SIDERALIS
cosmic SIlence in Deep underground Environments for RAdiation and LIfe Studies

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INFN-CSN5 experiment proposal

INFN-LNGS, Assergi (AQ), Italy

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Istituto Nazionale di Fisica Nucleare

ELSE NUCLEAR

Centro Fermi
Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi

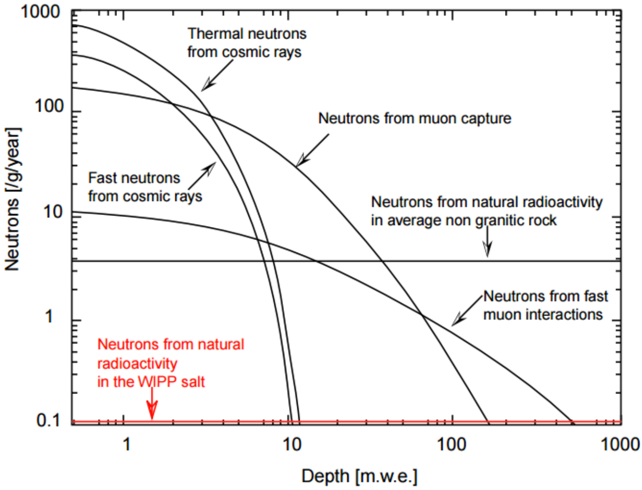
Università degli Studi de L'Aquila

ENEA
Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

INAIL
Istituto Nazionale per l'Assicurazione contro gli Infortuni sul Lavoro

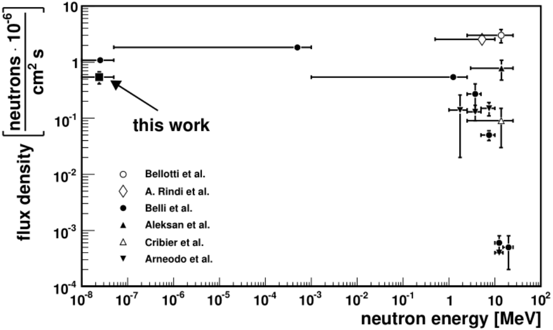
1. Many modern Physics experiments challenge the measurement of very small event rates ($\lesssim$ *few events*/*year*)$\Rightarrow$ equipments location deep underground
2. Deep underground experiments are sensitive to background neutrons:
   - I n elastic scattering affects signals from WIMP interactions
   - II n inelastic scattering or n capture produce γ rays influencing $0\nu\beta\beta$ decay
3. From radiobiology studies in Deep Underground Environments (LNGS PULEX facility):
   - I less efficient DNA repair mechanisms
   - II ROS scavenging processes on cells *in-vitro*
   - III *n* component responsible?
4. An evident lack of coherent data does exist in literature on n background in DUE. Direct comparison of the results is made difficult, probably because of
   - wide variety of experimental setups
   - wide variety of detected neutron energy ranges
   - simulations of DUE n background have shown results affected by several uncertainties (different assumptions on material compositions, physical models and cross sections libraries available in Monte Carlo codes, different codes used)
5. Cosmic rays induced outdoor n background does impact on experiments at high latitudes and altitudes, for which high sensitivity neutron spectrometer are being demanded

Contributions to the *n* background in DUE[1]



[1] E.-I. Esch, *"Detector Development for Dark Matter Research"*, PhD thesis

A very useful plot showing the state of the art of n background measurements @ LNGS[2,3]



The neutron background needs to be understood in detail, in order to:

- limit its impact on fundamental physics experimental sensitivity
- discriminate its role in radiobiology experimental results (both *in-vitro* and *in-vivo*)

[2] Z. Debicki *et al.*, Nuclear Physics B (Proc. Suppl.) 196 (2009) 429-432

[3] The plot above does not include a more recent result of $0.32 \cdot 10^{-6}\text{cm}^{-2}\text{s}^{-1}$ thermal neutron flux in LNGS interferometer tunnel (A. Best *et al.*, 2015, arXiv:1509.00770v1)

