Measurement of the Total $^{40}Ar(n,2n)^{39}Ar$ and $^{40}Ar(n,\gamma)^{41}Ar$ Reaction Cross Sections

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30th June 2026

Outline

- **First experimental determination of the total ^{40}Ar(n,2n)^{39}Ar reaction cross section and ^{39}Ar production in Earth's atmosphere**
  - **Experimental details for ^{40}Ar(n,2n)^{39}Ar reaction**
  - **Noble Gas Accelerator Mass Spectrometry (NOGAMS)**
  - **^{39}Ar cosmogenic production at different altitudes**
  - **^{39}Ar anthropogenic production**
- **Thermal ^{41}Ar(n,γ)^{42}Ar reaction cross section**
  - **Introduction**
  - **^{42}Ar production with the radiative capture process**
  - **Measuring ^{41}Ar(n,γ)^{42}Ar cross section**
- **Summary**

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- **Summary**

Background & Motivation

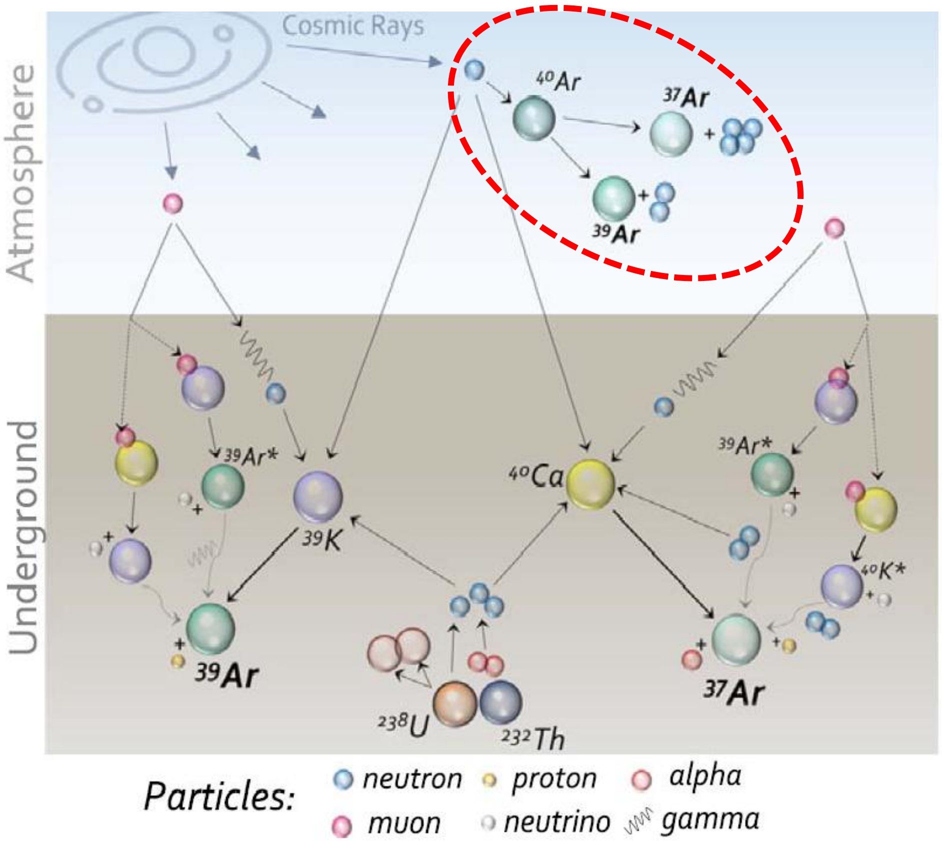
Science of the Total Environment

Reviewing ^{39}Ar and ^{37}Ar underground production in shallow depths with implications for groundwater dating

Stephanie Musy *, Roland Purtschert

Climate and Environmental Physics and Oeschger Center for Climate Change Research, University of Bern, Sidlerstrasse 5, 3012 Bern, Switzerland

Science of the Total Environment 884 (2023) 163868



^{39}Ar (268 y):

1. Cosmogenic production
2. Radiogenic production
3. Anthropogenic production

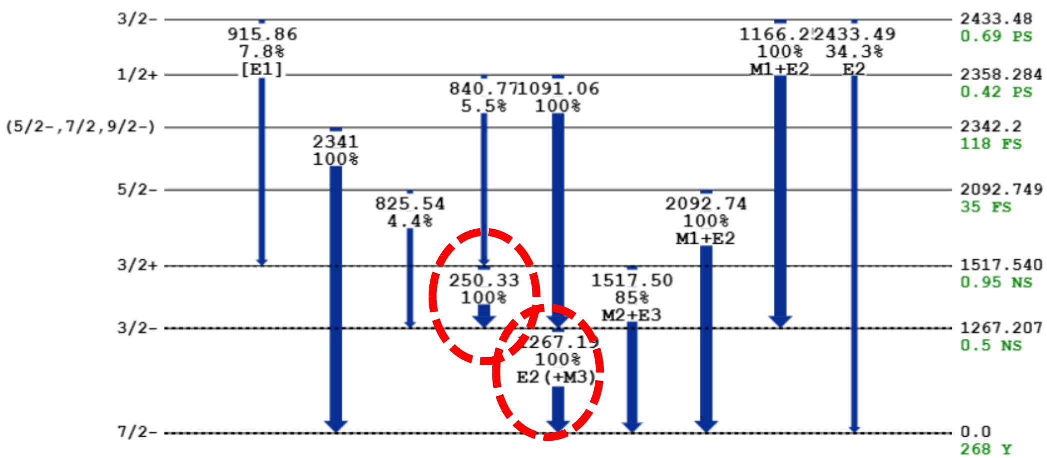
Atmospheric cosmogenic production via $^{40}Ar(n,2n)^{39}Ar$ by fast neutrons is the largest contribution, but its cross section is poorly known.

