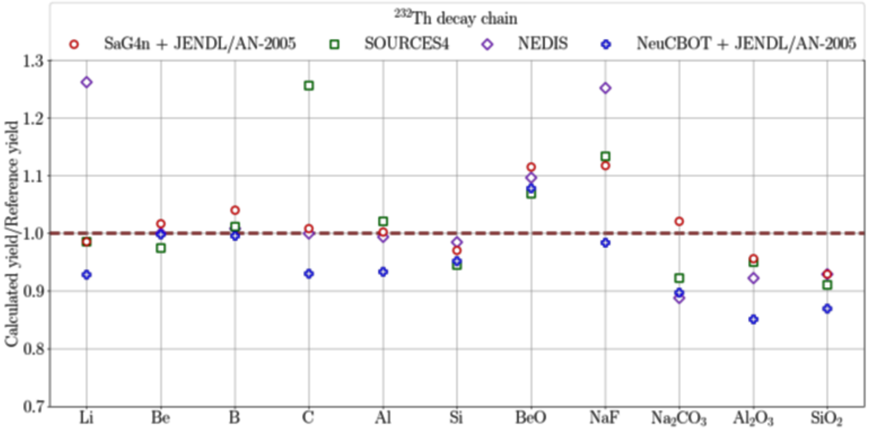
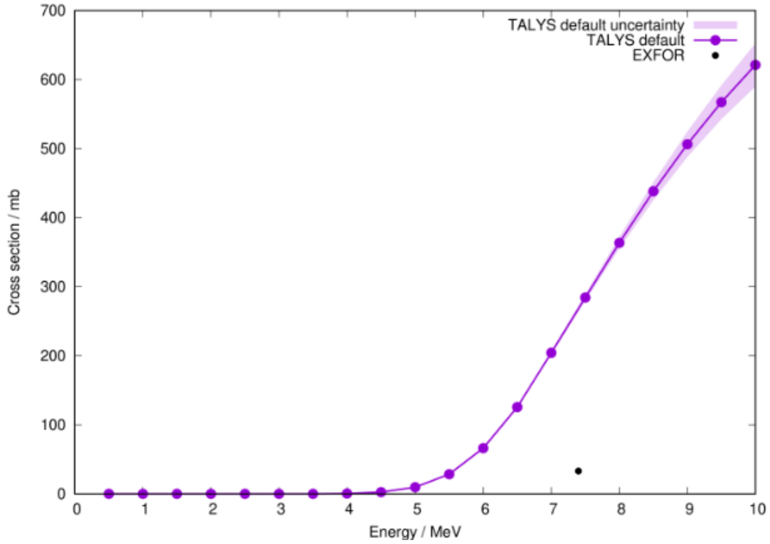


Neutron yields calculated for light nuclei by applying different codes,
(The numerical values are normalized to evaluated data from various alpha-beam measurements)

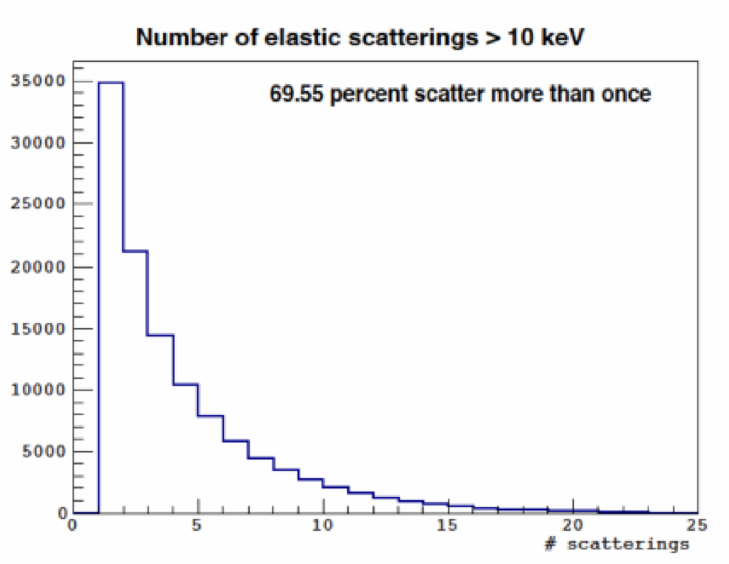


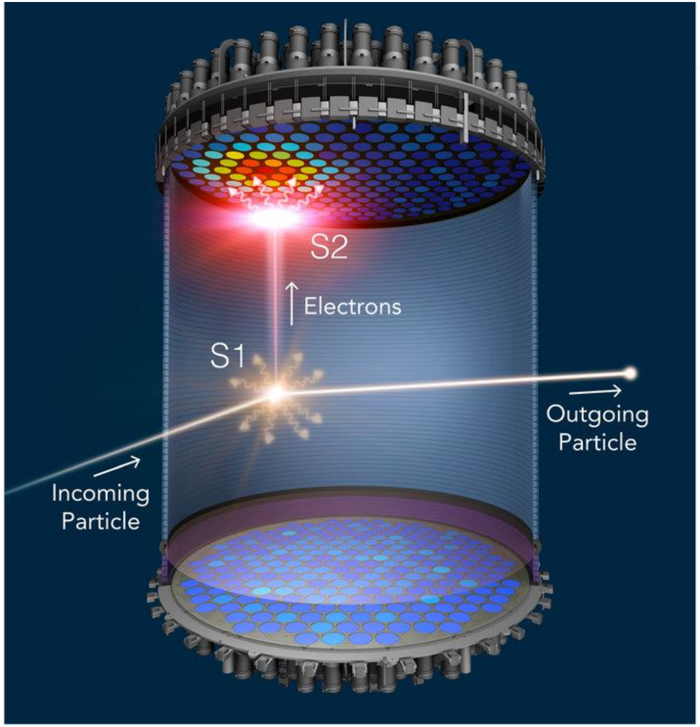
Excitation function for 40Ar(α, n) as calculated with TALYS 1.96 (*line*) based on default settings with the associated uncertainty (*band*) is based on sampling the input parameter space

