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Low radioactivity argon for rare event searches

Sagar Sharma Poudel

Low Radioactivity Technique (LRT) workshop 2022

U.S. DEPARTMENT OF ENERGY BATTELLE

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Talk outline

- Argon as a detector medium in rare event searches
- Decay backgrounds from radioactive isotopes of argon 39Ar and 42K
- Estimate of 42Ar production underground
- Underground argon and associated challenges
- Feasibility and reach of kton scale underground detector

Argon as a target material for rare event searches

- Liquid argon is an excellent scintillator.
- Pulse Shape Discrimination (PSD) of the event signals (e.g electronic recoil vs nuclear recoil signal)
- Dual phase argon TPC technology allows collection of both scintillation and ionization signal (additional PSD, 3D position reconstruction)
- Scalable (homogeneous detector medium, large radiation attenuation length, large drift time)

Radioactive isotopes of Argon

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- Long-lived radioactive isotopes in argon :
  39Ar (half-life: 269 years), 42Ar (32.9 years)

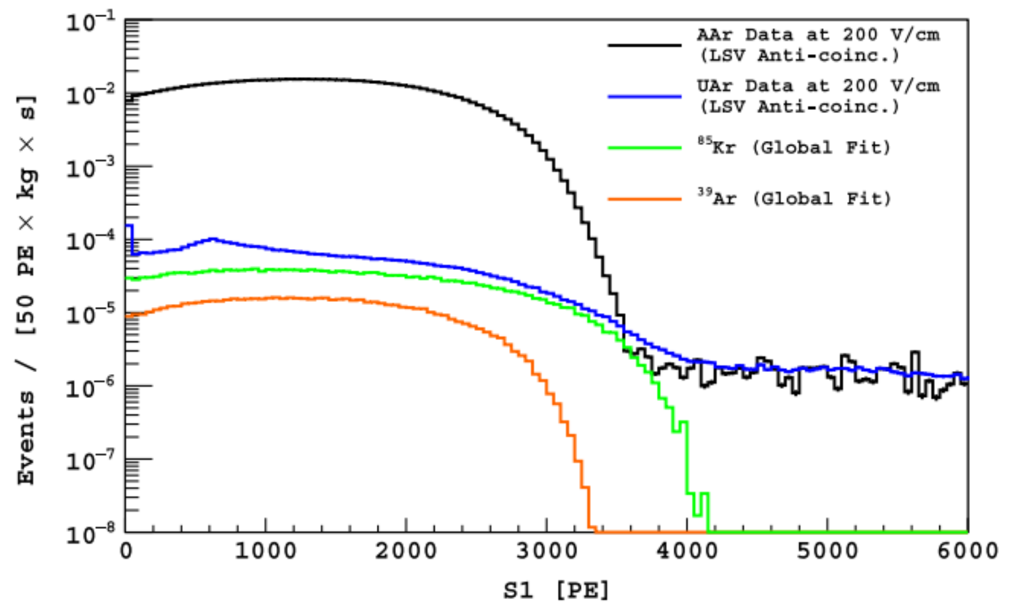
- 39Ar and 42Ar have similar beta spectrum and end point energy (Q_{39Ar} = 565 keV, Q_{42Ar} = 599 keV)

- In atmosphere, specific radioactivity:
  39Ar ~ 1 Bq per kg of Ar, 42Ar ~ 10^{-4} Bq per kg of Ar
  39Ar and 42Ar in atmosphere are primarily produced by cosmogenic activation on 40Ar.

- DarkSide-50 demonstrated UAr is significantly depleted of 39Ar (Activity: 0.7 mBq/kg, i.e factor of 1400 x reduction)

Reaction	Estimated ^{39}Ar Production rate [atoms/kg/day]	Fraction of total AAr [%]
^{40}Ar(n, 2n)^{39}Ar + ^{40}Ar(n, d)^{39}Cl	759 ± 122	72.3
^{40}Ar(μ, n)^{39}Cl	172 ± 19	16.4
^{40}Ar(γ, n)^{39}Ar	89 ± 19	8.5
^{40}Ar(γ, p)^{39}Cl	23.8 ± 8.7	2.3
^{40}Ar(p, 2p)^{39}Cl	<0.1	< 0.01
^{40}Ar(p, pn)^{39}Ar	3.6 ± 2.2	0.3
^{38}Ar(n, γ)^{39}Ar	$\ll$0.1 (UAr)	-
	1.1 ± 0.3 (AAr)	0.1
Total	1048 ± 126	100

Saldanha et al. PhysRevC.100.024608



x 1400 reduction in 39Ar activity

P. Agnes et al. Physical Review D 93, 081101(R) (2016)

42Ar/42K

- 42Ar production in the atmosphere :

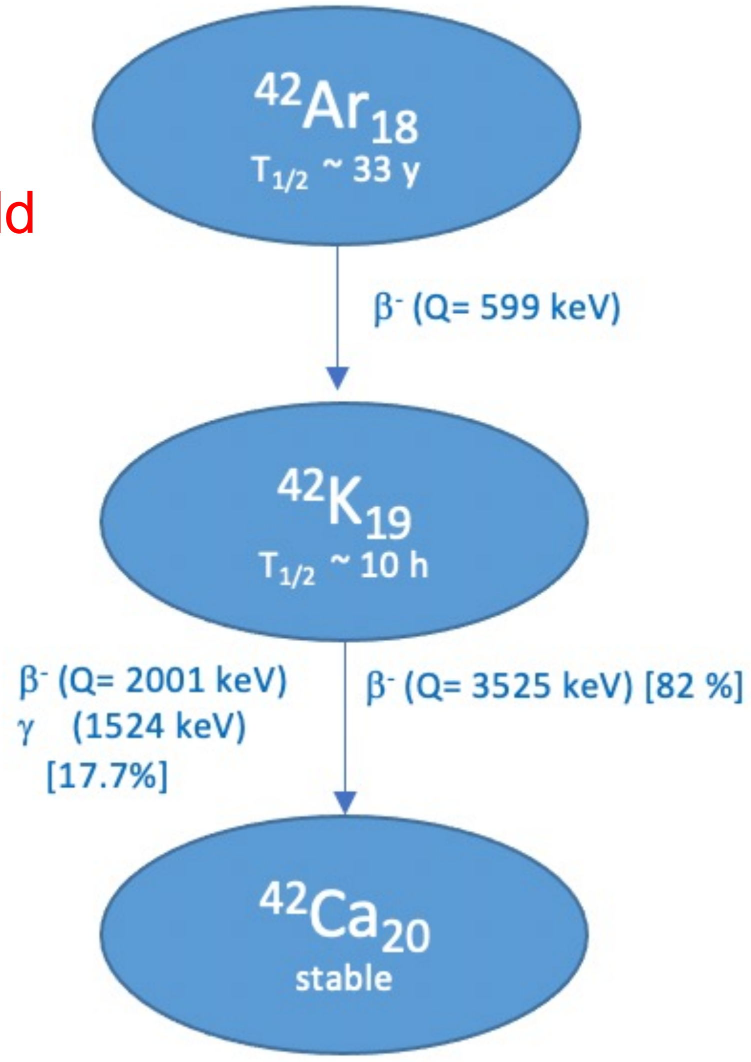
  i) 40Ar(n,γ)41Ar, 40Ar(n,γ)42Ar

  ii) 40Ar(∝,2p)42Ar → 14 MeV threshold

  A.J. Peurrung, T.W. Bowyer, R.A. Craig and P.L. Reeder, Nucl. Inst. Meth. A 396 (1997) 425

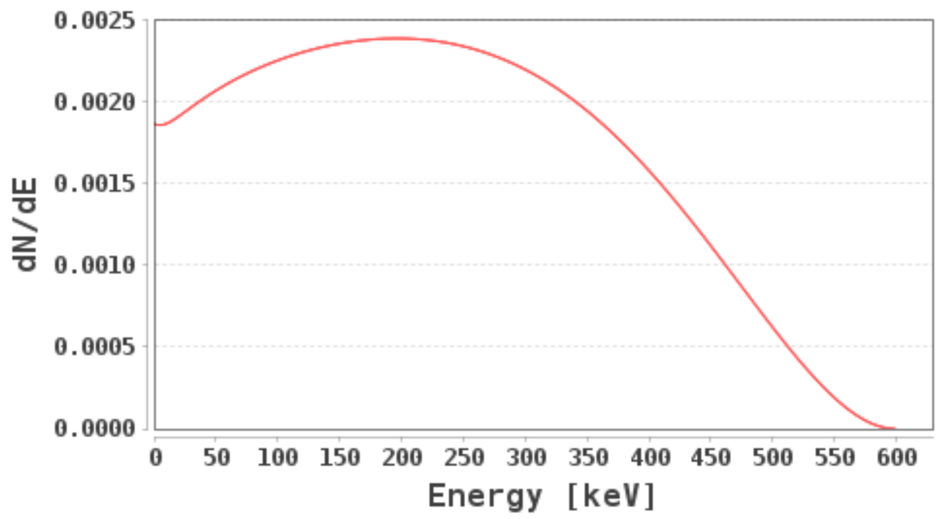
- 42Ar activity has been measured by many experiments (ICARUS, DBA, DEAP, GERDA)