Background & Motivation

PHYSICAL REVIEW C **85**, 064614 (2012)

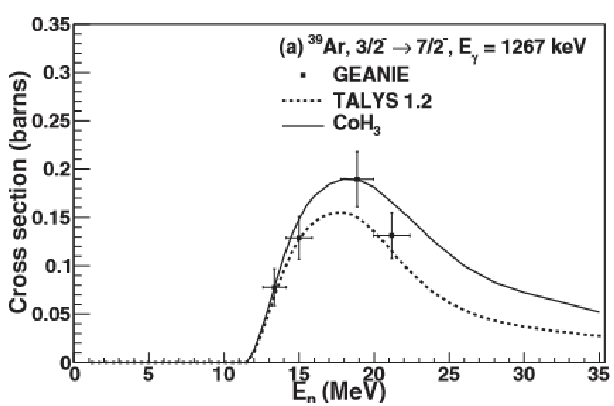
Partial γ-ray production cross sections for $(n, xn\gamma)$ reactions in natural argon at 1–30 MeV

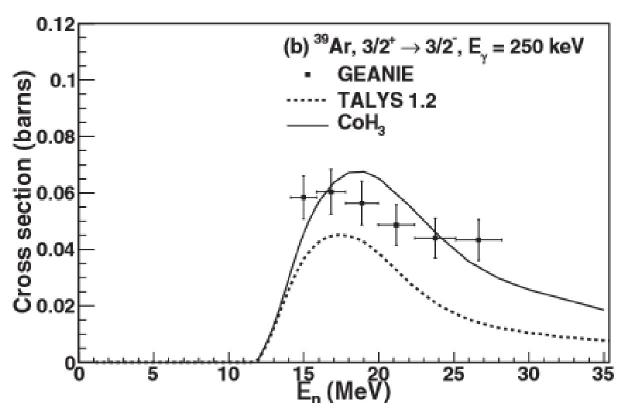
S. MacMullin,[1,2,3,*] M. Boswell,[3] M. Devlin,[4] S. R. Elliott,[3] N. Fotiades,[4] V. E. Guiseppe,[5] R. Henning,[1,2] T. Kawano,[6]
B. H. LaRoque,[3,†] R. O. Nelson,[4] and J. M. O'Donnell[4]
[1]*Department of Physics and Astronomy, University of North Carolina, Chapel Hill, North Carolina 27599, USA*

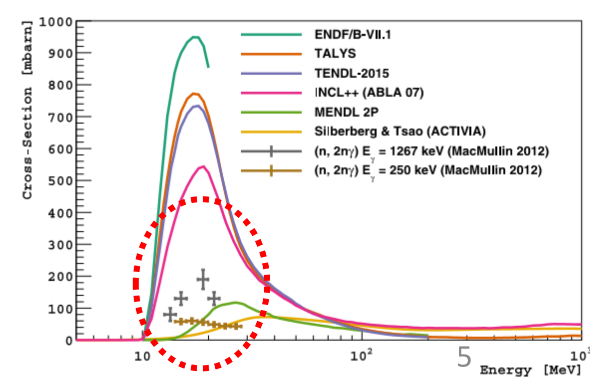


$^{40}Ar(n,2n)^{39}Ar(3/2^-)$

- Experiment performed at Los Alamos Neutron Science Centre (LANSCE).
- A broad-spectrum (~0.2–800 MeV) pulsed neutron beam was produced via spallation on a ^{nat}W target by an 800-MeV proton linear accelerator beam.
- During the argon runs 1.9×10^{11} neutrons of energies from 1 to 100 MeV on the argon target.
- Data collected at the GEANIE array with 20 Compton-suppressed HPGe detectors.







Background & Motivation

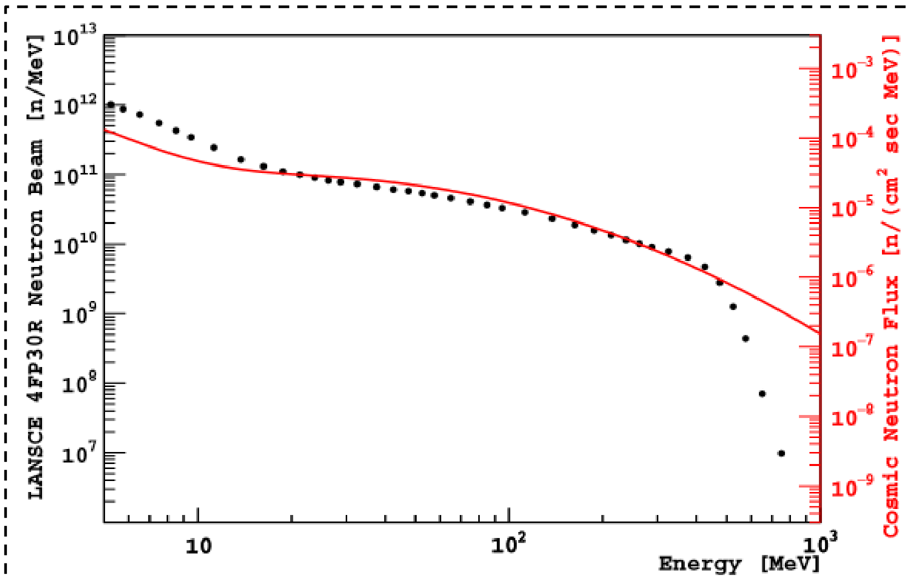
PHYSICAL REVIEW C **100**, 024608 (2019)

Cosmogenic production of ^{39}Ar and ^{37}Ar in argon

R. Saldanha,[1,*] H. O. Back,[1] R. H. M. Tsang,[1] T. Alexander,[1] S. R. Elliott,[2] S. Ferrara,[1]
E. Mace,[1] C. Overman,[1] and M. Zalavadia[1]
[1]*Pacific Northwest National Laboratory, Richland, Washington 99352, USA*
[2]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

Experiment:

- The samples were irradiated at the LANSCE WNR ICEHOUSE II facility).