Rejection / Mitigation of the neutron background

- Neutrons
  - Tagging
    - Multiplicity (target tagging)
    - Veto (external tagging)
  - Mitigation
    - Material composition
    - Radiopurity

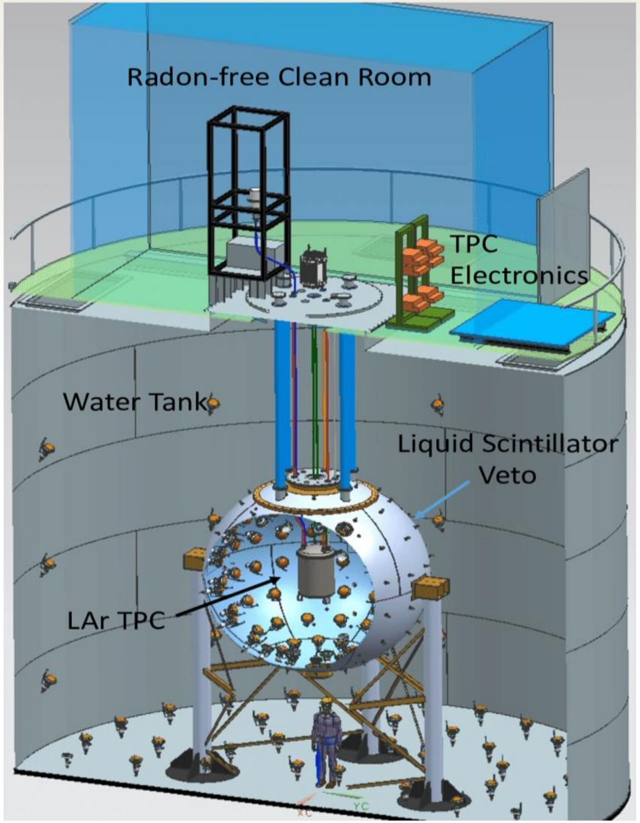
Multiplicity

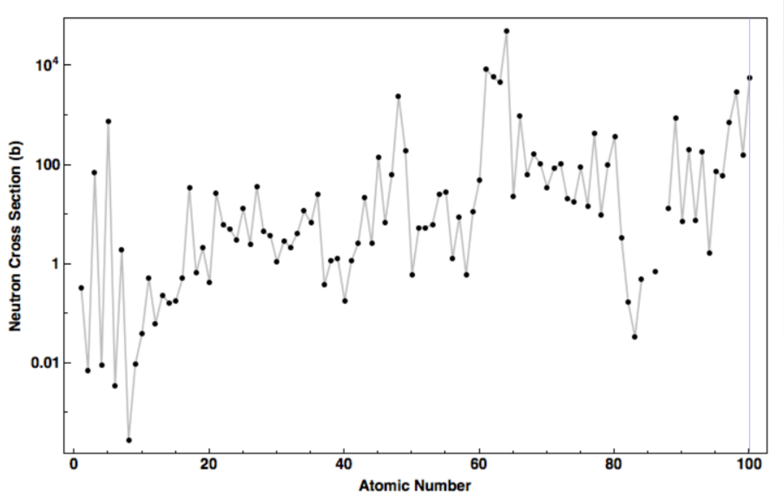




~70% of neutrons produce multiple site events (MC)

Veto Rejection





Gd-doped acrylic

➢ *JINST* 19 (2024) 09, P09021

- Gadolinium oxide nanoparticles dispersed in poly(methyl methacrylate) (PMMA) matrix.
- A few percent of gadolinium (Gd) by weight
- Key advantage: capture cross-section

Issues:

- Operation in liquid argon at 87 K
- Full containment of Gd (no dispersion into the environment)
- Homogeneous distribution of gadolinium / sufficient concentration : neutron tagging inefficiency < 10^{-6}
- Scalability / cost / radioactivity

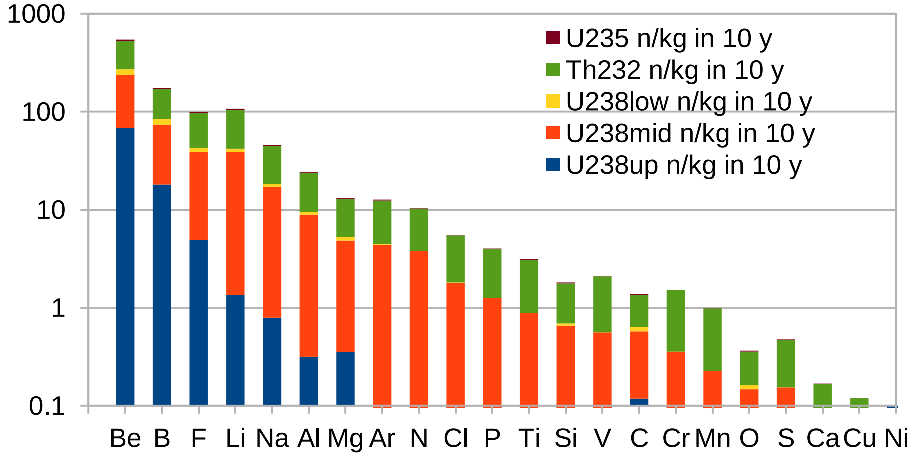
Parameter	Value
Gd concentration (weight)	0.5% < Gd < 1%
Gd homogeneity	≃ 50%
Transparency of the hybrid Gd-PMMA material	not necessary
Machinable	yes
Stable at 87 K	yes
Thickness[a]	~ 17 cm
Maximum size [a]	sheets of ~ 4 m × 2 m
^{238}U, ^{235}U, ^{232}Th activity of Gd_2O_3	< 20 mBq/kg
γ contaminants activity of Gd_2O_3	< 2 mBq/kg
Amount needed [a]	about 20 t