- 42Ar specific radioactivity in Ar ~ 50 μBq/kg

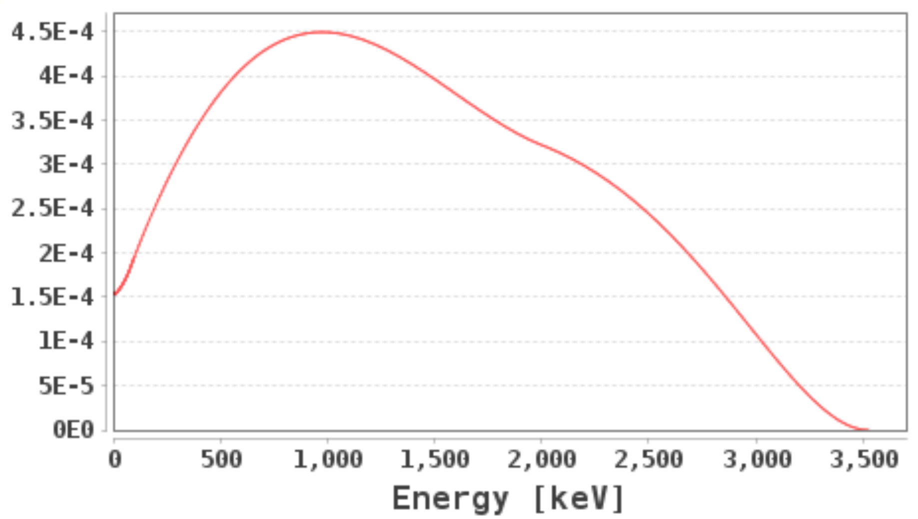


https://www-nds.iaea.org/

Beta spectrum: 42Ar



42K decay spectrum



➢ For most argon-based neutrino experiments, energetic β 's and γ's from 42K decays are concerning.

42Ar/42K decay backgrounds

42Ar/42K presence in bulk of detector-argon is problematic.

42K decay backgrounds to

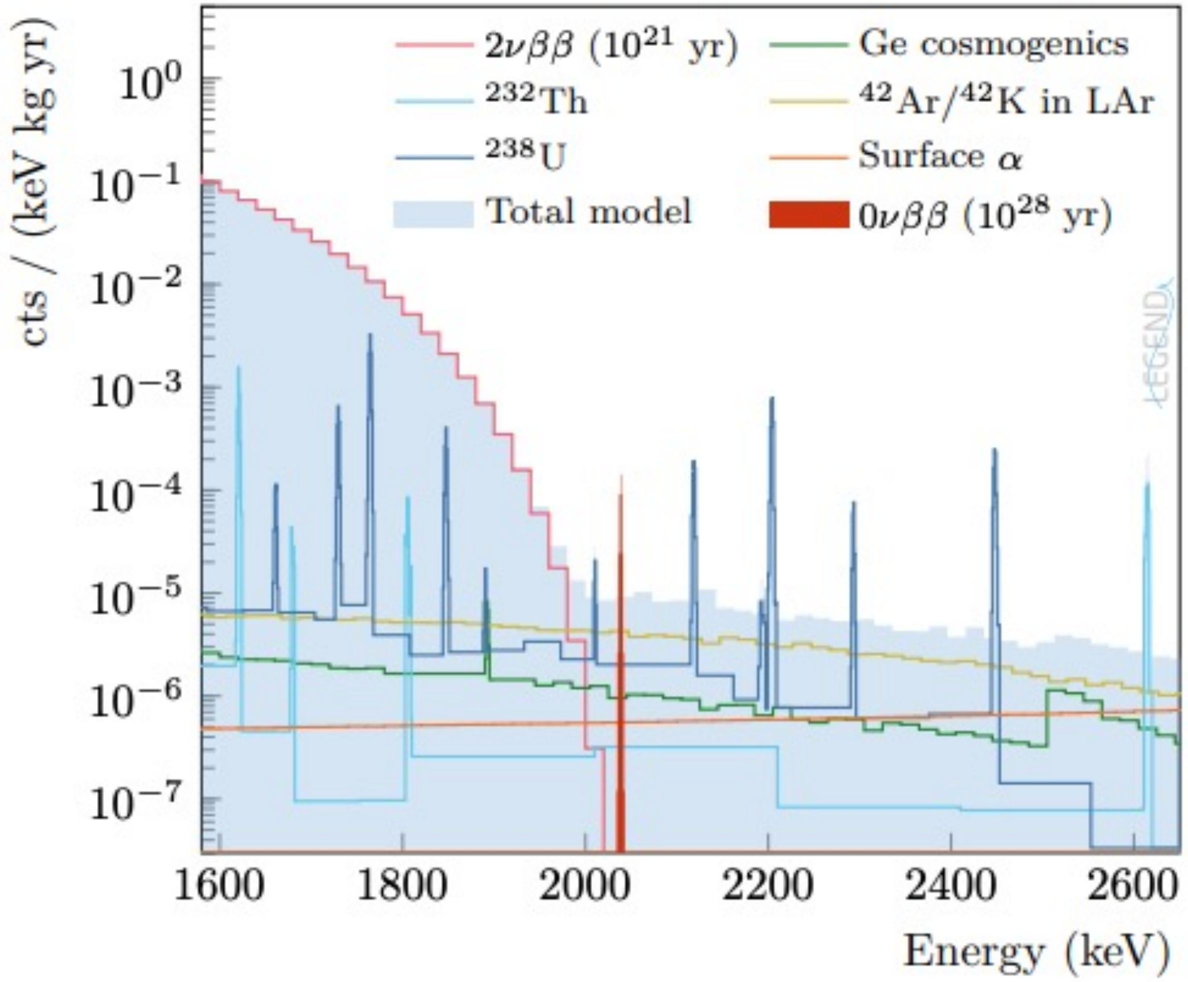
- GERDA/LEGEND (Ge detector, LAr veto) search of 2039 keV $0\upsilon\beta\beta$ 76Ge signal

[Mitigation strategies for LEGEND:

See Björn Lehnert's Talk]

- Low energy neutrino measurements (e.g DUNE (Ar detector))
- Xenon-doped argon-based detector (136Xe 2458 keV $0\upsilon\beta\beta$ signal searches)

- 42Ar/42K decays can cause
  - Event pile-up and reconstruction issues in multi-ton scale detector like DUNE, DarkSide-20k



https://arxiv.org/pdf/2107.11462.pdf

Estimate of 42Ar production underground

Sagar Sharma Poudel
Ben M. Loer
Richard Saldanha
Henning O. Back
Brianne R. Hackett

This work was funded by PNNL Laboratory Directed Research and Development (LDRD) funds under the Nuclear Physics, Particle Physics, Astrophysics, and Cosmology (NPAC) Initiative

42Ar production underground

- 42Ar production underground should be significantly suppressed:

➢ 42Ar's "neighbour" isotopes are short-lived.

➢ 42Ar production from abundant and stable isotopes of K, Ca, possible but limited energetically due to high energy threshold for the nuclear reactions.

^{42}Ca stable 0.647%	^{43}Ca stable 0.135%	^{44}Ca stable 2.086%	^{45}Ca 162.7 d	^{46}Ca stable 0.004%
^{41}K stable 6.7%	^{42}K 12.36 hr	^{43}K 22.3 hr	^{44}K 22.1 m	^{45}K 17.8 m
^{40}Ar stable 99.603%	^{41}Ar 1.83 hr	^{42}Ar 33 yr ?	^{43}Ar 5.4 m	^{44}Ar 11.87 m
^{39}Cl 55.6 m	^{40}Cl 1.38 m	^{41}Cl 34 s	^{42}Cl 6.8 s	^{43}Cl 3.1 s
^{38}S 2.84 hr	^{39}S 11.5 s	^{40}S 9 s	^{41}S 2 s	^{42}S 1 s