- A broad-spectrum (0.2–800 MeV) neutron beam was produced via spallation of 800 MeV protons on a tungsten target, generating the neutron fluence for the experiment.
- The resulting activity was measured using ultra–low-background gas proportional counters (ULBPCs) at the Pacific Northwest National Laboratory (PNNL)

Godhagen et al., 2003

Background & Motivation

PHYSICAL REVIEW C **100**, 024608 (2019)

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[1]*Pacific Northwest National Laboratory, Richland, Washington 99352, USA*
[2]*Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

Results:

❖ They measured the beam-induced activity of an underground Ar sample 155 ± 4 mBq. The production rate is calculated using the relation

$$P = n \times \int_0^{E_{max}} \frac{d\phi}{dE}\,\sigma(E)\,dE$$

Cross-section model	Pred. LANSCE ^{39}Ar activity (mBq)	Meas./Pred. LANSCE ^{39}Ar activity	Pred. cosmogenic ^{39}Ar prod. rate [atoms/(kg$_{Ar}$day)]	Scaled cosmogenic ^{39}Ar prod. rate [atoms/(kg$_{Ar}$day)]
Silberberg & Tsao (ACTIVIA)	37.1 ± 2.5	4.19 ± 0.31	200 ± 25	840 ± 120
MENDL-2P	36.0 ± 2.5	4.31 ± 0.32	188 ± 24	810 ± 120
TENDL-2015	162 ± 11	0.961 ± 0.071	726 ± 91	700 ± 100
TALYS	168 ± 12	0.924 ± 0.068	753 ± 94	700 ± 100
INCL++ (ABLA07)	172 ± 12	0.902 ± 0.067	832 ± 104	750 ± 110

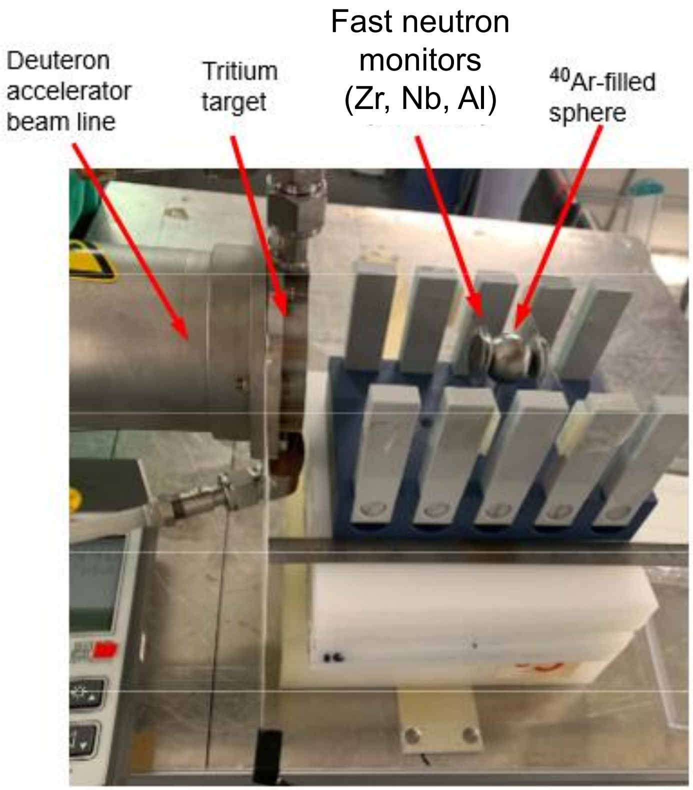
Different models suggest different predicted activities and production rates.
The scaling factor is determined by the ratio of the experimental to the predicted production rate for each model and is then used to estimate the cosmogenic production rate.

Reaction	Estimated ^{39}Ar production rate [atoms/(kg$_{Ar}$day)]	Fraction of total AAr (%)
^{40}Ar (n, 2n)^{39}Ar+ ^{40}Ar(n, d)^{39}Cl	759 ± 128	72.3

Geochimica et Cosmochimica Acta 415 (2026) 196–203

First experimental determination of the $^{40}Ar(n, 2n)^{39}Ar$ reaction cross section and ^{39}Ar production in Earth's atmosphere

S. Bhattacharya [a], M. Paul [a,*], R.N. Sahoo [a], R. Purtschert [b], H.F.R. Hoffmann [c], M. Pichotta [c], K. Zuber [c], D. Bemmerer [d], T. Döring [d], R. Schwengner [d], M.L. Avila [e], E. Lopez-Saavedra [e], J.C. Dickerson [e], C. Fougères [e], J. McLain [e], R.C. Pardo [e], K.E. Rehm [e], R. Scott [e], I. Tolstukhin [e], R. Vondrasek [e], T. Bailey [f], L. Callahan [f], A.M. Clark [f], P. Collon [f], Y. Kashiv [f], A. Nelson [f], D. Robertson [f], D. Neto [g], C. Ugalde [g], M. Tessler [h], S. Vaintraub [h]



Technical University Dresden
Helmholtz Zentrum Dresden-Rossendorf (HZDR)

Direct measurement of $^{40}Ar(n,2n)^{39}Ar$

sphere: stainless steel : volume: 4.18 cm^3 ;
content : ^{40}Ar gas ;pressure: 20 bar

- 300 keV deuteron beam hits the 1 cm diameter TiT_2 target (T; tritium), produced ≈ 7.3(3)×10^{11} neutrons.
- Irradiation time: 4 h.
- The neutron energy, determined using the cross section of the $^{90}Zr(n,2n)^{89}Zr$ reaction, was 14.8 ± 0.3 MeV.
- Neutron flux/fluence was determined through $^{93}Nb(n,2n)^{93m}Nb$(10.15 d) and $^{27}Al(n,\alpha)^{24}Na$ (14.96 hr) reaction.
- Measure $^{39}Ar/^{40}Ar$ by **Noble Gas Accelerator Mass Spectrometry and LLC-> Low Level Counting**
- Extract cross-section σ from