"[...] *a variety of different and inconsistent methods are being used for both the modeling and the experimental measurements of detector efficiencies. In many cases, the modeling parameters and methods are vaguely described, unrealistic, or unsubstantiated. Likewise, there is often an information deficit for reported experimentally determined neutron detection efficiencies. Sadly, many reported results, although ambitious and initially impressive, are so vaguely described or different from standard practice that their validity is suspect.*
The primary reason for these varied reporting methods is a lack of standard for 1) modeling the detector response to incident neutrons and 2) measuring properly the neutron detection efficiency."[4]

- Can the above statements describe the origins of the non consistent results for *n* background in DUE?

[4] D. S. McGregor, J. K. Shultis, NIMA 623 (2011) 167-174

Absolute efficiency

$$\boxed{\varepsilon_A = \frac{R_{det}}{AB}}$$

- strongly dependent on source/detector geometrical arrangement $\Rightarrow$ poor significance if the experimental arrangement does not allow reproducibility
- defines the detector performance wrt both detector properties AND source/detector geometry
- not a good FOM for neutron detection in DUE

Likewise the same conclusion holds for the Relative efficiency

$$\boxed{\varepsilon_R = \frac{R_{det}}{AB\varepsilon_A^{ref}}}$$

Intrinsic efficiency

$$\boxed{\varepsilon_i = \frac{R_{det}}{AB\Omega}} \text{ or } \boxed{\%\varepsilon_i = 100\frac{4\pi R_{det}}{AB\Omega}}$$

- mitigates the geometric dependence of ε_A though not completely eliminating it
- if measured (or estimated) from a point source, the parallax of the radiation emissions becomes important for small source/detector distances $\Rightarrow$ can introduce appreciable errors

This could be the case of large (length $\sim$ 1m) proportional counters in LNGS bypass tunnels

Effective intrinsic efficiency in a radiation beam

$$\boxed{\varepsilon_{ei} = \frac{R_{det} M(\theta)}{I M_{\perp}^{2}}}$$

- normalized to the perpendicular irradiation orientation ($\theta_{\hat{I}\hat{M}} \approx 0^{\circ}$)
- best FOM for detectors irradiated SIMULTANEOUSLY from multiple directions or for detectors that may be turned through various angles during operations

According to NIST[5]

1. there is no reliable method to produce an omnidirectional thermal-neutron source to test a detector in an isotropic flux
2. the MCNP code[6] can be used to understand the experimental conditions and optimize a measurement but it is inadequate for efficiency calibrations

Thus a question arises from the above considerations (and never answered by the literature in the field), namely, what is the efficiency several authors refer to in the experiments history on *n* flux measurements in DUE (LNGS in particular), by means of proportional counters count rates, based on the formula

$$\boxed{\phi = \frac{R_{det} - R_{bg}}{\varepsilon M}} \ ?$$

- Detectors calibration with high rate sources (e.g. AmBe)⇒ suitable for low level background DUE?
- Detectors efficiency estimations with MC codes assuming isotropic (spherical) irradiation
- *n* energy groups discriminated on the assumptions of interaction cross sections with moderating materials (e.g. 0.3 eV for Cd cutoff)

[5] D. S. McGregor, J. K. Shultis, NIMA 623 (2011) 167-174

[6] The statement is valid for any other Monte Carlo code

For LNGS n background flux measurement only one attempt has been made to UNFOLD the n spectrum[7], solving the degenerate case of the homogeneous Fredholm equation of the first kind:

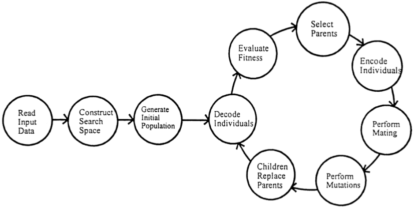
$$\boxed{R_{det} = \int_0^\infty R_j(E)\phi(E)\mathrm{d}E \approx \sum_{k=1}^{N} R_{jk}\phi_k, \quad i = 1, 2, \ldots, M}$$