Isotope	A [mBq/kg]
^{235}U	< 0.64
^{238}U/^{234m}Pa	< 17
^{238}U/^{226}Ra	< 0.26
^{232}Th/^{228}Ac	0.4 ± 0.2
^{232}Th/^{228}Th	0.4 ± 0.2
^{40}K	14 ± 3
^{137}Cs	< 0.24

Mitigation: Material selection

- Carbon (^{13}C - 1.06%): liquid scintillators, plastics (acrylic, polyethylene, nylon, PTFE), SS
- Oxygen (^{17}O - 0.03% and ^{18}O - 0.2%): water liquid scintillators, plastics and rock
- Nitrogen (^{14}N – 99%): plastics, wavelength shifters, fluors used in liquid scintillators
- Aluminum (^{27}Al – 100%): resistors, ceramics
- Fluorine (^{19}F – 100%): component of PTFE
- Beryllium (^{9}Be – 100%) present in wires
- Titanium & Copper: used in cryostats, shielding, support structures,
- Silicon: present in quartz, glass, light sensors

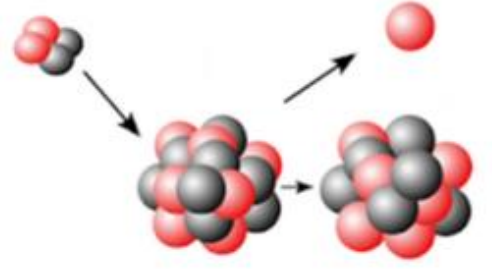
➢ Values for 1 ppb Th-232 and U-238 (U-235 with its natural abundance)



Mitigation: Radiopurity

Potential alpha sources:

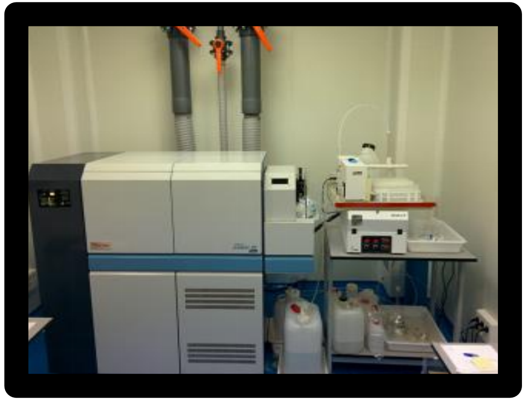
- U & Th chain decays in the target material + detector's structure
- ^{210}Po from Rn decay plating onto surfaces (accumulation over time, long lived ^{210}Pb)
- Rn (freshly introduced or emanated)



Strategy:

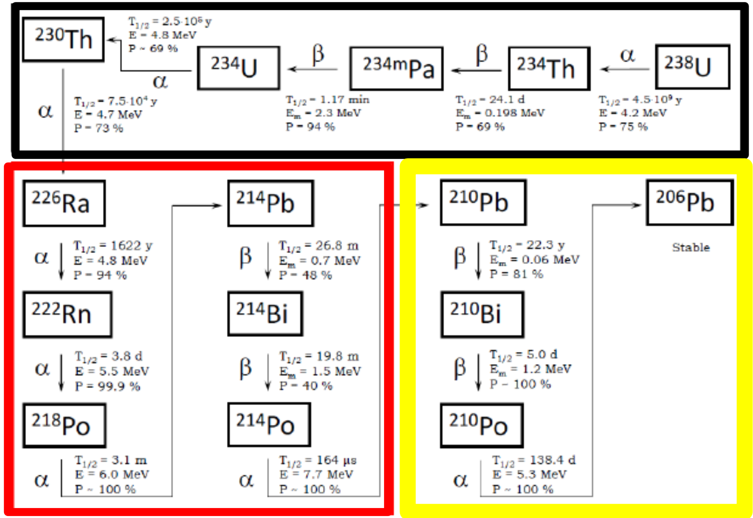
→ Extensive material assay campaign

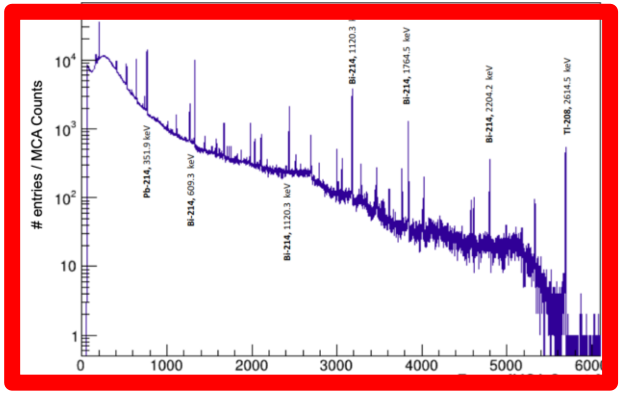
Equilibrium in the U-238 chain



ICPMS

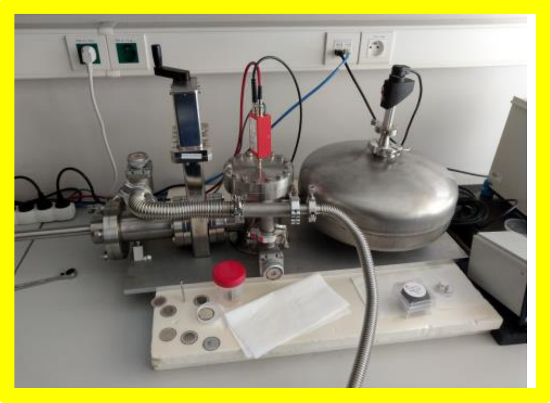
- Very little mass needed
- Relatively fast
- Digestion
- Destructive
- Only U-238 (Th-232)