Credit: Henning O. Back

42Ar production in the continental crust

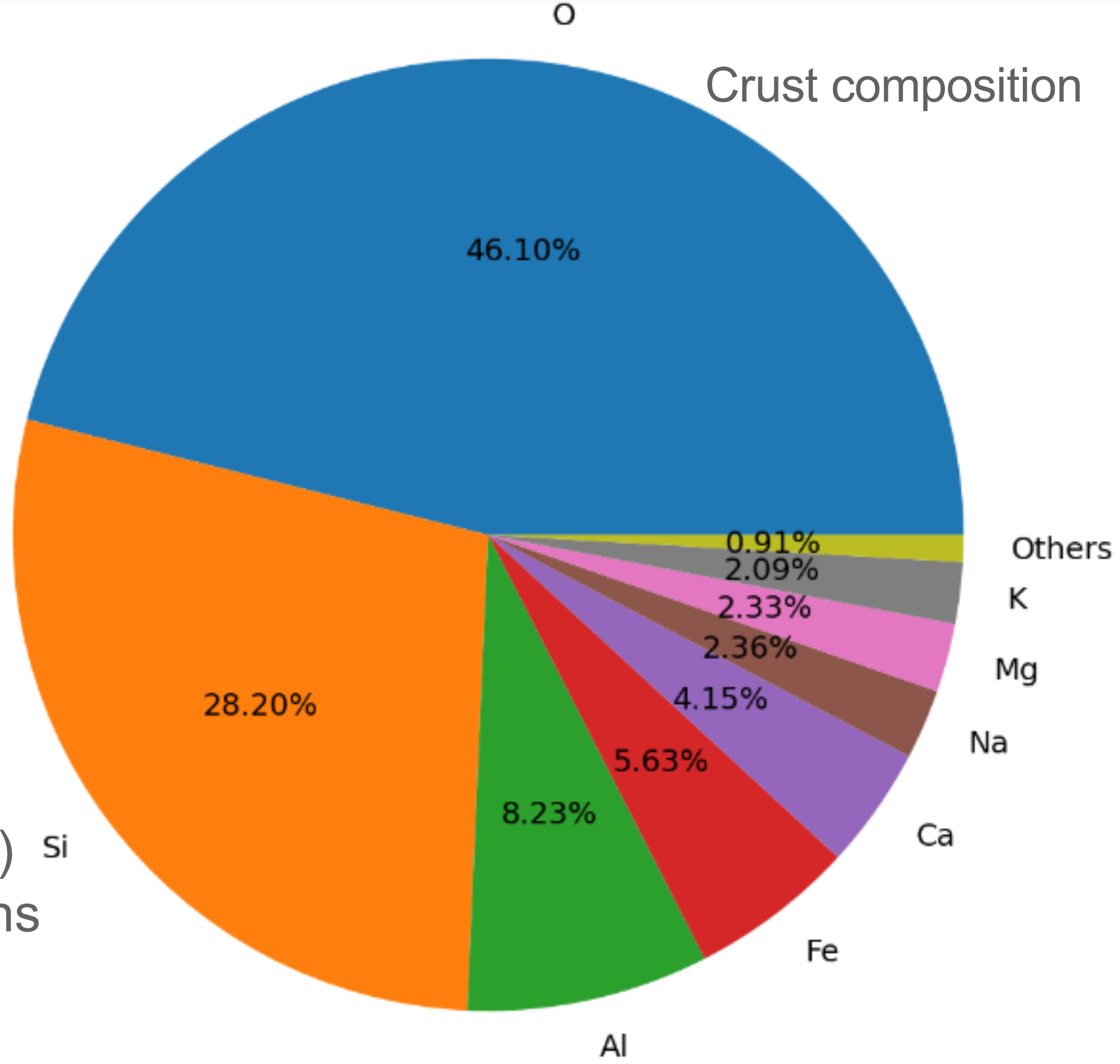
- Elemental abundances implemented down to 10 ppm level in the simulated crust (density = 2.7 gm/cm^3) [Natural isotopic abundances considered]

- Separate calculations for Radiogenic and Cosmogenic Production

What nuclear processes ?

- Natural radioactivity (42Cl, 43Cl decays)
- Interactions of spont. fission neutrons and (α,n) neutrons from natural radioactivity decay-chains
- Cosmic ray muon-induced interactions

Crust composition



CRC Handbook of Chemistry and Physics, 2021

Recipe for estimating 42Ar production (I)

TALYS-based estimate

Production yield

$$P = n \int \frac{d\phi(E)}{dE} \sigma(E) dE$$

$n \rightarrow$ no. of target atoms/isotopes per kg of crustal rock
$\phi(\mathrm{E}) \rightarrow$ particle flux (number of particles per sq. cm per sec)
$\sigma(\mathrm{E}) \rightarrow$ isotope production cross-section

Number density of target isotopes in the crust

differential particle flux

production cross-sections

What "target" isotopes?

All stable and long-lived isotopes within ($Z_{Ar} - 4$, $Z_{Ar} + 4$) , and isotopes of Mn and Fe

What particle projectiles?

(neutron, proton, triton, alpha) of radiogenic and cosmogenic origin

- **Evaluate above integral for all relevant reactions**

Recipe for estimating 42Ar production (II)

FLUKA-based estimate by recording residual isotopes produced by cosmic ray muon interactions in the crust

- Full particle transport through simulated crust
- Record residual nuclei produced from all cosmic ray muon-induced interactions in the simulated crust
- The elemental abundances implemented down to 10 ppm level

(continental crust composition taken from CRC Handbook, 2021)

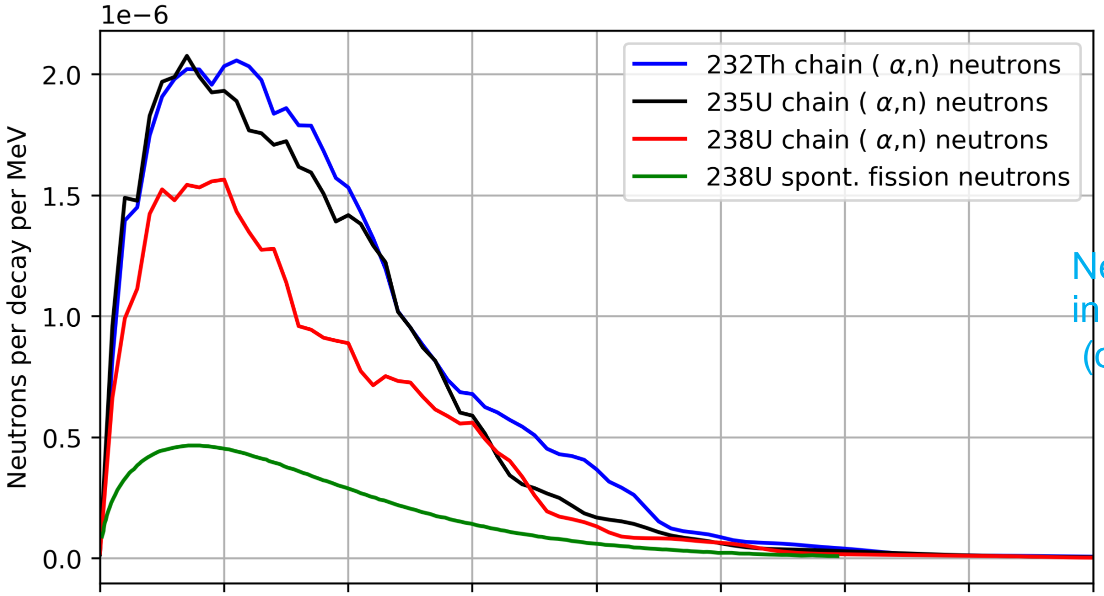
Physics Tools	Purpose
FLUKA [G. Battistoni et al. Annals of Nuclear Energy 82, (2015)	Generate and transport particles through simulated crust
EXPACS T. Sato et al., *J Nucl Sci Technol* **50**, 913-923 (2013)	Generate cosmic ray muon spectra over ground [for validation against MUSIC's flux numbers]
TALYS https://tendl.web.psi.ch/tendl_2019/	Obtain 42Ar isotope production cross-section for various nuclear reaction channels
MUSIC [V.A.Kudryavtsev,*Comput.Phys.Commun.* 180 (2009) 339-346]	Obtain cosmic ray muon flux and energy spectra at various crustal depths
NeuCBOT https://github.com/shawest/neucbot	Obtain neutron yield from (∝,n) reactions in continental crust

Radiogenic Particle flux in the earth's crust

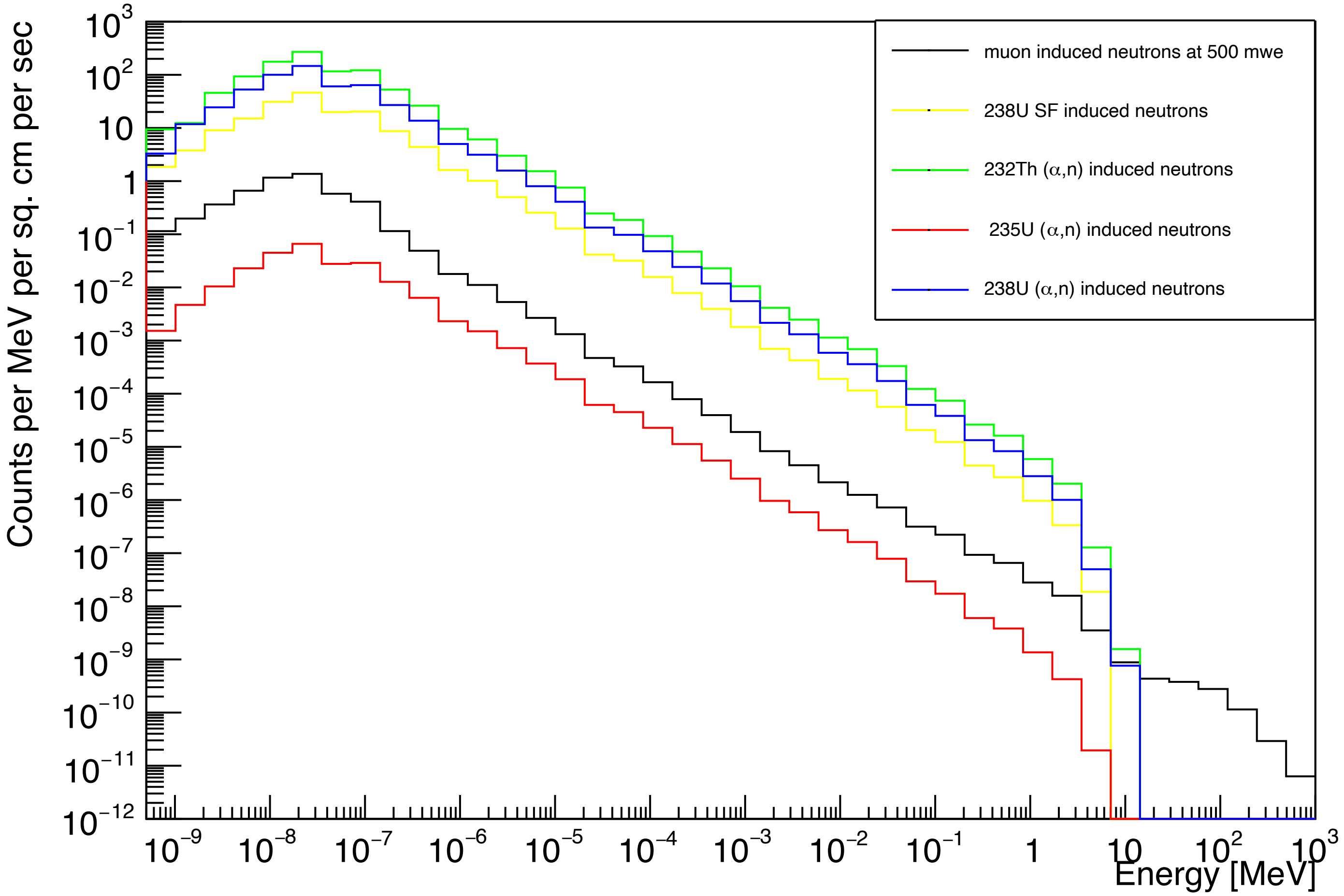
- Neutron yield and neutron energy distribution obtained from NeucBOT for our crustal composition
- Given the abundance of light elements like O, Mg, Al and Si in the crust, (α, n) neutron flux is significant
- Radiogenic neutron flux number is very sensitive to assumed concentration of U and Th in the crust.