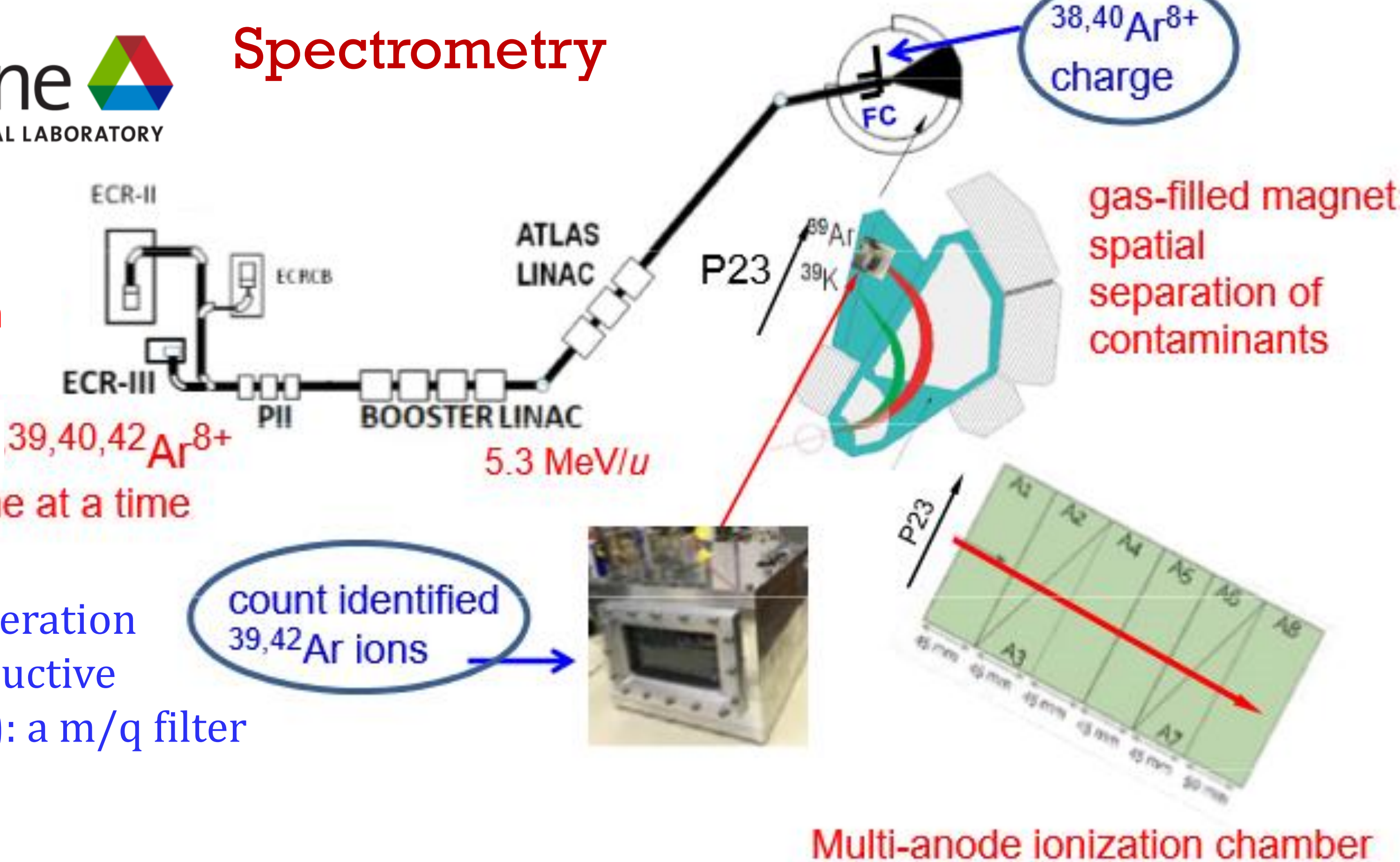
$$^{39}Ar/^{40}Ar = \sigma.\varphi.t$$

where neutron fluence φ.t is measured by monitors.

NOGAMS: Noble Gas Accelerator Mass Spectrometry

Argonne NATIONAL LABORATORY

positive ion accelerator



linear acceleration (superconductive RF cavities): a m/q filter

The technique measures
an isotopic ratio: r = rare/abundant.
Total number of rare atoms =
N(rare) = $r \times$ N(abundant)
$N(^{39}Ar) = r\,(^{39}Ar/^{40}Ar) \times N(^{40}Ar)$
$N(^{42}Ar) = r\,(^{42}Ar/^{40}Ar) \times N(^{40}Ar)$

Noble-Gas Accelerator Mass Spectrometry (NOGAMS):
$^{39,42}Ar$ detection An atom-counting mass spectrometry at high energy

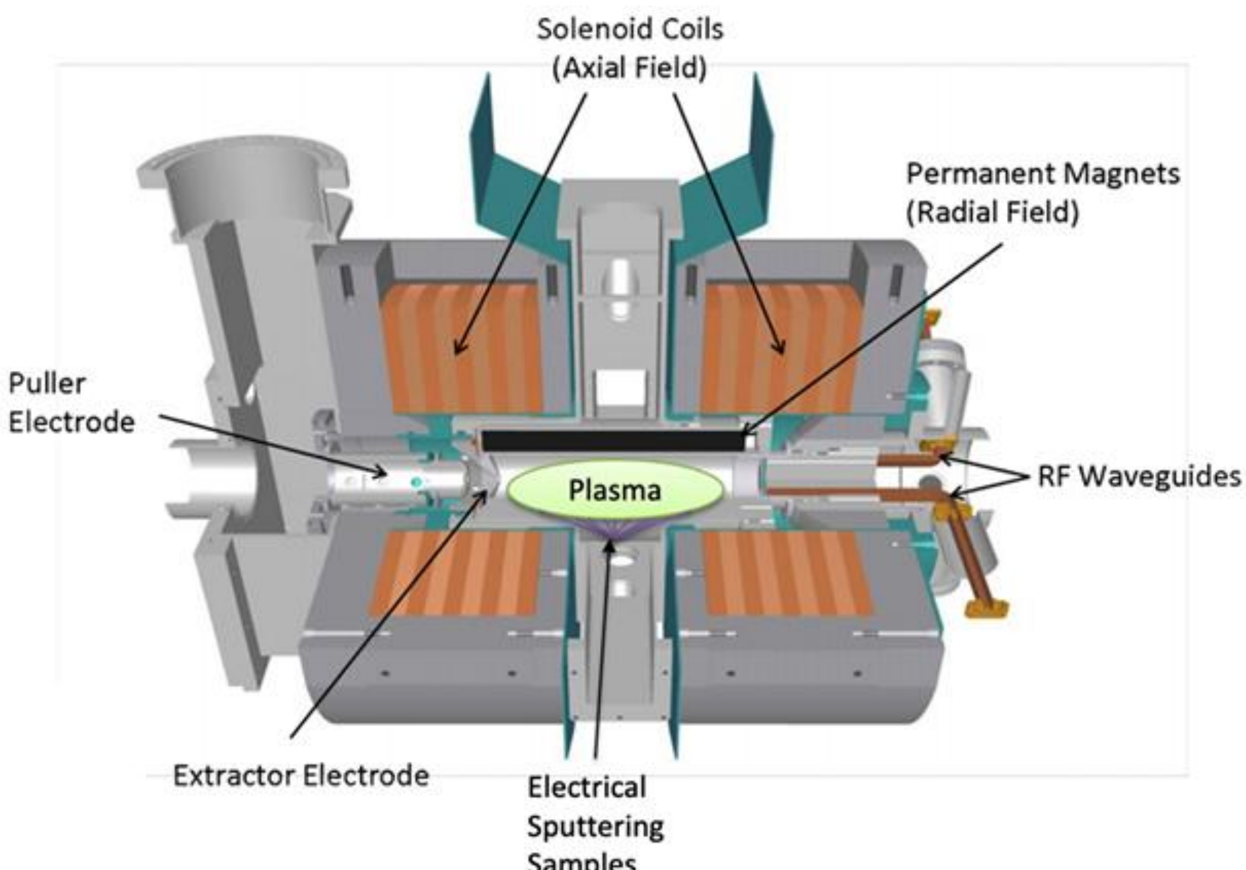
Author: SCOTT, Robert (Argonne National Laboratory)