Radiochemical

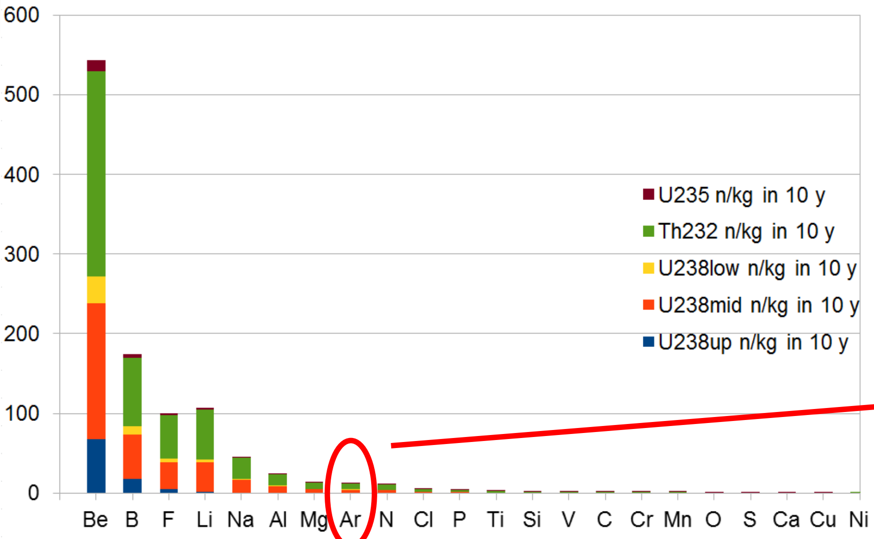
- Little mass needed
- Relatively fast
- Digestion
- Destructive
- Only Po-210 (Pb-210)

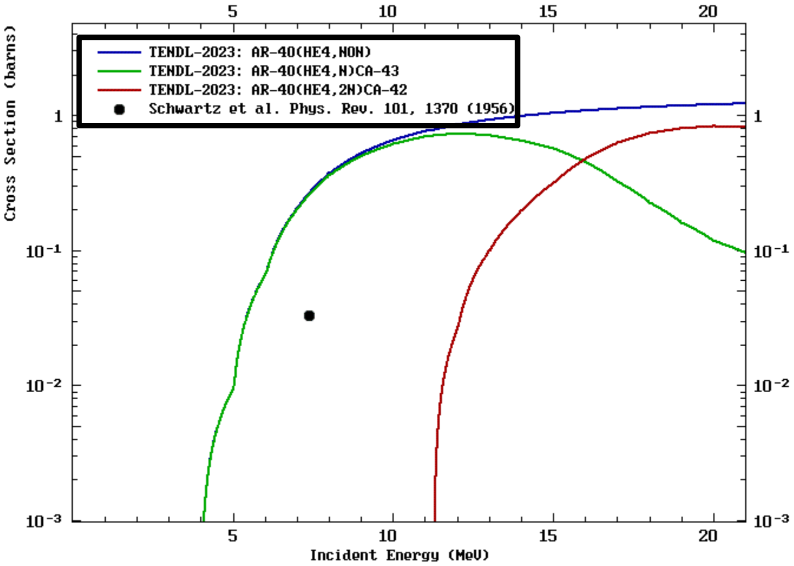


HPGe

- Larger mass needed
- Slow
- Non-destructive
- Gamma activity (^{40}K+...)

(α,n) on Argon





PHYSICAL REVIEW VOLUME 101, NUMBER 4 FEBRUARY 15, 1956

Alpha-Particle Bombardment of A^{36} and A^{40}†*

R. B. Schwartz,‡ J. W. Corbett,§‖ and W. W. Watson
Sloane Physics Laboratory, Yale University, New Haven, Connecticut
(Received August 15, 1955)

Gas targets (130-kev thick) of natural argon (99.6% A^{40}; 0.34% A^{36}) and of argon enriched in A^{36} (97.4% A^{36}; 2.5% A^{40}) have been bombarded with 7.4-Mev alpha particles from the Yale cyclotron. Protons and neutrons at 90° to the incident beam have been studied by means of 50μ Ilford C-2 emulsions, placed 16 cm from the target. The ground-state Q-value for the $A^{36}(\alpha,p)K^{39}$ reaction is −1.28 Mev, with excited states at 2.50 and 2.87 Mev. The ground state Q for $A^{40}(\alpha,p)K^{43}$ is −3.36 Mev, with excited states at 0.65 and 1.18 Mev. The cross sections for these two reactions, as well as for the $A^{40}(\alpha,n)Ca^{43}$ reaction, have been measured and are found to be in general agreement with the predictions of simple compound-nucleus theory.

INTRODUCTION

In 1924, Rutherford and Chadwick[1] reported particles emitted from argon under alpha bombardment. This reaction was then reinvestigated by Pollard and Brasefield,[2] Buchanan,[3] and others using natural argon (99.6% A^{40}, 0.34% A^{36}) and argon considerably enriched in A^{36}. However, since no protons were ever observed in these later experiments, this is the only part of Rutherford's early work in this field which has not been verified by later, more exact measurements. Our

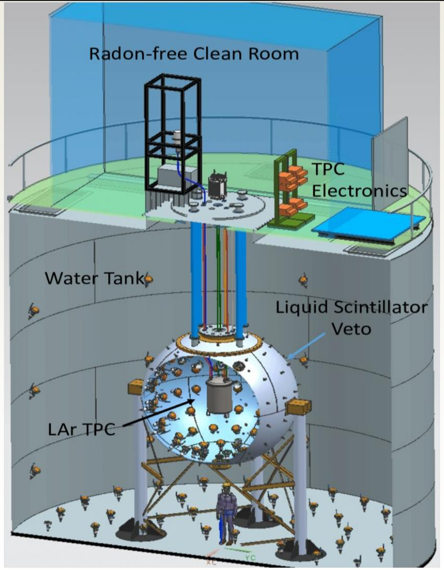
(1) the difficulty in handling gas targets, (2) the low alpha-beam currents available, (3) the fact that the most abundant isotope (A^{40}) has a low cross section, (4) the negative Q-values for these reactions, resulting in low-energy protons which were difficult to detect.

