GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

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Radiogenic Neutron Background Calculation: Uncertainties of the (α,n) Neutron Yields in Argon and New Cross-Section Measurement

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DARKSIDE

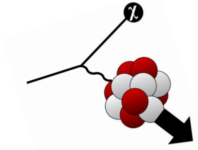
Outline

- Radiogenic (α,n) backgrounds in dark matter experiments
- Calculation of the (α,n) background in DarkSide-20k
- Sources of uncertainty in (α,n) background
    - Activity
    - Material composition
    - Neutron yields
    - Cross-sections ⟶ the $^{40}Ar(\alpha,n)$ problem for dark matter experiments
- New $^{40}Ar(\alpha,xn)$ measurement

Neutron background in dark matter experiments

Natural α-emitting decaying chains: ^{238}U, ^{232}Th, ^{235}U

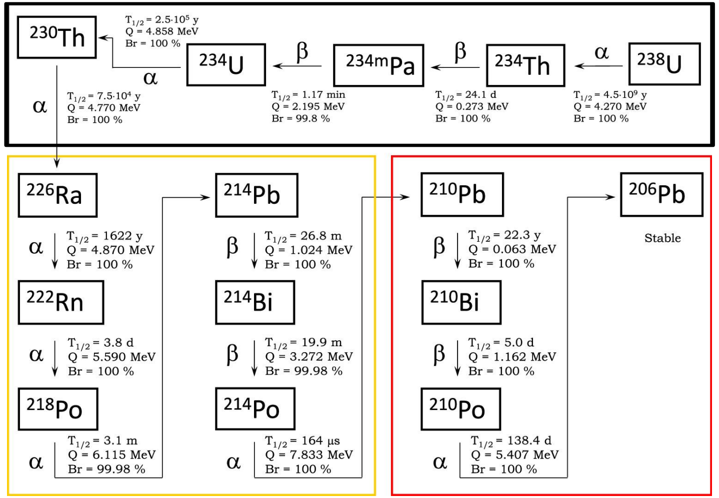
This radiogenic activity is present in small amounts in all detector materials



WIMP signal

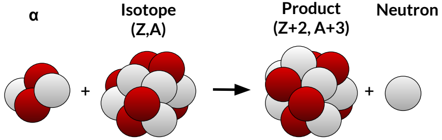
Single Nuclear Recoil in the fiducial volume in the WIMP energy range with no signal in veto-detectors in a given time window

Neutrons producing single NRs in the keV energy range can mimic WIMP signals



^{238}U decay chain

Secular eq.: usually broken (^{226}Ra & ^{210}Pb)

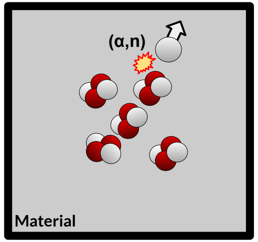


(α,n) neutrons coming from radiogenic α-activity

Current frontier in sensitivity !

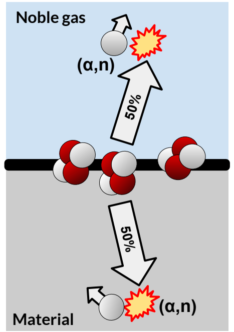
Types of (α,n) radiogenic activity

Bulk activity



- α-decays from ^{238}U, ^{232}Th, ^{235}U chains

Surface activity



- ^{222}Rn exposure: ^{210}Po after plate-out (~tens of μm)
- Dust contamination
- Machining process

Material selection after screening
Veto the neutron signals

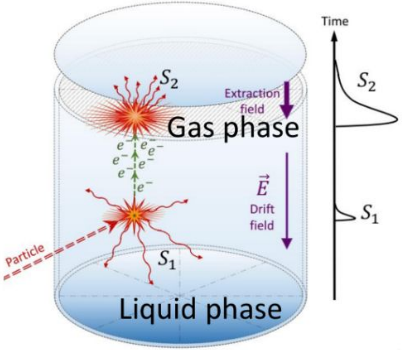
Minimize Rn exposure
Repeat screening after machining process
Surface cleaning