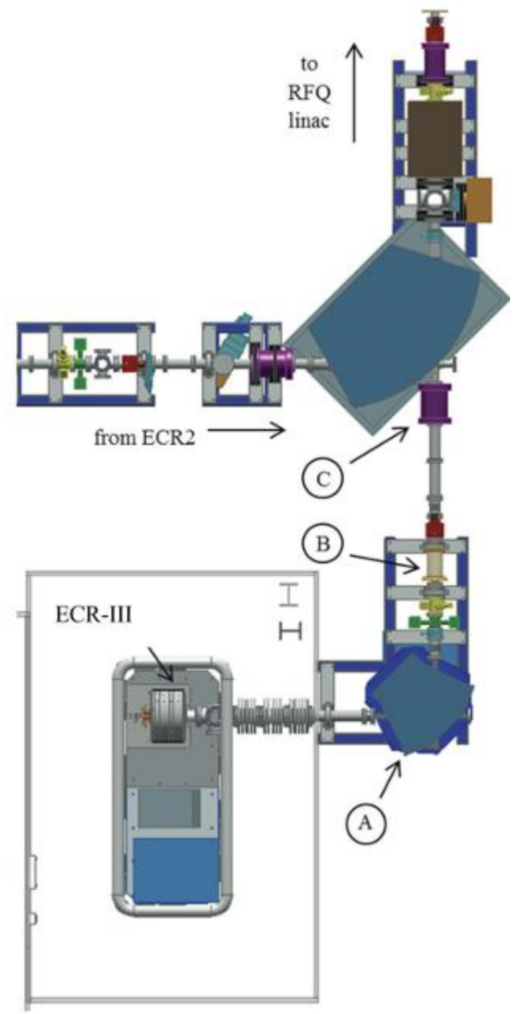
Co-authors: MCLAIN, Jake (Argonne National Laboratory); PAUL, Michael (The Hebrew University of Jerusalem); VON-DRASEK, Richard (Argonne National Laboratory); BHATTACHARYA, Sutanu (The Hebrew University of Jerusalem)

Contribution ID: **21** Contribution code: **MOP15** Type: **Poster Presentation**

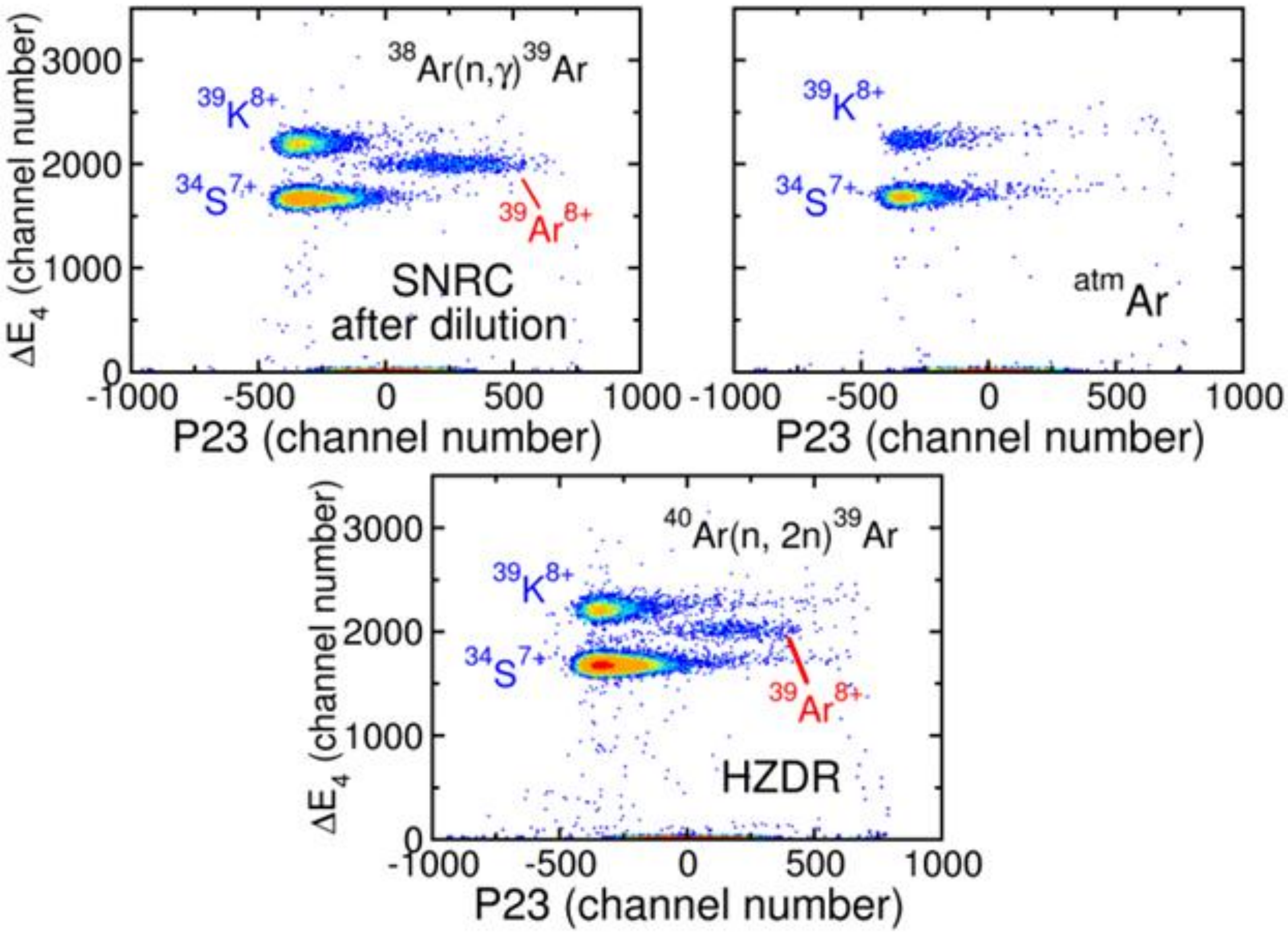
Study of noble gas memory effect of ECR3 at ATLAS