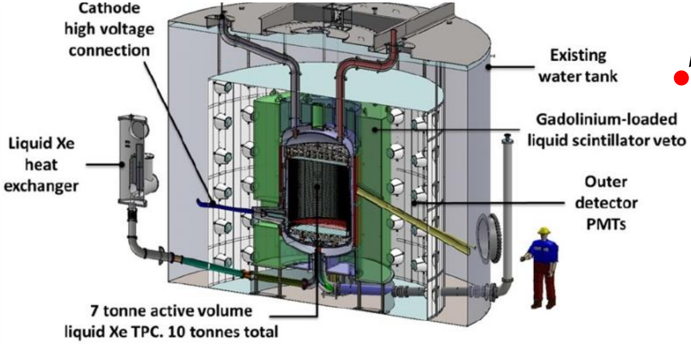
ALPHA-PARTICLE BOMBARDMENT

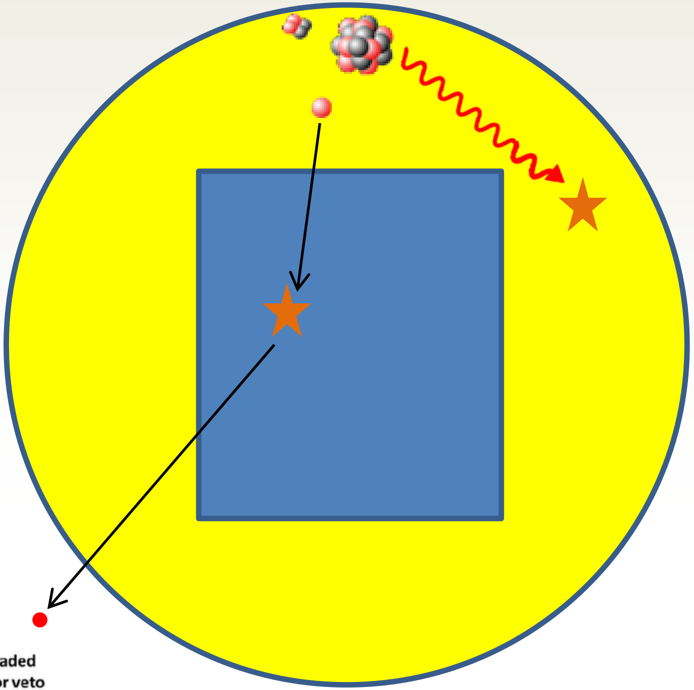
Argon gas targets were bombarded with 7.4-Mev alpha particles from the Yale cyclotron. The target

Reaction	Cross section (millibarns)
$A^{40}(\alpha,p)K^{43}$	0.26
$A^{36}(\alpha,p)K^{39}$	8.5
$A^{40}(\alpha,n)Ca^{43}$	33.0

(a,nγ)







(α,nγ) might be subdominant in most of the cases with respect to (α,n) but is still very relevant for many experiments

The correlated gamma emission is fundamental for understanding the background in Dark Matter

Conclusions

- Neutron background in rare events search experiments: big headache
- Different codes used for the neutron yield calculation with evaluated libraries
- White paper recently published (comparison of the codes, uncertainties …etc)
- New data needed: some of them are fundamental for the next generation of experiments -> $^{40}Ar(^{4}He,n)^{43}Ca$
- Missing (α,nγ) data

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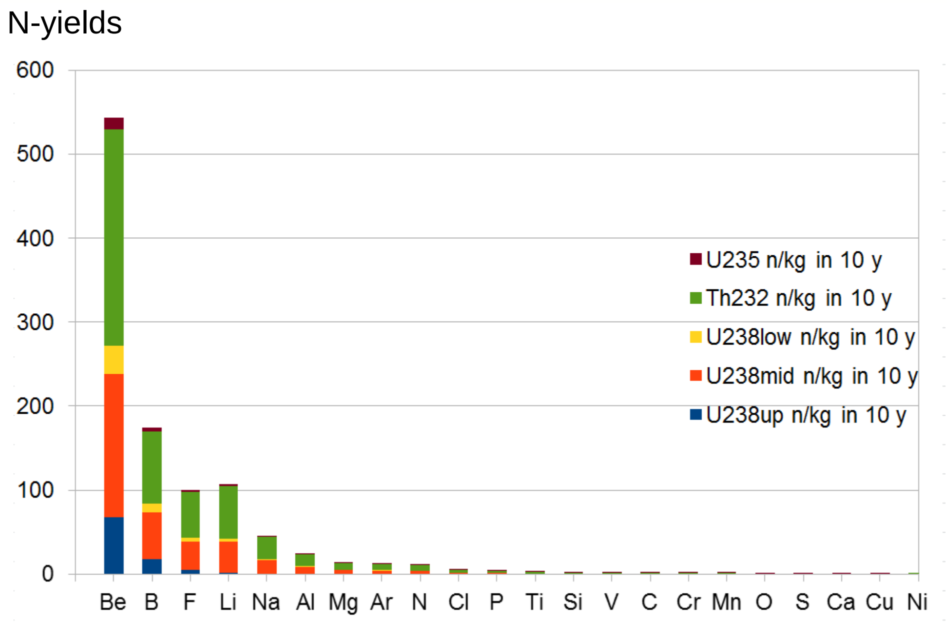
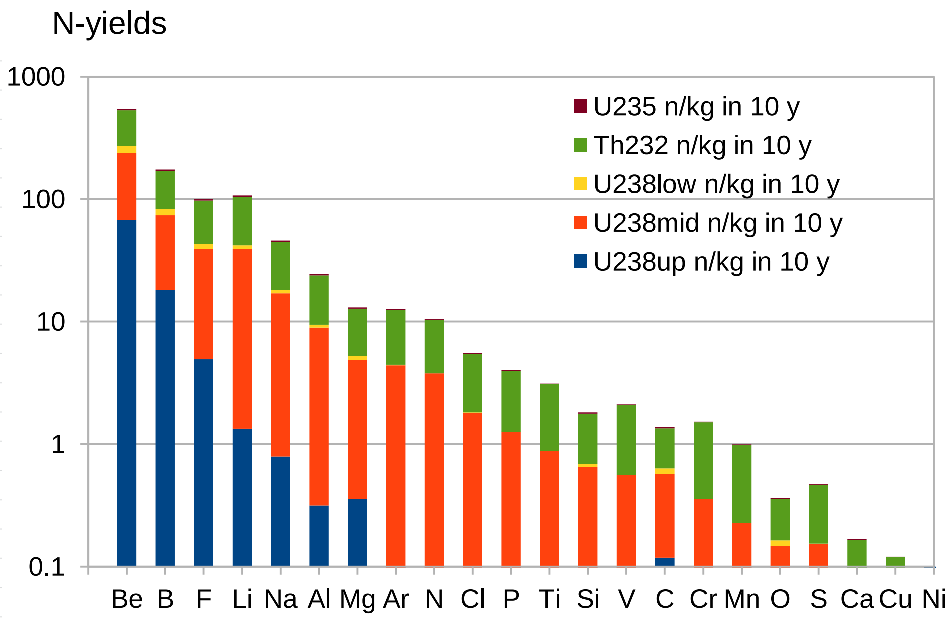
Bonus Slides