Mitigation strategies

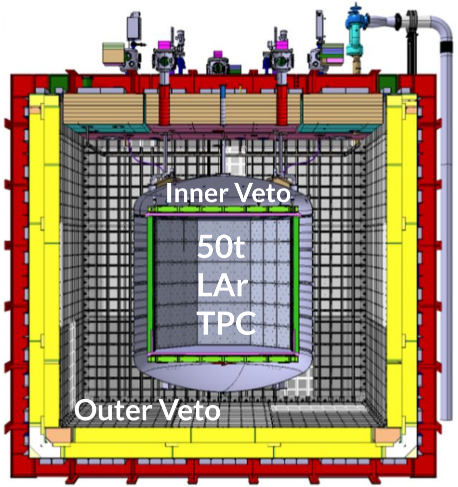
DarkSide-20k experiment

See V. Pesudo's slides

- Global Argon Dark Matter Collaboration (GADMC)
- Currently under construction at Hall C in **LNGS** (Italy)
- **Dual-phase TPC** with 50 tonnes of low-radioactivity **underground Ar** (UAr)
- **Pulse Shape Discrimination**: Nuclear Recoils vs Electronic Recoils



- **Active neutron veto (Inner Veto)**: 32 tonnes of liquid UAr inside SS vessel
- **Cosmogenic muon veto (Outer Veto)**: 700 tonnes of liquid AAr inside cryostat



- **WIMP search**: best sensitivity to spin independent WIMP-nucleon interaction cross-section of 10^{-48}cm^2 at 90% CL for m_χ = 100 GeV/c^2 in 200 t · yr exposure

Calculation of the (α,n) neutron background

Bulk (α,n)

For a component i in a position k:

$$\boxed{N_{ik} = \Delta t \; m_i \; \epsilon_k \sum_j a_{ij} \; y_{ij}}$$

- N_{ik} : Background neutrons from (α,n) in 200 t yr
- Δt : DS-20k run time (10 years)
- m_i : Component mass [kg]
- ϵ_k : Inefficiency to tag neutrons from a position k, determined from a Monte Carlo simulation
- a_{ij} : Measured specific activity [mBq/kg]
- y_{ij} : (α,n) yield, calculated by SaG4n [n/decay]

- i : Component of DS-20k
- j : Alpha decay chain (^{232}Th, ^{235}U, ^{238}U upper, middle and lower)
- k : Position in DS-20k (TPC barrel, SS barrel, Cryo Walls, Cryo roof…)

Sources of uncertainty of the (α,n) neutron background

Activity assay results

- ^{238}U **upper chain** (^{238}U, ^{234}Th, ^{234m}Pa, ^{234}U, ^{230}Th): measured using **ICP-MS** or **HPGe**
- ^{238}U **mid chain** (^{226}Ra, ^{222}Rn, ^{218}Po, ^{214}Po, ^{214}Bi, ^{214}Po): **γ-ray spectrometry**
- ^{238}U **lower chain** (^{210}Pb, ^{210}Bi, ^{210}Po, ^{206}Pb): **chemical extraction** of ^{210}Po and **α-counting**

See G. Zuzel's poster

Material composition

- Provided by manufacturer?
  - Yes → but no uncertainties are given
  - No → needs to be measured
- Small differences in composition ⟶ significant differences in neutron production when isotopes with a high (α,n) cross-section are present: ^{9}Be, ^{13}C, ^{19}F, ^{27}Al, …

Sources of uncertainty of the (α,n) neutron background

(α,n) yield calculation

$$\boxed{Y_i(E_\alpha) = \frac{\eta_i}{\eta}\int_0^{E_\alpha} \frac{\sigma^i_{(\alpha,xn)}(E'_\alpha)}{S(E'_\alpha)}dE'_\alpha}$$

- $Y_i(E_\alpha)$: Neutron yield of isotope *i* for an initial α energy E_α
- $\sigma^i(\alpha,xn)(E'_\alpha)$: (α, n) cross-section → TENDL or JENDL
- $S(E'_\alpha) =$ - dE/dx : α stopping power in the nuclide i
- η_i: number density of the nuclide i
- η : number density of the material

➢ Evaluated Nuclear Data Libraries for (α, n) cross-sections:
- **TENDL**: TALYS-based Evaluated Nuclear Data Library
  Calculations from TALYS nuclear model code including (α,n) reactions for a wide group of isotopes
- **JENDL/AN-2005**: The Japanese Evaluated Nuclear Data Library
  17 nuclides (low Z) for α-reactions. Better fit for most of the nuclear resonances (^{9}Be, ^{13}C, ^{14}N, ^{16}O ...)