  Upper continental crust
  Th content $=1.05 \times 10^{-5}$ g/g
  U content $= 2.7 \times 10^{-6}$ g/g
  (O. Shramek et al. / Geochimica et Cosmochimica Acta 196 (2017) 370–387)

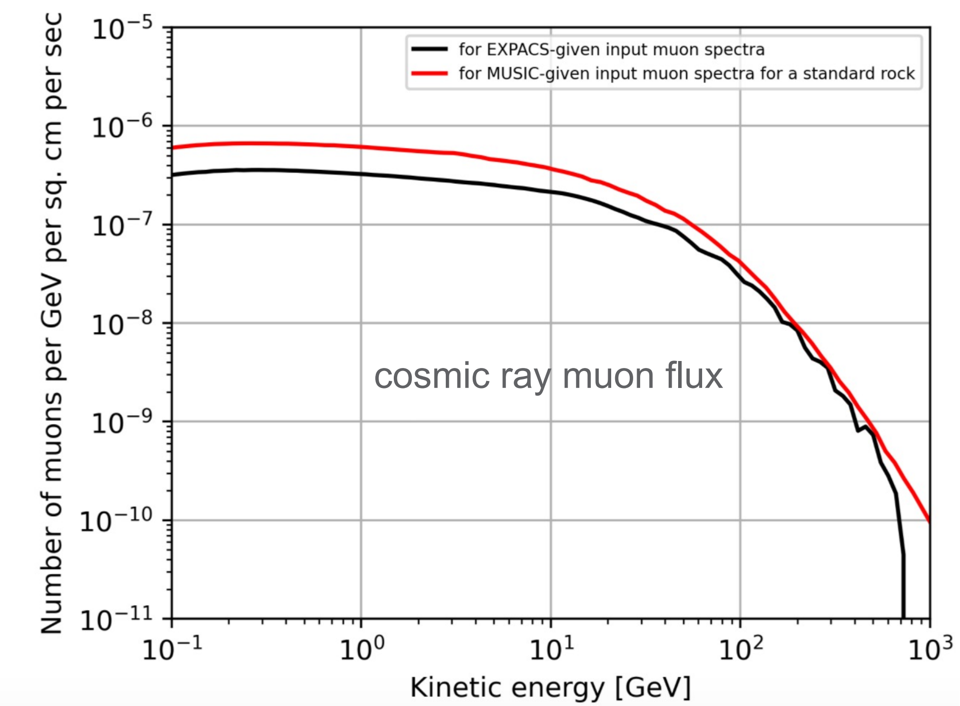
- At 500 mwe, cosmogenic neutron flux is two orders of magnitude smaller than radiogenic neutron flux.

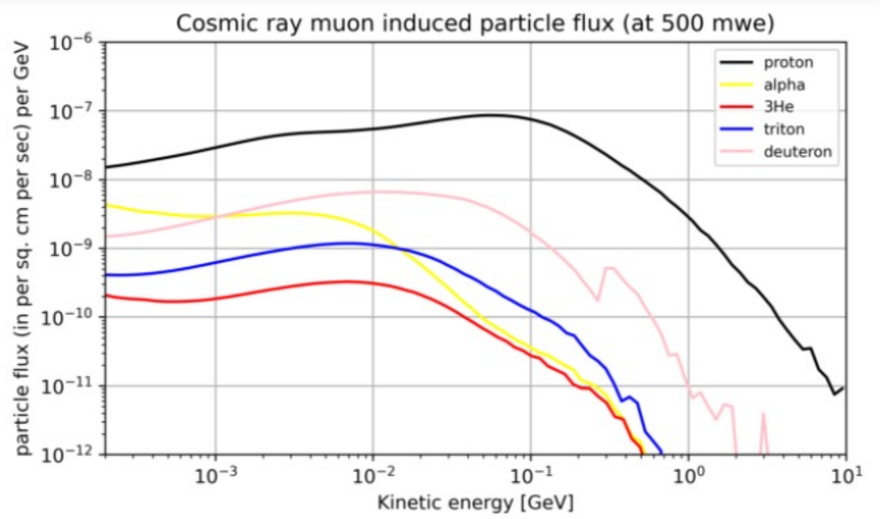


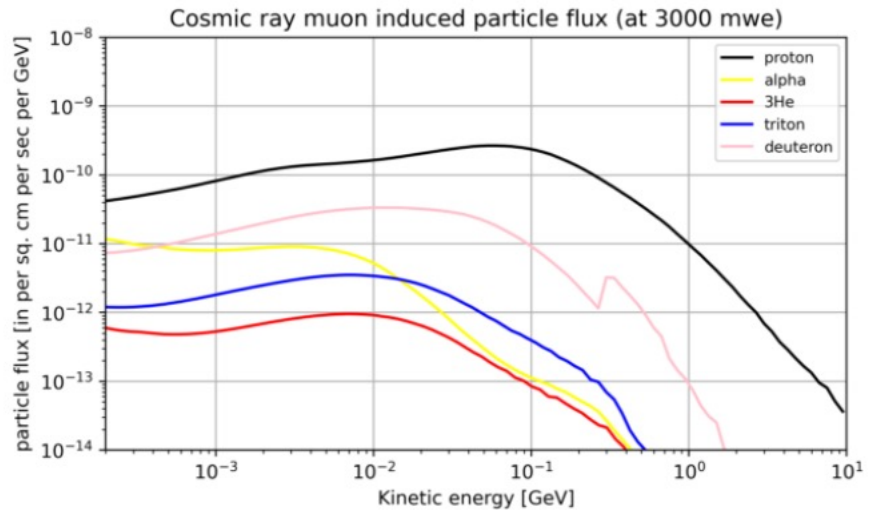
Neutron yield dist. in the crust (obtained using NeucBOT)

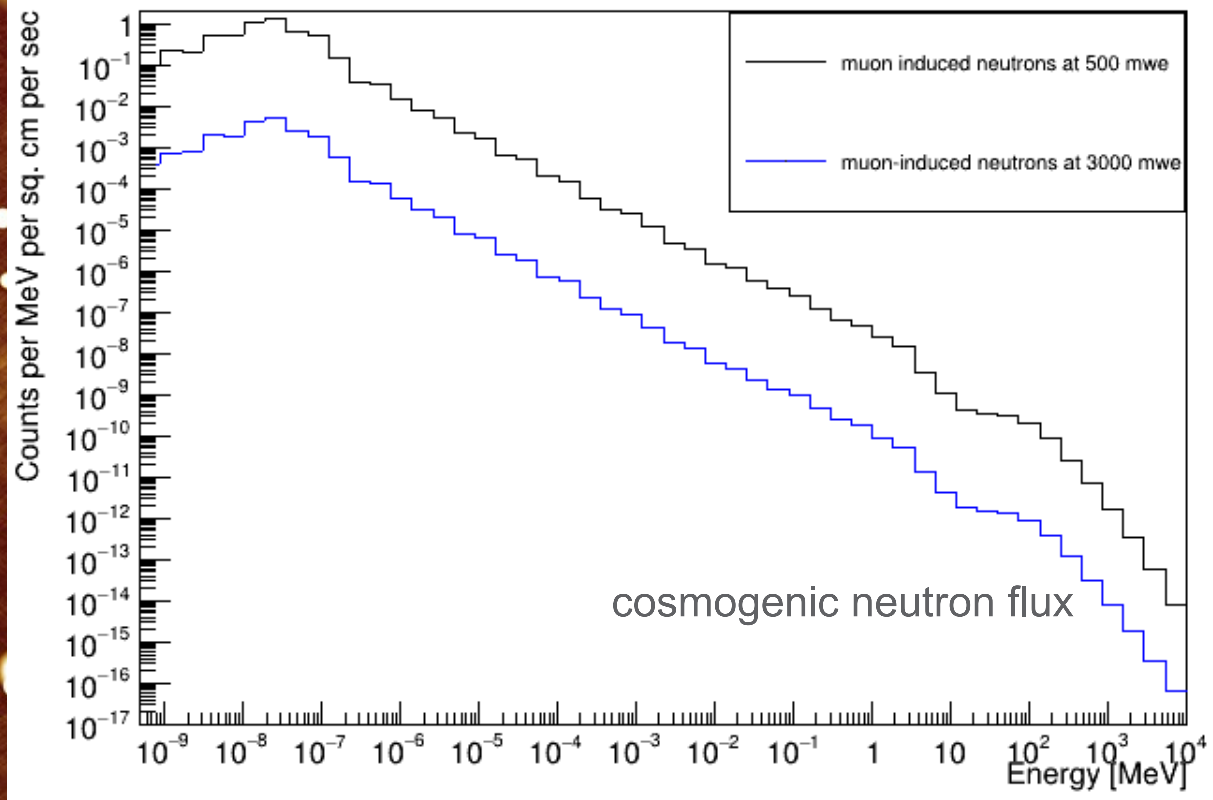


Cosmogenic Particle flux in the earth's crust









Input muon spectra and flux : MUSIC-given for a standard rock

Depth	Muon flux (standard rock)	Cosmogenic neutron flux (neutrons per sq. cm per sec) in the continental crust
500 mwe	2.07×10^{-5}	5.26×10^{-7}
3000 mwe	3.09×10^{-8}	2.02×10^{-9}