Neutron-yields

- Values for 1 ppb Th-232 and U-238 (U-235 with its natural abundance)





Radiogenic neutrons from detectors materials

Strategy:

- ➢ Extensive material assay campaign
  - U-238, Th-232, U235… contamination
- ➢ (α,n) n-yields calculations
  - Codes (SOURCES4C, NeuCBOT, SaG4n)
  - Libraries (JENDL, TENDL…)
- ➢ MC simulation
  - G4, FLUKA…

Typical elements

- Avoid Be and B, F (as much as possible)

- Resistors → Al, N, B (+Si, Mg…)
- PCB → C, N, O…
- Acrylic → C, O
- Teflon → C, F
- Mechanical parts → SS, Cu, Ti…
- Sensors → Si…
- Target → Ar, Xe, Ge….

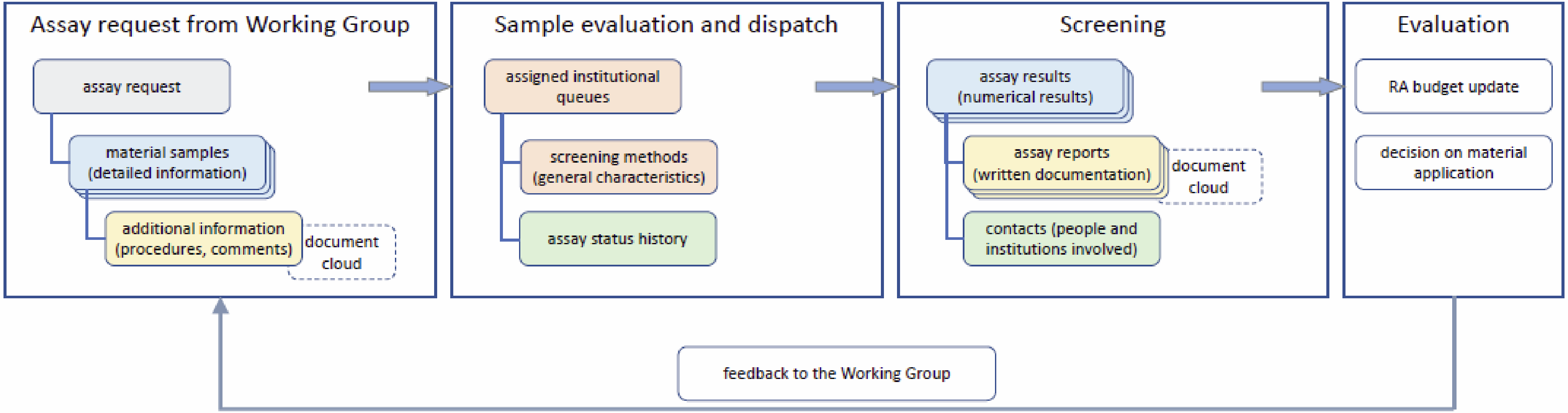
Material	Activity (mBq/kg)		Activity (ppb)	
	^{232}Th	^{238}U	^{232}Th	^{238}U
Stainless steel cryostat	0.89	1.34	0.22	0.11
Titanium cryostat	0.77	5.47	0.19	0.44

Material	Y_n (n/s/g)			Total (n/s/g)	Mean energy (MeV)
	^{232}Th	^{235}U	^{238}U		
Stainless steel	1.62×10^{-12}	3.58×10^{-14}	6.99×10^{-13}	2.3×10^{-12}	1.38
Titanium	5.38×10^{-12}	8.37×10^{-13}	1.42×10^{-11}	2.04×10^{-11}	1.77

DarkSide materials DB structure

Online database that centralizes the full assay process

- New material or component? Assay request!
- Sample allocation depending on available mass and needs
- Information on sample/assay status
- Storage and organization of results.