➢ **Lack of experimental data**:
- **Neutron energy spectra** and **angular distribution**
- **Correlated emissions** (γ-rays, protons, 2n...)
- Many relevant **(α,n) cross sections**: either not measured, with few data points, large uncertainties or inconsistencies

Sources of uncertainty of the (α,n) neutron background

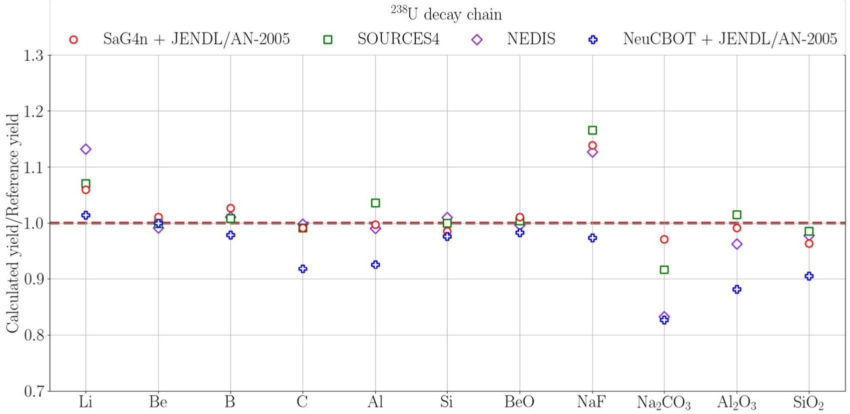
- **(α,n) yield calculation**

➢ **SOURCES-4C**: New upgrades include optimization of the cross-sections and BRs

➢ **NeuCBOT**: the Neutron Calculator Based On TALYS. Stopping powers are imported from **SRIM**, and cross-sections from **TALYS**. Last upgrades: optimization, adding **JENDL**'s cross-sections and neutron angle distributions

➢ **SaG4n**: Geant4-based code. **Geant4** advantages: accurate transportation, stopping powers, visualization, and complex geometries. Recommendation: **JENDL-TENDL** mixed library (*JENDLTENDL01*)

Currently used by DarkSide-20k



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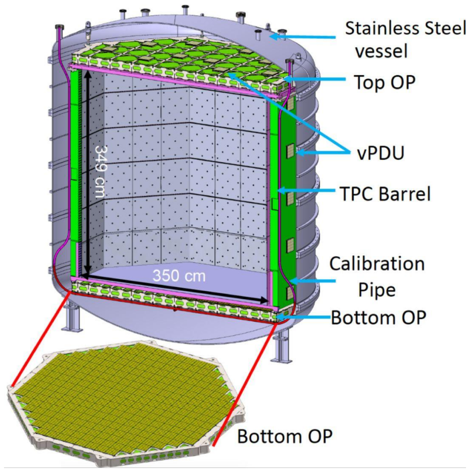
DarkSide-20k neutron background



- **Radiopurity in DS-20k**:

-Assay campaign of intrinsic activity of materials: (on-going for 9 years)
- ➔ ICP-MS
- ➔ γ-ray spectrometry
- ➔ ^{210}Po extraction
- ➔ ^{222}Rn emanation

-Surface cleaning

-Radon-suppressed clean rooms

-Fiducialization: selecting events in the central 20 tonnes of UAr

- **Current estimate of the neutron background from bulk (α,n) :**

PRELIMINARY

$0.123^{+0.009}_{-0.008}$ neutron-induced events in 200 t · yr

➔ **for the materials assayed so far** (~86% of all DS-20k materials)

- Photoelectronics induce 0.04 background events in 200 t · yr
- SS (due to the many tonnes used) induce 0.05 events in total

(α,n) cross-section uncertainties

Several mid-Z range isotopes lack experimental data

For them, their yield uncertainty is **unknown**

Measurements of these cross-sections are **crucial**

Missing mid-Z (α,n) cross-section experimental data in EXFOR (4 - 10 MeV)

^{32,33,36}S	^{37}Cl	*Ar	^{39,40}K	$^{42-44,46}$Ca	^{47,49,50}Ti	^{50}V
$^{52-54}$Cr	$^{56-58}$Fe	^{61}Ni	^{67}Zn	^{73}Ge	^{74,77,78,80,82}Se	*Br
*Kr	*Rb	^{84,87,88}Sr	*Zr	$^{95,96-98}$Mo	$^{96,99-102,104}$Ru	*Rh
*Pd	*Cd	^{113}In	*Sn	$^{120,122-126,128}$Te		