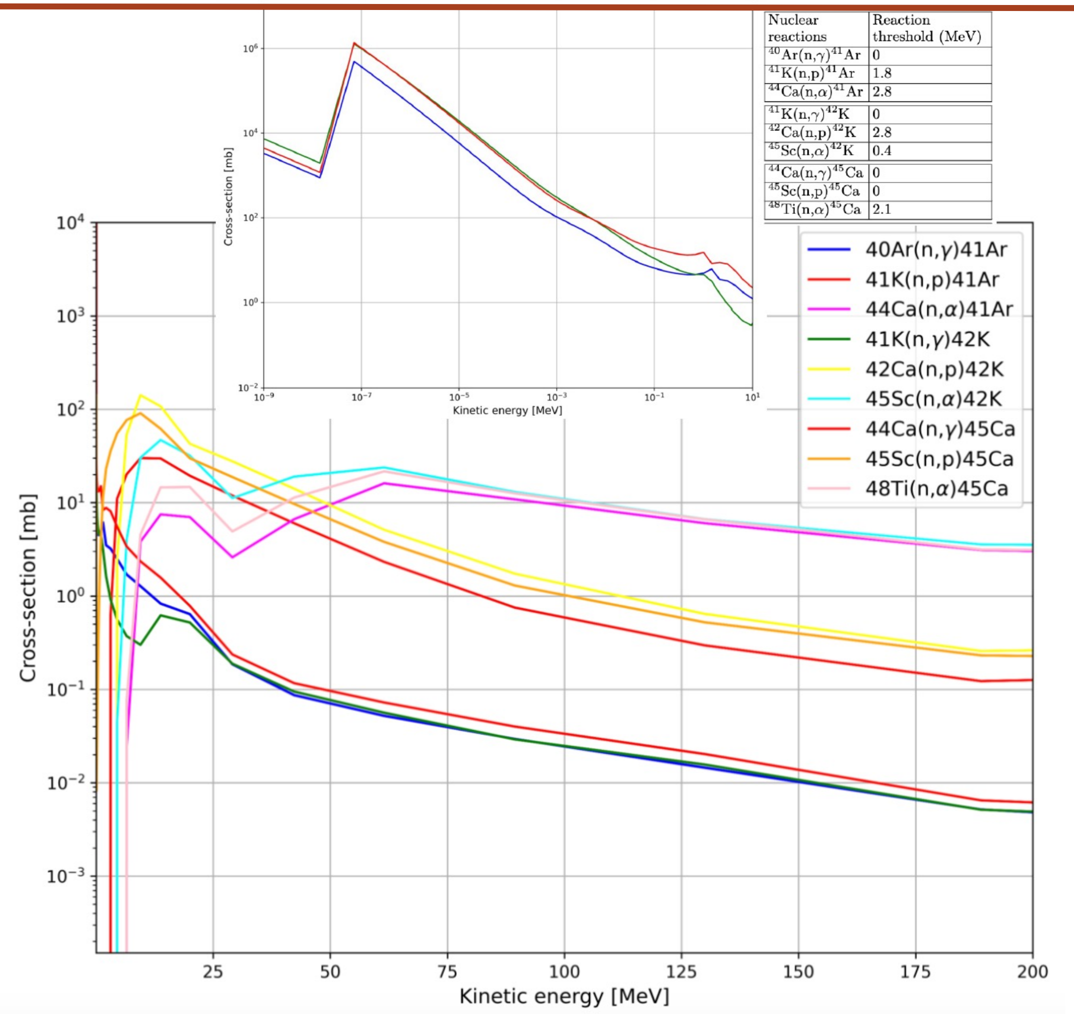
number comparable to the cosmogenic neutron flux at Gran Sasso
[However, cosmogenic neutron flux depends strongly on muon flux and composition]

Radiogenic production of 42Ar in the earth's crust

42Ar production in the earth's crust (Radiogenic production)

- 42Ar production from one step (radiogenic) neutron and alpha-induced nuclear reactions on stable isotopes highly unlikely: > 10 MeV energy thresholds

1) Estimate 41Ar, 42K , 45Ca production



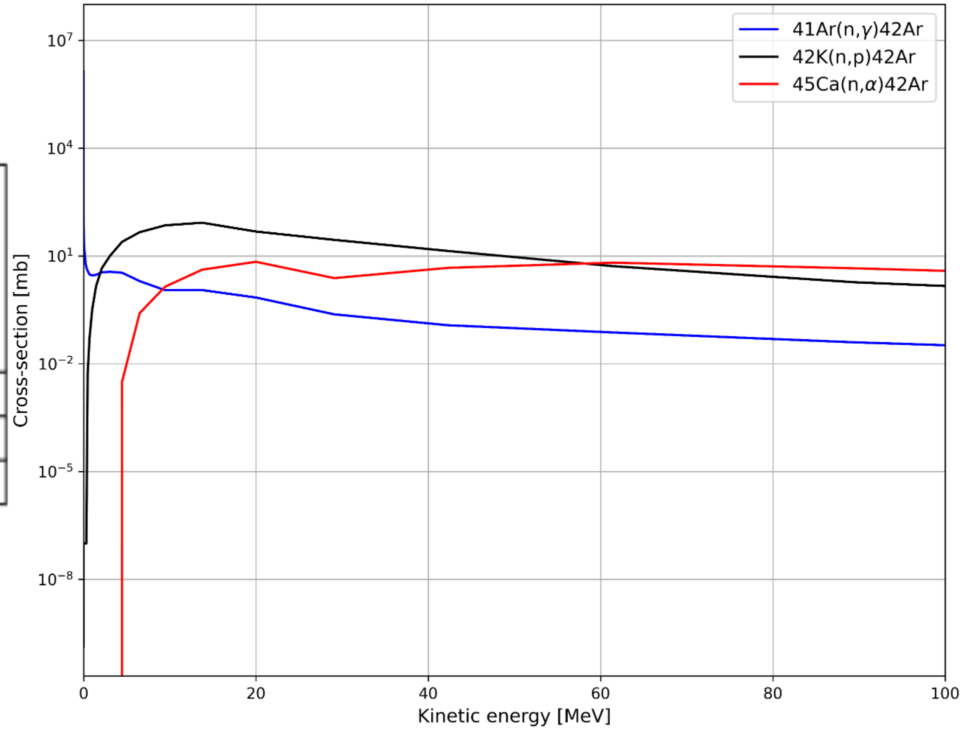
Nuclear reactions	Reaction threshold (MeV)
^{40}Ar(n,γ)^{41}Ar	0
^{41}K(n,p)^{41}Ar	1.8
^{44}Ca(n,α)^{41}Ar	2.8
^{41}K(n,γ)^{42}K	0
^{42}Ca(n,p)^{42}K	2.8
^{45}Sc(n,α)^{42}K	0.4
^{44}Ca(n,γ)^{45}Ca	0
^{45}Sc(n,p)^{45}Ca	0
^{48}Ti(n,α)^{45}Ca	2.1

Isotopes	Isotope half-life	Cosmogenic production rate (/ton/yr) at 500 mwe	Radiogenic production rate (/ton/yr)	Dominant production channel
^{41}Ar	109 min	18.2	1.82×10^4	^{40}Ar(n,γ)^{41}Ar
^{42}K	12 hr	2.24×10^4	1.56×10^7	^{41}K(n,γ)^{42}K
^{45}Ca	163 d	2.12×10^4	1.47×10^7	^{44}Ca(n,γ)^{45}Ca

*** 40Ar concentration 3 ppm assumed

2) Estimate radiogenic 42Ar production

Nuclear reaction	Reaction threshold (MeV)	Equilibrium concentration of ^{42}Ar (atoms/target atom)	Production rate (/ton/yr)
^{41}Ar(n,γ)^{42}Ar	0	4.13×10^{-17}	4.75×10^{-18}
^{42}K(n,p)^{42}Ar	0	5.00×10^{-23}	3.35×10^{-20}
^{45}Ca(n,α)^{42}Ar	0.7	1.84×10^{-26}	3.68×10^{-21}



Radiogenic 42Ar production rate in earth's crust

: 4.75×10^{-18} 42Ar atoms per ton of crust per year

*** It may be possible to set uppper limit for radiogenic production from from** one-step reaction 43Ca(n, 2p)42Ar)
43Ca(n, 2p)42Ar, energy threshold is 10.7 MeV, TALYS gives non-zero cross-section above 15 MeV]