DarkSide materials Web interface

Online database that centralizes the full assay process

- New material or component? Assay request!
- Sample allocation depending on available mass and needs
- Information on sample/assay status

DB: Web-interface

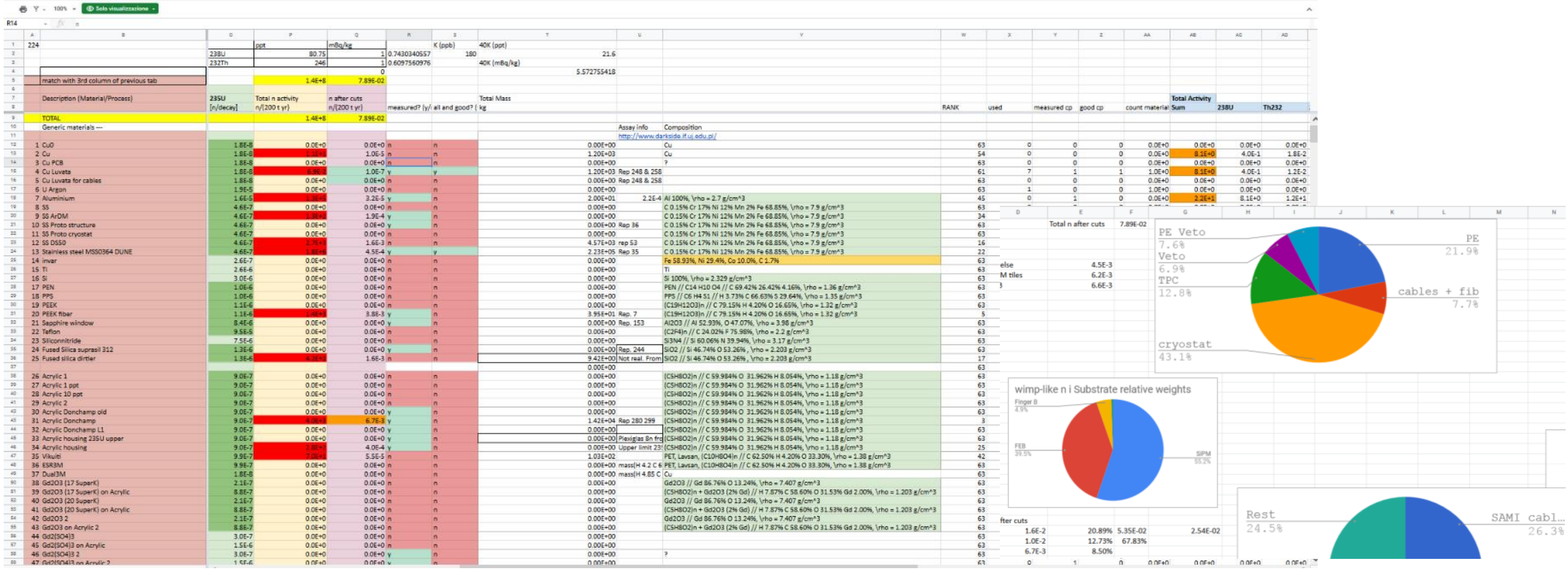
ID	Report	Name	Reference	Method	Sample	Date	^{227}Ac	^{228}Ac	^{210}Po	^{210}Po, gross alpha activity	^{226}Ra	^{228}Ra	^{220}Rn	^{222}Rn	^{46}Sc	Th	^{228}Th	^{232}Th	^{234}Th	^{44}Ti
				SNOLAB),																
2124	289	Gadolinium sulfate 301 Decision pending	DarkSide-20k	HPGe GeOroel (Iulian Catalin Bandac, *LSC CANFRANC*),	complete	2019-08-27		387±24 [mBq/kg] (1 sigma)			9.4±1.4 [mBq/kg] (1 sigma)						274±14 [mBq/kg] (1 sigma)			
2121	288	OPA838 284 More assays needed	PDM module	Polonium-210 chemical extraction (Grzegorz Zuzel, *IF UJ*),	complete	2019-08-27			5.64±0.69 [Bq/kg] (1 sigma)											
2112	286	Harwin clips (clamp) 272 Satisfactory	PDM module	HPGe GeMPI (Matthias Laubenstein, *LNGS, INFN*),	complete	2019-08-13					30±9 [mBq/kg] (1 sigma)	<36 [mBq/kg] (2 sigma)					<27 [mBq/kg] (2 sigma)		<0.95 [Bq/kg] (2 sigma)	
2105	286	OPA838 284 More assays needed	PDM module	HPGe GeMPI (Matthias Laubenstein, *LNGS, INFN*),	complete	2019-08-13					77±8 [mBq/kg] (1 sigma)	25±10 [mBq/kg] (1 sigma)					19±6 [mBq/kg] (1 sigma)		<0.95 [Bq/kg] (2 sigma)	
2119	287	Silver loaded epoxy EJ2189 294 Decision pending	PDM module	HR-ICP-MS (Stefano Nisi, *LNGS, INFN*),	complete	2019-08-13										850±300 [ppt] (30 %)				

Background budget spreadsheet

R.A. budget spreadsheet

Storing the results of the samples, materials composition, contribution to the bkg …