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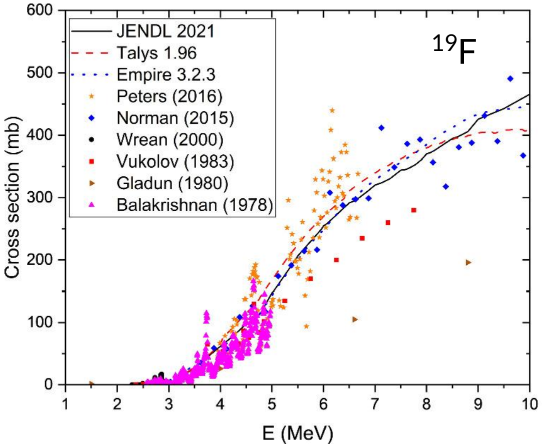
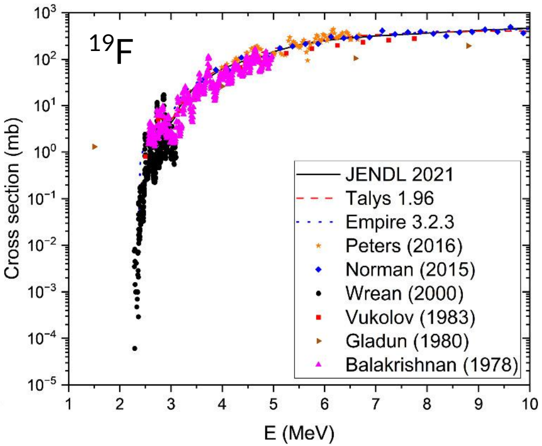
Other isotopes need more precise evaluations:

Example: **^{19}F**

- 2.3 MeV (α,n) reaction threshold
- PTFE, $(C_2F_4)_n$, **Teflon^{TM}: ^{19}F (76% total mass)**
- **Significant difference among data**

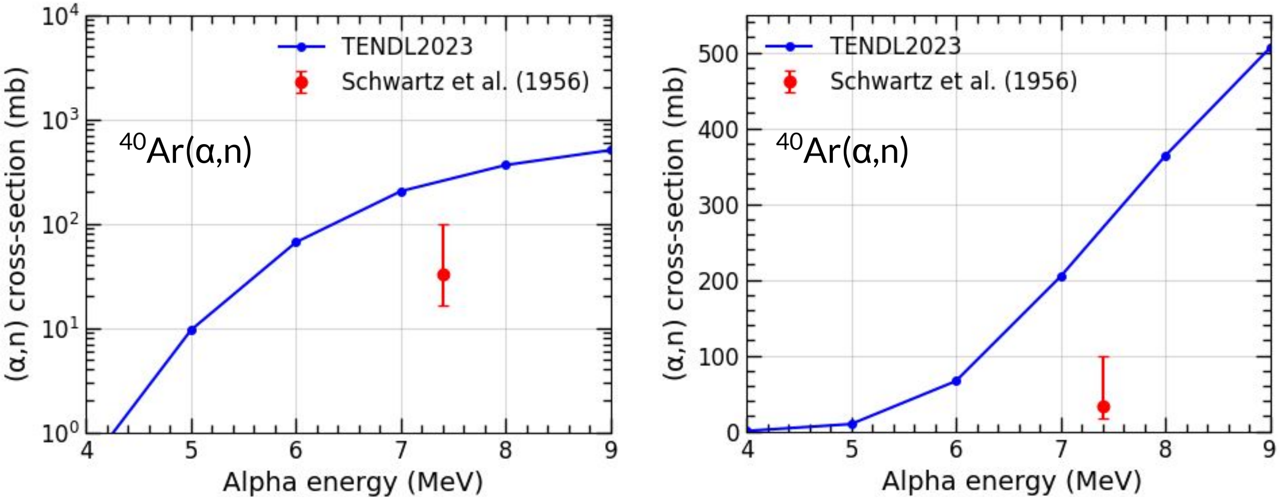


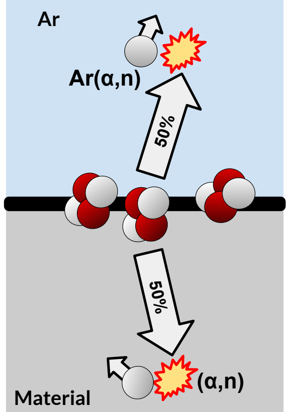


The ^{40}Ar(α,n) cross-section problem

^{40}Ar(α,n) cross-section is larger than in most metals and many plastics

➢ Main source of neutrons from **surface contamination**





Dark matter experiments calculations are based on non-existing data!!