Sagar, LRT2022

Henning O. Back

Cosmogenic production of 42Ar in the earth's crust

42Ar production in the earth's crust (Cosmogenic production)

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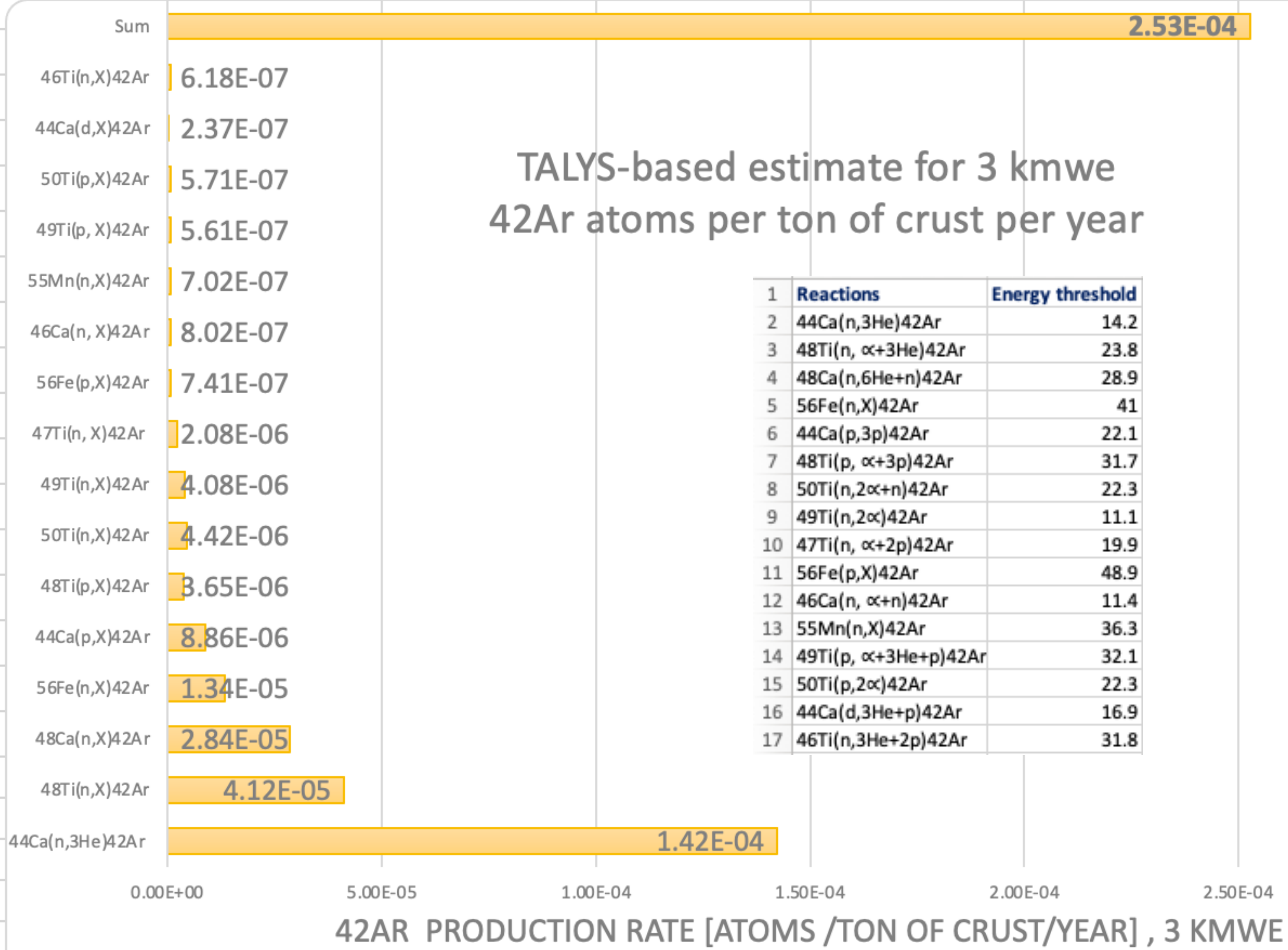
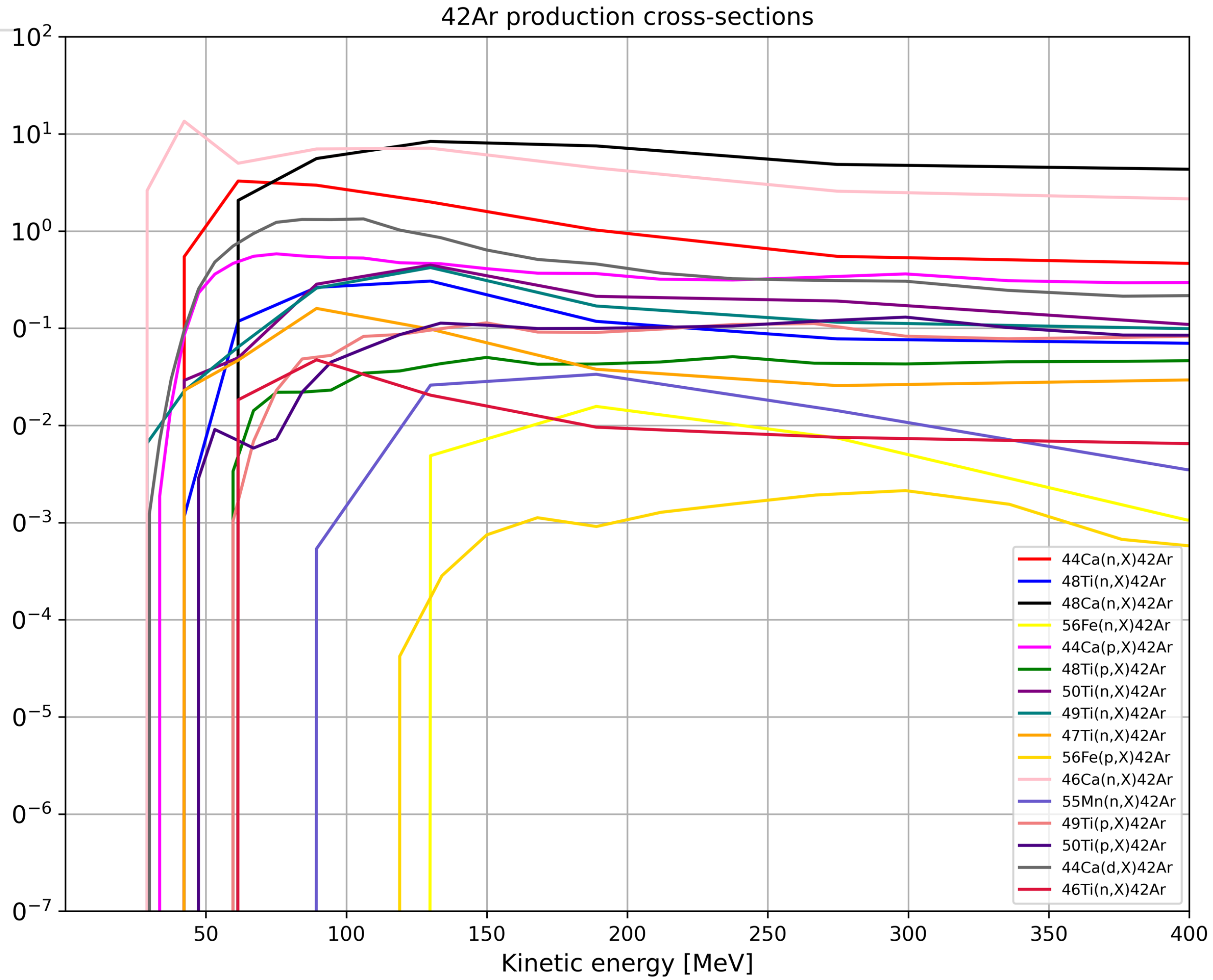
**Reactions that contribute ~ 99 % of the total production yield and the corresponding production rates



1	Reactions	Energy threshold
2	44Ca(n,3He)42Ar	14.2
3	48Ti(n, ∝+3He)42Ar	23.8
4	48Ca(n,6He+n)42Ar	28.9
5	56Fe(n,X)42Ar	41
6	44Ca(p,3p)42Ar	22.1
7	48Ti(p, ∝+3p)42Ar	31.7
8	50Ti(n,2∝+n)42Ar	22.3
9	49Ti(n,2∝)42Ar	11.1
10	47Ti(n, ∝+2p)42Ar	19.9
11	56Fe(p,X)42Ar	48.9
12	46Ca(n, ∝+n)42Ar	11.4
13	55Mn(n,X)42Ar	36.3
14	49Ti(p, ∝+3He+p)42Ar	32.1
15	50Ti(p,2∝)42Ar	22.3
16	44Ca(d,3He+p)42Ar	16.9
17	46Ti(n,3He+2p)42Ar	31.8



- Cross-sections within few orders of magnitude and similar thresholds for these reactions
- Highest 42Ar-yielding nuclear reaction largely determined by the abundance of the target isotope

42Ar production in the earth's crust (Cosmogenic production)

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At 3 kmwe

TALYS-based 42Ar estimate from selected reactions
: **2.5 x 10^{-4}** 42Ar atoms per ton of crust per year

42Ar estimate from residual isotope recording
: **3 x 10^{-3}** 42Ar atoms per ton of crust per year

Nuclear reactions	% contribution to ^{42}Ar production
^{44}Ca(n,3He)^{42}Ar	15 %
^{44}Ca(H*,X)^{42}Ar	12 %
^{44}Ca(μ^-,2p)^{42}Ar	5 %
^{48}Ca(H*,X)^{42}Ar	7 %
^{48}Ca(π^-,X)^{42}Ar	5 %
^{48}Ti(H*,X)^{42}Ar	5 %
^{50}Ti(H*,X)^{42}Ar	7 %
^{56}Fe(H*,X)^{42}Ar	12 %

H* -> heavy ion
X -> product particles/nuclei

- In the earth's crust, cosmogenic production of 42Ar may dominate up to large crustal depths.