(α,n) neutron background | **γ event rate(VETO+TPC)**



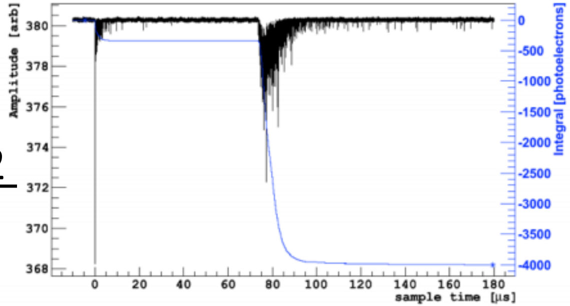
Event discrimination technique in Ar

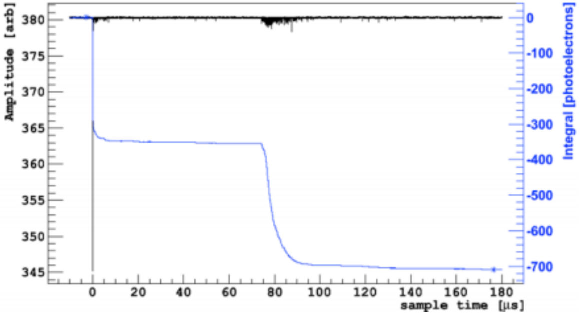
ER-like event

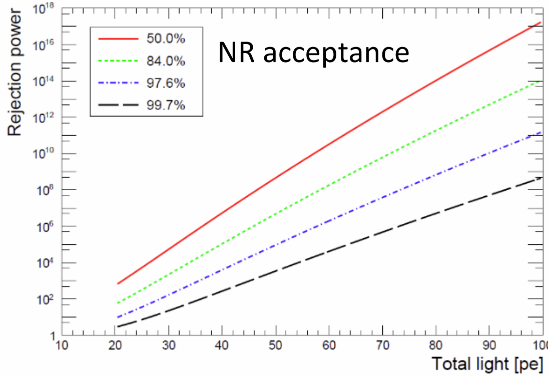
NR-like event

ArDM @ LSC JCAP 12 (2018) 011

S1/S2



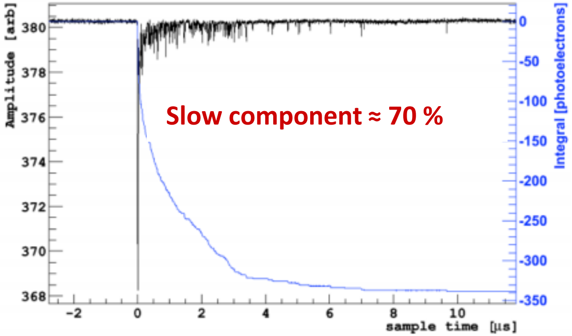


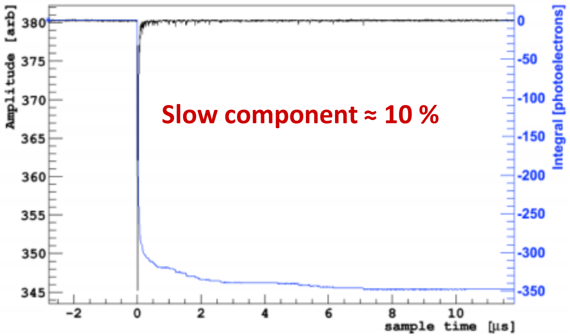


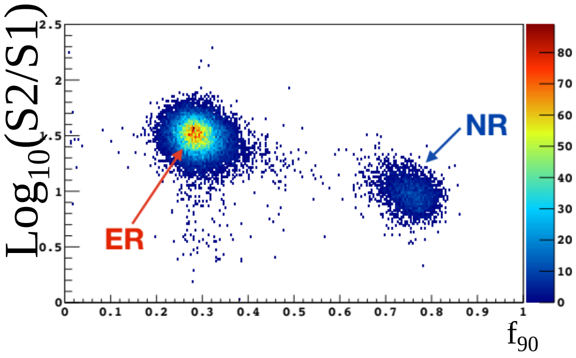
$$\left.\frac{S_2}{S_1}\right|_{ER} > \left.\frac{S_2}{S_1}\right|_{NR}$$

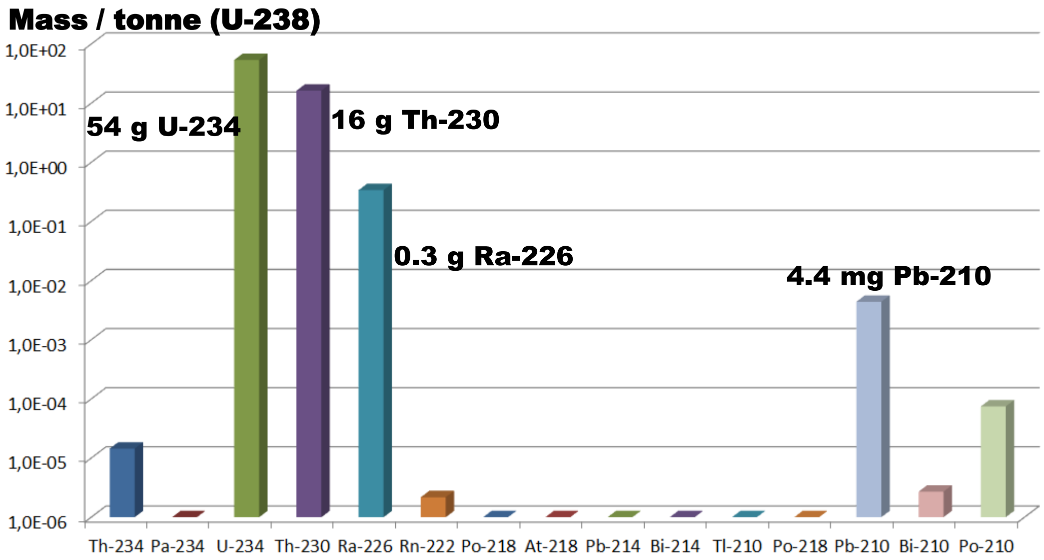
Due to an enhancement of the recombination process

S1 only








Mass / tonne (U-238)
1,0E+02
1,0E+01
1,0E+00
1,0E-01
1,0E-02
1,0E-03
1,0E-04
1,0E-05
1,0E-06
54 g U-234
16 g Th-230
0.3 g Ra-226
4.4 mg Pb-210
Th-234 Pa-234 U-234 Th-230 Ra-226 Rn-222 Po-218 At-218 Pb-214 Bi-214 Tl-210 Po-218 Pb-210 Bi-210 Po-210