The only **^{40}Ar(α,n)** measurement in EXFOR dates from **1956**, only for **one energy**, with a **high uncertainty** associated, and ~ **3 σ** apart from the TALYS/TENDL result.

Also potential impact in **thin materials**: bulk activity reaching the Ar

Measurement of ^{40}Ar(α,xn) cross-section

Incident **α-beam** (4 - 9 MeV) into an **argon gas chamber** → measure the **neutrons** produced

- Some of the challenges:
  - ➢ Low density of gaseous Ar may lead to low neutron counts
  - ➢ **Ultra-thin** (~μm) vacuum window: transparent while withstanding the ΔP, and **low (α,n) cross-section**
  - ➢ A sophisticated gas circulation system: vacuum, refilling, and heat dissipation
  - ➢ **Background** from the beam scattering to the walls

- Current status: planning phase of the experiment
  - ➢ **Thin argon target**
  - ➢ A high-threshold material (Ta, W) is needed at the back to stop the α-beam
  - ➢ **Gas chamber:** designed and under construction at CIEMAT
  - ➢ **Detector**

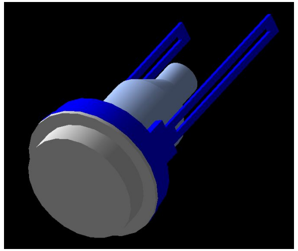
Ongoing collaboration:

Dark Matter group @ CIEMAT

Nuclear Innovation Unit @ CIEMAT

Measurement of ^{40}Ar(α,xn) cross-section

Two types of detectors considered can offer different **measurements**:



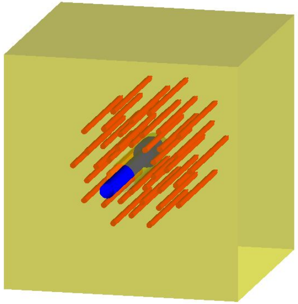
- **MONSTER**: Neutron Time-of-Flight spectrometer
  - **Neutron energy spectra and angle distribution**
  - Unfolding (R-matrix)
  - Single cell properties:
    - Low energy threshold (~ 30 keVee)
    - Intrinsic neutron detection efficiency of ~ 30 %
    - PSD: γ-rays and neutrons
    - Good time resolution (~ 1 ns)

$$\boxed{TOF = R \cdot E_n}$$

- **Array of He-3 neutron proportional counters inside a neutron moderator**
  - **Only neutron counting**
  - Higher total efficiency
  - Designed to be energy-independent ("flat efficiency")
  - **Low energy resolution**

$$He^3 + n_{\text{thermal}} \longrightarrow p + H^3 + Q\,(764\ keV)$$

$$\boxed{A = I_\alpha N \sigma}$$



Example of an array of He-3 counters inside a polyethylene neutron moderator

Ongoing collaboration:

Dark Matter group @ CIEMAT

Nuclear Innovation Unit @ CIEMAT

Summary

- **Neutron backgrounds** are a central source of WIMP-like events in all WIMP searches.
- **DarkSide-20k** has worked on a thorough multi-location **assay campaign** for the last 9 years and has a very robust data-driven neutron background model.
- An important source of **uncertainty** in that estimate is due to the **lack of experimental data on (α,n) cross sections**.
- Although **^{40}Ar(α,n)** is the main source of background from **surface contamination** in dark matter experiments, **there is no ^{40}Ar(α,n) cross-section data** in our range of interest.
- The only existing point presents high uncertainties and difference with the evaluated cross-section used in dark matter experiments.
- We are setting up an experimental program to tackle this, starting with a **measurement** on the **(α,n)** cross section on **^{40}Ar** itself

Thank you for your attention

IDM2026 at Unizar

DarkSide-20k Fall Collaboration Meeting at GSSI, 2025