Monday, September 16, 2024 5:00 PM (1h 30m)

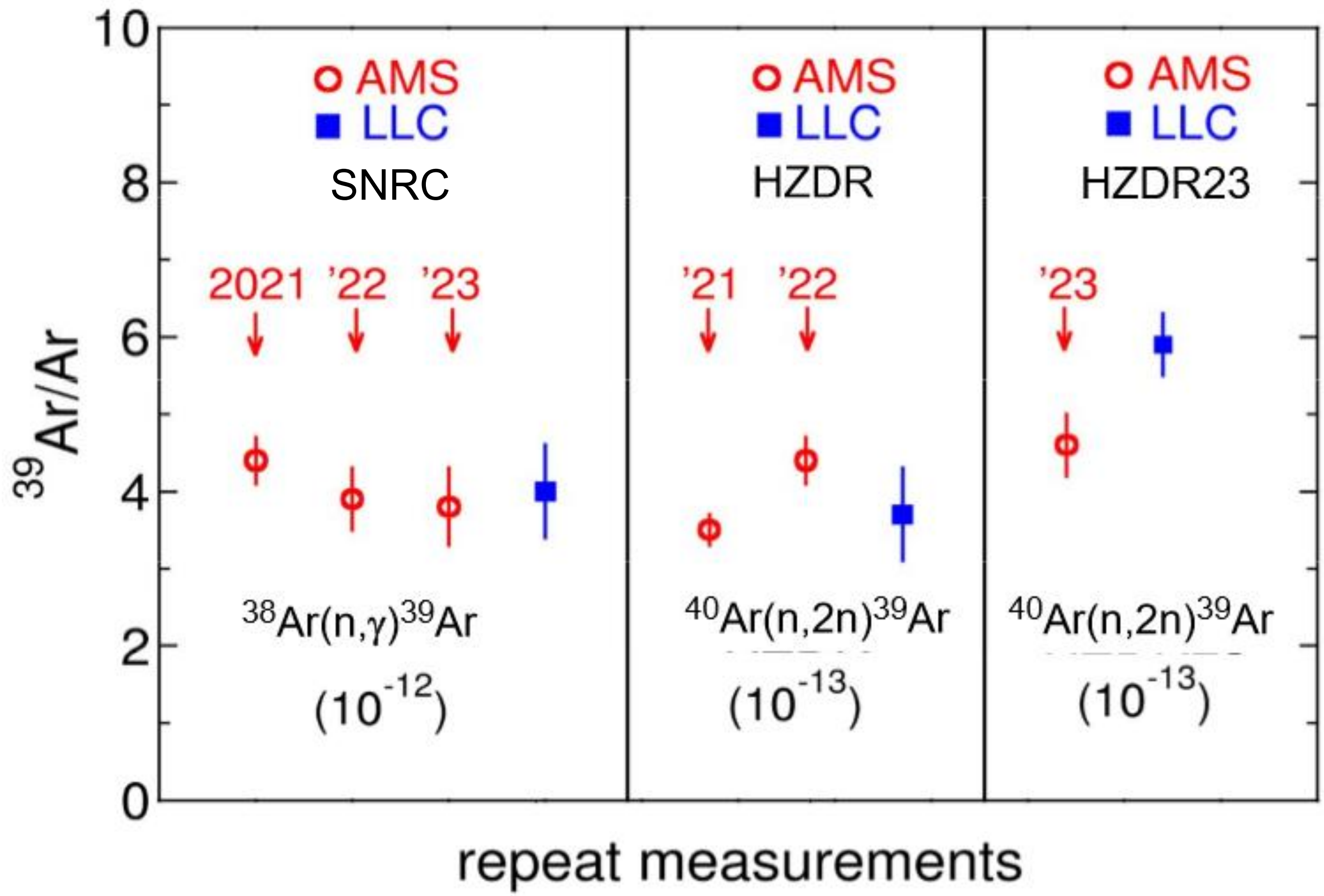




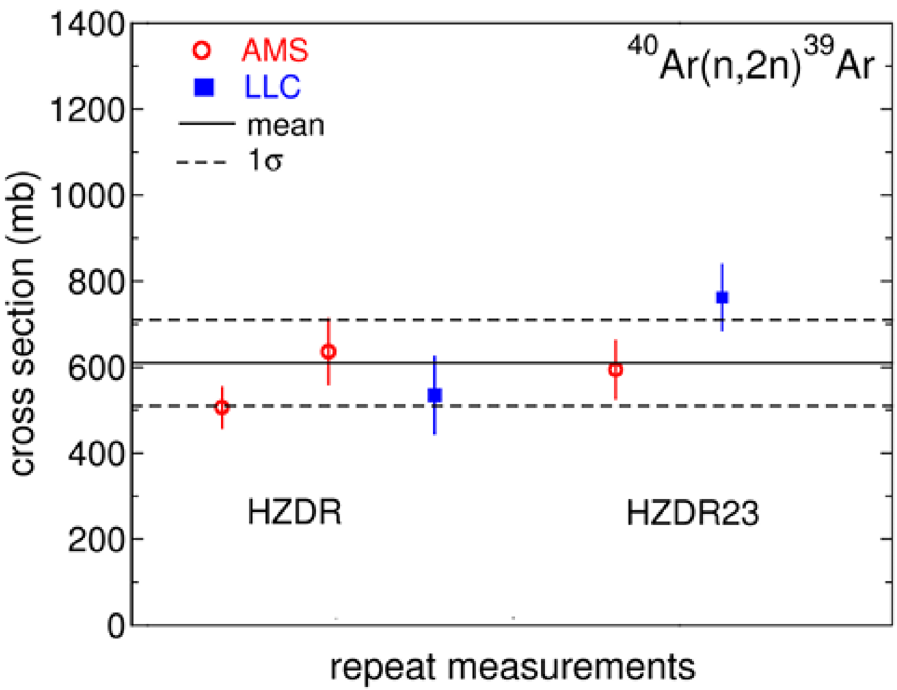
AMS measurement



Ratio of $^{39}Ar/Ar$

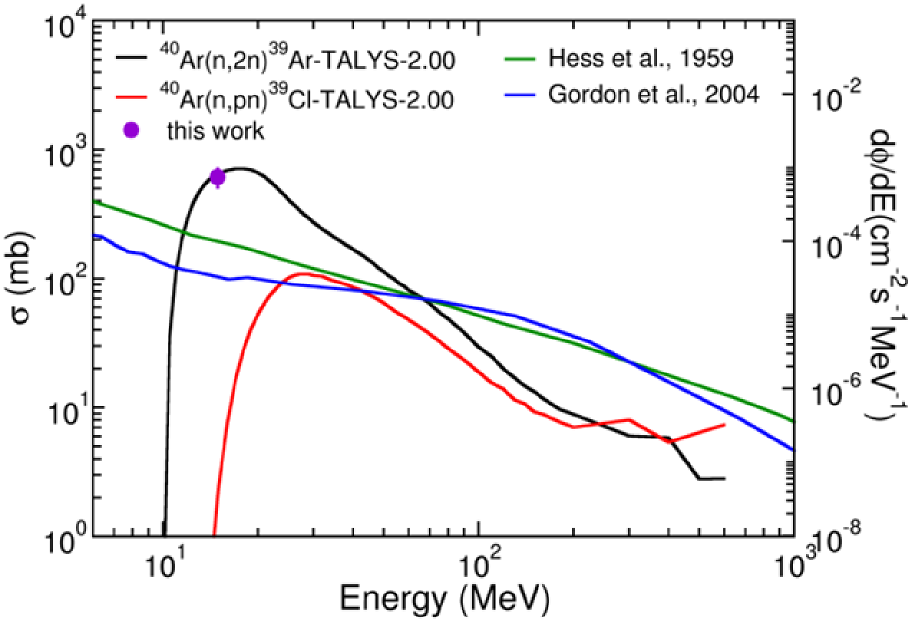


Cross section $^{40}Ar(n,2n)^{39}Ar$@14.8 MeV



Model / Reference	σ (mb)
ACTIVIA (2008)	10.1
INCL++ (ABLA07, 2014)	438
TALYS-2.00 (2023)	649
TALYS-2.03 (2024)	645
ENDF/B-VIII.1 (2024)	667
ENDF/B-VII.1 (2011)	900
JENDL-5 (2021)	900
This work	**610(100)**

^{39}Ar production rate at different altitude z