- The quantities R_{jk} were simulated with MCNP code then ϕ_k calculated by *least squares method* (although not specifically mentioned and described in detail)
- Least squares methods need an initial guess on ϕ_k. Expecially for underdetermined cases ($M < N$, 5 detectors for 7 energy intervals in the case of interest), this can produce misleading results when no *a priori* knowledge is available on ϕ_k

[7] P. Belli *et al.*, Il Nuovo Cimento, Vol. 101 A, N. 6 (1989)

In order to avoid initial guess spectrum and covariance data as *a priori* information and to guarantee positive solution, two unfolding algorithms have attracted worldwide interest in the scientific community during the last 15 years:

1. Maximum Entropy combined with Maximum Likelihood[8] $S = H + L$, where $H = \sum_{k=1}^{N} p_k \ln p_k$ is the Shannon information entropy, $p \equiv <\phi> / \alpha$, α is the total number of neutrons incident on the detector and $L = \sum_{j=1}^{M} (R_j \ln < R_j > - \ln(R_j!) - < R_j >)$ is the likelihood relevant to the Poisson statistics of neutron detection
2. Genetic algorithm[9]



8 S. Maeda *et al.*, Progr. in Nuc. Scie. and Tech., Vol. 1, p233-236 (2011)
9 D.W. Freeman *et al.*, NIMA 425 (1999) 549-576

The SIDERALIS experiment will join together the collaboration and expertise of several Italian research institutes and one industrial partner, namely:

- INFN, within its laboratories and sections
  1. INFN-LNF
  2. INFN-LNGS (hosting lab)
  3. INFN-RM1
  4. potential collaboration with INFN-TO and Argentine Antarctic Institute (IAA)
- ISS
- ELSE nuclear (industrial partner)
- Museo Storico della Fisica e Centro Studi e Ricerche Enrico Fermi
- ENEA
- INAIL
- Università degli Studi de L'Aquila
- Università degli Studi di Roma "La Sapienza"

INFN personnel and associates

People	INFN section/LAB	FTE
Adolfo Esposito (technologist executive)	LNF	0.3
Oscar Frasciello[10] (technologist)	LNF	0.7
Maurizio Chiti (technician)	LNF	-
Giuseppe Carinci (technician)	LNF	-
Alfonso Gentile (technician)	LNF	-
Total	LNF	1.0
Emanuela Bortolin (researcher)	ISS-Roma 1	0.2
Cinzia De Angelis (senior researcher)	ISS-Roma 1	0.2
Giuseppe Esposito (researcher)	ISS-Roma 1	0.3
Maria Antonella Tabocchini[11] (senior researcher)	ISS-Roma 1	0.3
Maria Cristina Quattrini (technician)	ISS-Roma 1	-
Total	ISS-Roma 1	1.0
Total	INFN	2.0

[10] National and LNF local SIDERALIS responsible

[11] Roma 1 local SIDERALIS responsible

Other institutions' personnel

People	Institution
Cristina Nuccetelli (senior researcher)	ISS
Giacomo Manessi (R&D engineer)	ELSE Nuclear
Marcello Ballerini (R&D engineer)	ELSE Nuclear
Rosabianca Trevisi (researcher)	INAIL
Federica Leonardi (researcher)	INAIL
Francesco Cardellini (researcher)	ENEA
Francesca Cipressa (research fellow)	Centro Fermi
Patrizia Marciano (researcher)	University of L'Aquila
Giovanni Cenci (Associate Professor)	University of Rome "La Sapienza"

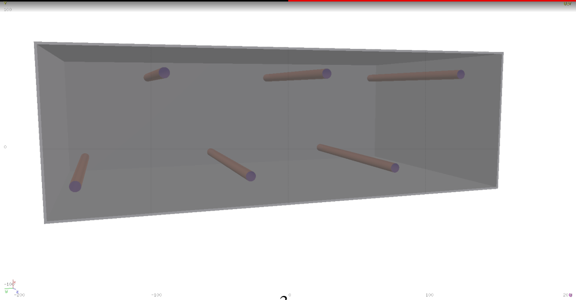
SIDERALIS experiment proposal relies on:

1. Extensive simulations campaign, by means of benchmarks with MCNP6 and FLUKA MC codes, for
   - I n background in LNGS halls and bypass tunnels numerical estimations experimental results will be compared to
   - II Preliminary study of the response function of a novel high sensitivity neutron compact macro-detector, based on BF_3 proportional counters
2. Prototype and calibration of the new detector, in strong collaboration with the industrial partner, involving the development of dedicated electronics and innovative moderating materials (doped flexible rubber sheets)
3. Test of the detector at LNGS $\Rightarrow$ detailed characterization of the LNGS neutron flux and spectrum

5. Completing the characterization of the underground radiation field by means of
   - I gamma spectroscopic measurements with HPGe spectrometers
   - II evaluations of the contributions from the different families of radionuclides to the detected gamma dose rates with TLD detectors
   - III measurements of radon activity concentrations in air with Radon Daughter Monitor
6. Set of biological measurements, complementary to the physical ones, addressed at discriminating the relative contribution of the different radiation components, by means of *in-vivo* experiments on the fruit fly *Drosophila Melanogaster*

- BF_3-filled proportional counters constitutes a valuable alternative to ^{3}He-filled ones, given the known issue of the ^{3}He shortage and the series of advantages and disadvantages of BF_3 gas
- It has already been shown in the past that BF_3 counters are a reliable tool for low level neutron backgrounds in underground laboratories, but...
    - I No experimental assessment of the detector efficiency in underground environmental conditions has been performed. Efficiency has always been calculated by means of MC simulations, without any benchmark
    - II Detected neutron energy spectrum has very often been somehow "inferred" from the neutron cross sections of the various moderators used and from the mixing of experimental and MC calculations

What we want to measure is not just $\phi^{(i)}(n)$, but $\frac{d\phi(n)}{dE}$!



For SIDERALIS a compact ($\sim$3x2x1.5 m^3) Multi Cylinder Neutron Detector (MCND) is conceived, following a different approach relying on

- Increasing the efficiency of a single tube increasing the number of tubes in the array (non linear dependence!)
- Employing different types and thickness of moderators (standard Cd or $(C_2H_4)_n$ and new doped flexible rubber sheets) - Bonner spheres method
- Employing Maximum Entropy & Maximum Likelihood and Genetic algorithms for n spectrum unfolding (using existing codes or creating new ones)

- HPGe spectroscopic measurements will allow to gain precious informations on
  1. γ fluxes populating the experimental sites
  2. activity concentration ratios between the ^{238}U and ^{232}Th radioactive series and their decay disequilibrium (useful also for accurate MC simulations!)
- γ dose rates measurements will be performed with high pressure ionization chambers and TLDs
- Ionization chamber and scintillation cell will allow monitoring of hourly and daily variation of indoor ^{222}Rn activity concentration in air
- Average Rn concentrations in experimental sites evaluations by means of passive Rn dosimeters

- *In-vivo* measurements on living organism fruit-fly *Drosophila Melanogaster* will study the effect of acute exposures to genotoxic agents on the genome stability in terms of chromosome break frequency and expression of DNA repair genes both in
    1. underground PULEX/Cosmic Silence facility at LNGS
    2. reference laboratory at University of L'Aquila/University of Rome "La Sapienza"
    3. LIBIS facility at ISS - LIBIS allows to expose biological samples at dose rates ranging from few $\mu Gy/h$ to few tens of mGy/h
- Genotoxic effects will rely on γ dose rate modulation and specific drugs after different periods of chronic low dose rate exposures
- The aim is to increase knowledge about the role of the radiation spectrum component(s) triggering the molecular mechanisms involved in the biological response to environmental radiation

Item	Cost estimate (k€)
Detectors	25.0
MCND Electronics & moderators	90.0
Other consumption goods	8.0
External services	7.0
Travels	30.0
Research Fellow	19.5
Total	**179.5**

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- In order to increase the CSN5(*SIDERALIS,success*) reaction cross section, an endorsment letter from LNGS Director could be strongly beneficial

Thanks for your kind attention!