- **At 3 kmwe depth, ~ 3 x 10^{-3} 42Ar atoms per ton of crust per year**

**Very sensitive to the Ca content assumed

42Ar in the underground argon (I)

- **Should be tiny but difficult to estimate**

➢ Argon: Crustal or mantle origin ?

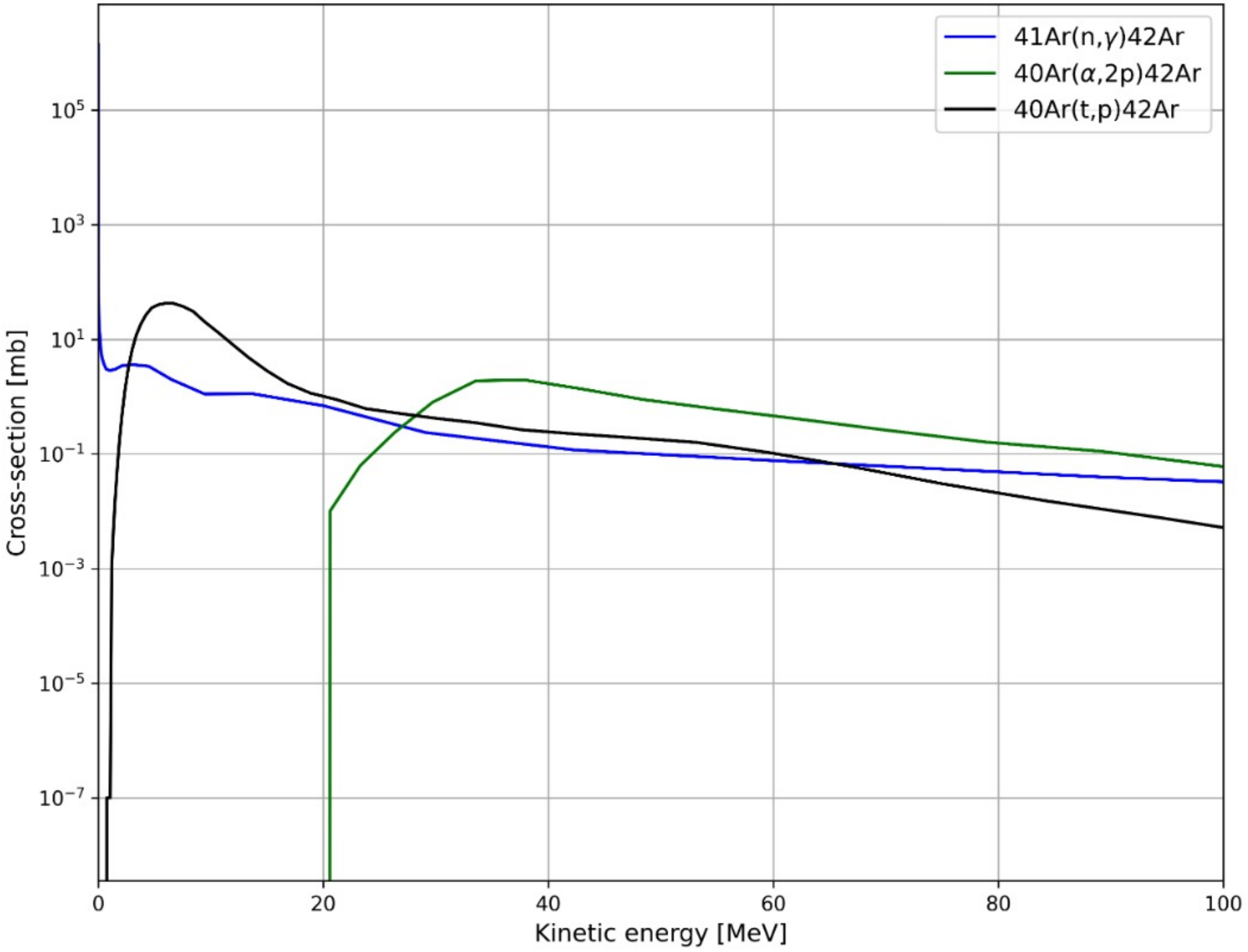
➢ Argon diffusion in rocks ?

(Geological time scale of diffusion vs 42Ar half-life)

➢ At > 12 kmwe depth, muon flux and shape unknown (neutrino-induced muons become important)

42Ar in the underground argon (II)

For an isolated argon-containing gas pocket in the earth's crust



- 40Ar(t,p)42Ar production highest and greater by three order of magnitude than 40Ar$(\alpha\,,2p)40Ar$

*** Assuming no diffusion of 42Ar in an out of the gas pocket and same particle flux at the gas pocket same as in crust

Depth	Equilibrium concentration of ^{42}Ar per ^{40}Ar	Dominant production channels
500 mwe 3 kmwe	4.64×10^{-28} 8.38×10^{-32}	^{40}Ar(t,p)^{42}Ar ^{40}Ar(t,p)^{42}Ar

11 orders of magnitude smaller than in atmospheric argon

Feasibility of a kiloton scale underground argon detector

Underground argon

- Known source of underground argon:

  : CO_2 gas wells in SW Colorado ,

  : Argon concentration: 400 ppm

  : ~ 300 kg/day

  : Will provide UAr for DarkSide-20K and Argo

DarkSide projects:
URANIA – extraction of UAr
ARIA – purification of UAr
DArt – measurement of 39Ar UAr

Craig E Aalseth et al. The European Physical Journal Plus, 133(3):1–129, 2018

There is a lot of argon underground

- 40Ar/36Ar ratio as a tool for geochronology and for understanding geochemical processes. [36Ar is primordial, 40Ar is a product of 40K (half-life of 1.2 billion years) decays

J.-Y.et al. Cosmochim. Acta70,4507–4512 (2006)

- 40Ar/36Ar in atmosphere: 299 , 40Ar/36Ar in mantle-rocks higher

- Fairly well established : Bulk of the atmospheric argon produced from the “mantle degassing”

Underground Argon: Challenges and Opportunities

Challenges

- Identifying Ar-enriched gas stream
- Cost-effective and commercial production
- Fast production to serve next generation argon-based experiments
- Techniques to measure 39Ar, 37Ar , 42Ar at ultra-low levels
- Proper storage of extracted argon to save it from air infiltration and contamination from cosmogenic activation.

R. Saldanha et al. Phys. Rev. C, 100:024608, 2019
C. Zhang, D. Mei . Astro. Part. Phy, Vol 142, 2022

https://arxiv.org/pdf/2203.09734.pdf

PNNL-SA-171232

Snowmass2021 White Paper

A Facility for Low-Radioactivity Underground Argon

Henning O. Back[1,*,†,‡] , Walter Bonivento[2,§] , Mark Boulay[3,‡,**], Eric Church[1,††], Steven R. Elliott[4,‡‡], Federico Gabriele[5,§] , Cristiano Galbiati[6,7,§§], Graham K. Giovanetti[8,§§] , Christopher Jackson[1,††], Art McDonald[9,§§,**], Andrew Renshaw[10,‡], Roberto Santorelli[11,***], Kate Scholberg[12,††,†††], Marino Simeone[13,‡] , Rex Tayloe[14,†††], Richard Van de Water[4,‡‡‡]

- PNNL working with a major gas supplier to obtain from underground sources
  - ~ 5000 ton/year
  - Estimated cost 3 X cost of atmospheric argon

https://arxiv.org/pdf/2203.08821.pdf.

****These numbers are rough estimates

Contact: Henning O. Back for more information

kton scale underground argon detector

- Use of underground argon in a kiloton scale detector like DUNE would make it a multipurpose detector : a neutrino and dark matter detector

Physics reach of the low background low threshold kton scale detector

- ➢ Supernova neutrino physics: Early and late time information, sensitivity to distant supernova (from Magellanic cloud), measurements of CEvNS neutrinos

- ➢ Solar neutrino physics: increased sensitivity to Δm_{21}^2, precision measurement of CNO flux

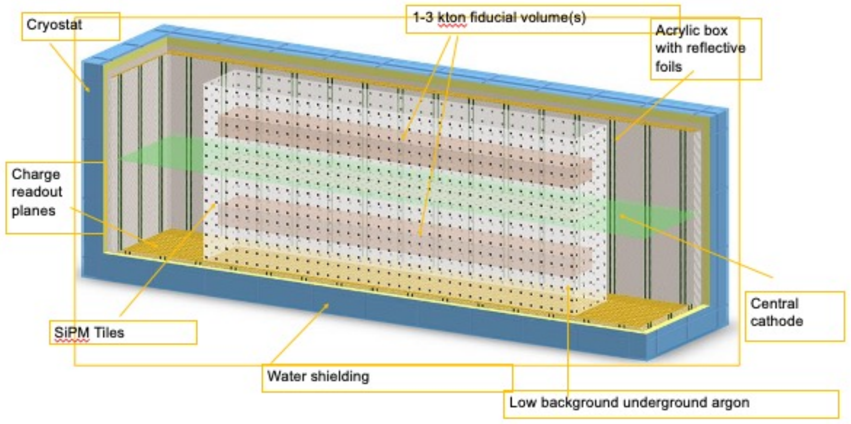
- ➢ Neutrinoless double beta decay($0\nu\beta\beta$) physics with Xenon-136 doping