Production rate P(z) (atoms/kgAr/day) at altitude z from the interaction of cosmic ray neutrons

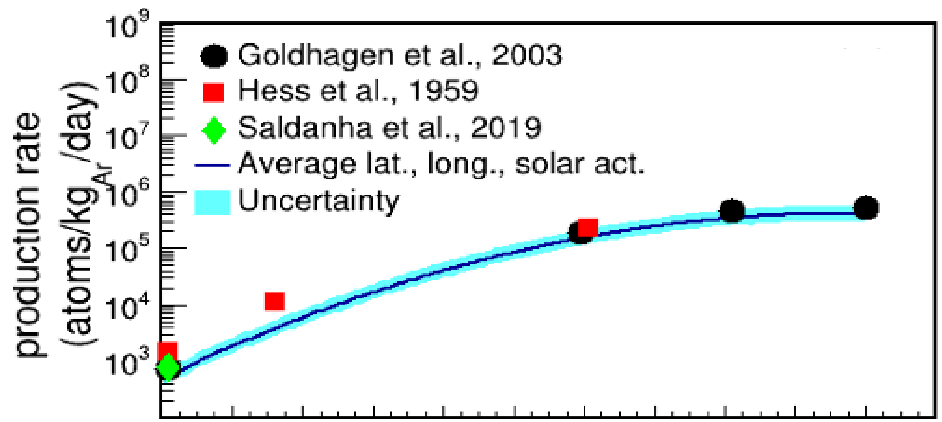
$$P = N_{Ar} \times 86400 \times \int_0^{E_{max}} \frac{d\phi(E,z)}{dE}\,\sigma(E)dE$$

N_{Ar} = no of Ar atoms/kg argon

$\frac{d\phi(E,z)}{dE}$ = cosmic ray induced neutron flux spectrum (neutrons/(cm^2/s/MeV))

$\sigma(E) = \sigma_{n,2n}(E) + \sigma_{n,pn}(E)$ = sum of the $^{40}Ar(n,2n)$ and $^{40}Ar(n,pn)$ cross sections (cm^2) calculated using the TALYS-2.00 code.