- ➢ Dark matter physics:
  WIMP dark matter searches, measurements of seasonal variations of WIMPs

Snowmass2021 - White Paper

Low Background kTon-Scale Liquid Argon Time Projection Chambers

A. Avasthi[1], T. Bezerra[2], A. Borkum[2], E. Church[3], J. Genovesi[4], J. Haiston[4], C. M. Jackson[3], I. Lazanu[5], B. Monreal[1], S. Munson[3], C. Ortiz[6], M. Parvu[5], S. J. M. Peeters[2], D. Pershey[6], S. S. Poudel[3], J. Reichenbacher[4], R. Saldanha[3], K. Scholberg[6], G. Sinev[4], J. Zennamo[7], H. O. Back[3], J. F. Beacom[8], F. Capozzi[9], C. Cuesta[10], Z. Djurcic[11], A. C. Ezeribe[12], I. Gil-Botella[10], S. W. Li[7], M. Mooney[13], M. Sorel[9], and S. Westerdale[14]



https://arxiv.org/pdf/2203.08821.pdf

Summary

- 39Ar and 42Ar/42K backgrounds are concerning for large-scale argon-based detectors.

- 42Ar production is largely cosmogenic in the earth's crust (at least to large crustal depths)

- Argon extracted from underground sources should be depleted of Ar radioactive isotopes 39Ar, 42Ar.

- Use of underground argon (UAr) will increase the sensitivity and expand the physics goals of next generation large argon-based experiments.

- The challenges are extracting argon in a kton scale and in time for next generation argon-based experiments.

Reactions considered in the TALYS-based estimate

Backup

TABLE VII: Cosmogenic production rates at 500 mwe (continental crust composition)

Reactions	Production rate(TALYS-based) from selected reactions [atoms/ton/yr]	Production rates based on FLUKA residual nuclei recording [atoms/ton/yr]	Major ^{42}Ar yielding reactions
n,p,d,t induced reactions	0.035	0.055	^{44}Ca(n,3He)^{42}Ar
heavy ion collisions	–	0.15	^{44}Ca(H*,X)^{42}Ar ^{48}Ca(H*,X)^{42}Ar
direct muon induced reactions	–	0.041	^{44}Ca(μ^-,2p)^{42}Ar
other reactions (photonuclear, radioactive decays, pion interactions)	–	0.044	^{48}Ca(Π^-,X)^{42}Ar

Element (Z)	Isotopes (Isotopic abundance)	Reactions	Energy threshold (MeV)
Si (Z=14)	^{28}Si(92.23%) ^{29}Si(4.67%) ^{30}Si(3.10%)	-	-
P (Z=15)	^{31}P(100%	-	-
S (Z=16)	^{32}S(95.02%) ^{33}S(0.75%) ^{34}S(4.21%) ^{36}S(0.02%) ^{38}S(trace, $\tau_{1/2}$=3h)	^{38}S(α,γ)^{42}Ar	0.0
Cl (Z=17)	^{35}Cl(75.77%) ^{37}Cl(24.23%) ^{42}Cl(trace,$\tau_{1/2}$=6s) ^{43}Cl(trace,$\tau_{1/2}$=280ms)	^{42}Cl β^-decay ^{43}Cl β^-+n decay	-
Ar (Z=18)	^{36}Ar(0.337%) ^{38}Ar(0.063%) ^{40}Ar(99.6%) ^{41}Ar(trace,$\tau_{1/2}$=109m)	^{40}Ar(α,2p)^{42}Ar ^{41}Ar(n,γ)^{42}Ar ^{40}Ar(t,p)^{42}Ar	14.0 0 0.7
K (Z=19)	^{39}K(93.3%) ^{40}K(0.011%) ^{41}K(6.73%) ^{42}K(trace,$\tau_{1/2}$=12h)	^{41}K(α,X)^{42}Ar ^{41}K(t,2p)^{42}Ar ^{42}K(n,p)^{42}Ar	22.6 0.8 0.2
Ca (Z=20)	^{40}Ca(96.9%) ^{42}Ca(0.647%) ^{43}Ca(0.135%) ^{44}Ca(2.086%) ^{45}Ca(trace,$\tau_{1/2}$=163d) ^{46}Ca(0.004%) ^{48}Ca(0.187%)	^{42}Ca(α,X)^{42}Ar ^{43}Ca(α,X)^{42}Ar ^{44}Ca(α,X)^{42}Ar ^{45}Ca(α,X)^{42}Ar ^{46}Ca(α,X)^{42}Ar ^{48}Ca(α,X)^{42}Ar ^{43}Ca(n,2p)^{42}Ar ^{44}Ca(n,3He)^{42}Ar ^{45}Ca(n,α)^{42}Ar ^{46}Ca(n,α+n)^{42}Ar ^{48}Ca(n,X)^{42}Ar ^{44}Ca(p,3p)^{42}Ar ^{43}Ca(d,2p)^{42}Ar ^{44}Ca(d,X)^{42}Ar ^{46}Ca(d,X)^{42}Ar ^{48}Ca(d,X)^{42}Ar	33.8 34.0 25.1 27.6 12.1 21.6 10.7 14.2 0.7 11.4 28.9 22.1 13.1 16.9 11.6 18.3
Sc (Z=21)	^{45}Sc(100%) ^{46}Sc(trace,$\tau_{1/2}$=84d)	^{45}Sc(n,X)^{42}Ar ^{45}Sc(p,4p)^{42}Ar ^{45}Sc(d,X)^{42}Ar	21.3 29.1 24.0
Ti (Z=22)	^{46}Ti(8.0%) ^{47}Ti(7.3%) ^{48}Ti(73.8%) ^{49}Ti(5.5%) ^{50}Ti(5.4%)	^{46}Ti(α,X)^{42}Ar ^{47}Ti(α,X)^{42}Ar ^{48}Ti(α,X)^{42}Ar ^{49}Ti(α,X)^{42}Ar ^{50}Ti(α,X)^{42}Ar ^{46}Ti(n,X)^{42}Ar ^{47}Ti(n,X)^{42}Ar ^{48}Ti(n,X)^{42}Ar ^{49}Ti(n,X)^{42}Ar ^{50}Ti(n,X)^{42}Ar ^{46}Ti(p,X)^{42}Ar ^{47}Ti(p,X)^{42}Ar ^{48}Ti(p,X)^{42}Ar ^{49}Ti(p,X)^{42}Ar ^{50}Ti(p,X)^{42}Ar ^{46}Ti(d,X)^{42}Ar ^{47}Ti(d,X)^{42}Ar ^{48}Ti(d,X)^{42}Ar ^{49}Ti(d,X)^{42}Ar ^{50}Ti(d,X)^{42}Ar ^{46}Ti(t,X)^{42}Ar ^{47}Ti(t,X)^{42}Ar ^{48}Ti(t,X)^{42}Ar ^{49}Ti(t,X)^{42}Ar ^{50}Ti(t,X)^{42}Ar	46.0 40.2 29.6 24.2 15.8 31.8 19.9 23.8 11.1 22.3 39.7 40.8 31.7 32.1 22.3 34.8 22.6 24.9 13.7 16.6 20.3 21.5 12.0 11.9 11.4
Mn (Z=25)	^{55}Mn(100%) ^{53}Mn(trace,$\tau_{1/2}$ =3.7E6y)	^{55}Mn(α,X)^{42}Ar ^{55}Mn(n,X)^{42}Ar ^{55}Mn(p,X)^{42}Ar ^{55}Mn(d,X)^{42}Ar ^{55}Mn(t,X)^{42}Ar	24.5 36.3 38.5 33.6 19.1
Fe (Z=26)	^{54}Fe(5.85%) ^{56}Fe(91.75%) ^{57}Fe(2.12%) ^{58}Fe(0.28%) ^{60}Fe(trace,$\tau_{1/2}$ =2.6E6y)	^{54}Fe(α,X)^{42}Ar ^{54}Fe(n,X)^{42}Ar ^{54}Fe(p,X)^{42}Ar ^{54}Fe(d,X)^{42}Ar ^{54}Fe(t,X)^{42}Ar ^{56}Fe(α,X)^{42}Ar ^{56}Fe(n,X)^{42}Ar ^{56}Fe(p,X)^{42}Ar ^{56}Fe(d,X)^{42}Ar ^{56}Fe(t,X)^{42}Ar ^{57}Fe(α,X)^{42}Ar ^{57}Fe(n,X)^{42}Ar ^{57}Fe(p,X)^{42}Ar ^{57}Fe(d,X)^{42}Ar ^{57}Fe(t,X)^{42}Ar ^{58}Fe(α,X)^{42}Ar ^{58}Fe(n,X)^{42}Ar ^{58}Fe(p,X)^{42}Ar ^{58}Fe(d,X)^{42}Ar ^{58}Fe(t,X)^{42}Ar	60.0 49.0 56.8 52.1 39.4 51.5 41.0 48.9 44.1 29.7 51.3 27.8 48.8 30.7 35.4 40.0 38.1 38.1 52.1 39.4

Thank you