Altitude (km)	P (×10³ atoms/kg$_{ar}$/day)
0.2	**0.744**
11.9	**192**
16.2	**474**
20.0	**530**
—	—
0	**1.47**
3.2	**112**
12.2	**237**



^{39}Ar production rate using:
Goldhagen et al., 2003, and Hess et al., 1959

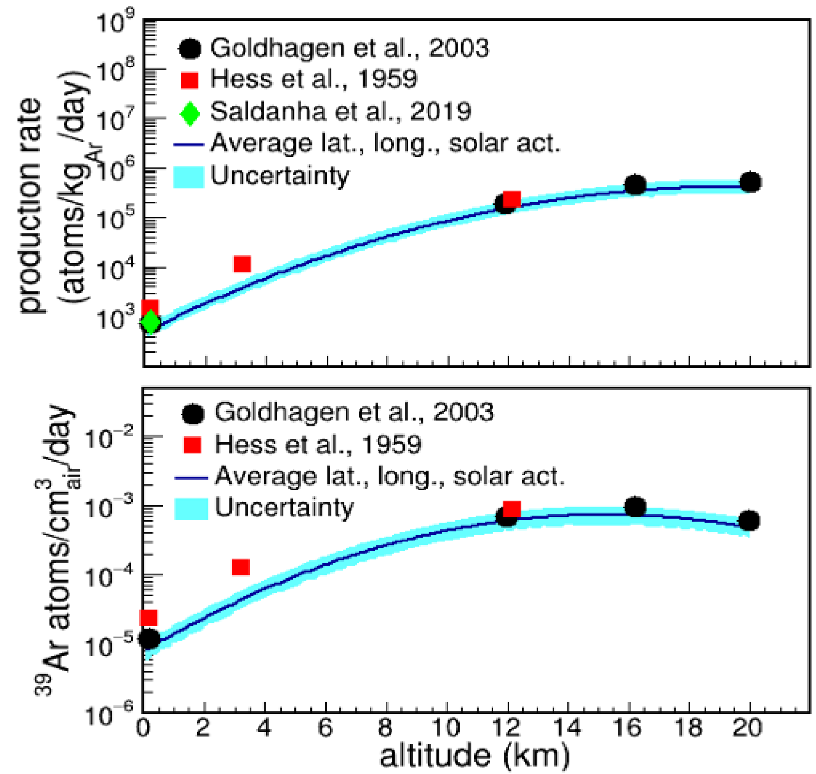
^{39}Ar production rate at different altitude z

The total (averaged) production rate, calculated from sea level to an altitude of 20 km, is 770 ± 240 ^{39}Ar atoms/cm^2/day.

The steady state ^{39}Ar/Ar ratio from neutron-induced production in the atmosphere up to an altitude of 20 km is $(5.9 \pm 1.8)\times 10^{-16}$.

Results included the (1) ^{40}Ar(*n*,2*n*)^{39}Ar and (2)^{40}Ar(*n*,)^{39}Cl reactions.

The experimental value of ^{39}Ar/Ar= $(8.12 \pm 0.30) \times 10^{-16}$ in the atmosphere.
So the result indicates that 73% of ^{39}Ar is produced by cosmic-ray induced neutrons.



^{39}Ar production rates using experimental cosmic ray data

^{39}Ar Anthropogenic production

INPUTS

Neutron source
14.1 MeV neutrons
(DT-neutrons from thermonuclear tests)

Atmosphere model
Standard atmosphere
(US Standard Atmosphere, 1976)

Geometry
Spherical atmosphere
(up to high altitudes)

SIMULATION WORKFLOW

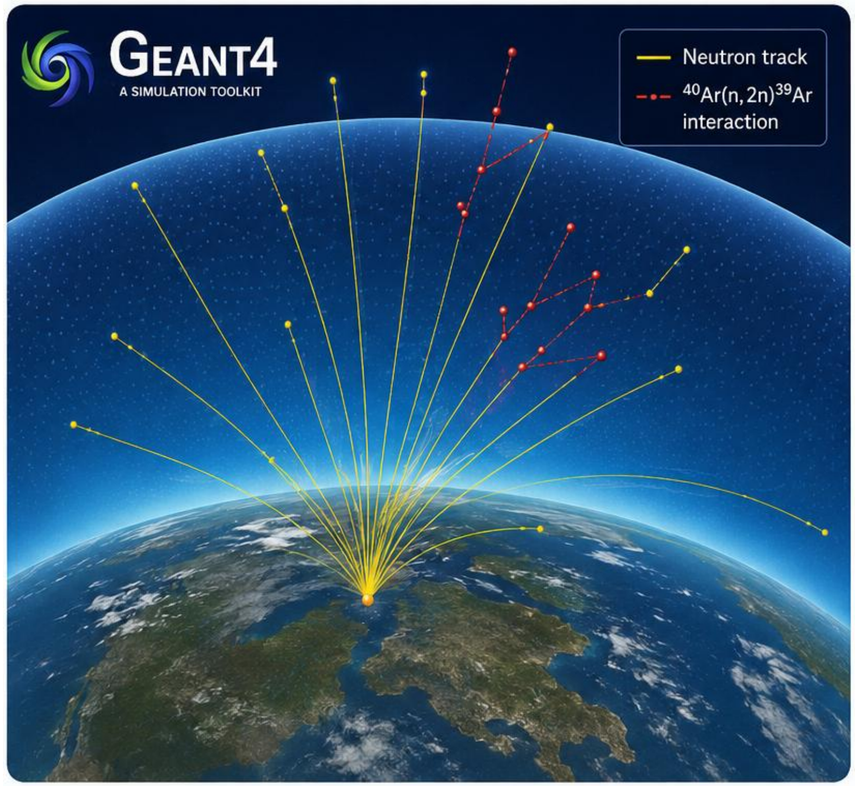
Neutrons emitted
14.1 MeV DT-neutrons isotropically emitted

↓

Transport & Interactions
Neutrons propagate and interact in the atmosphere

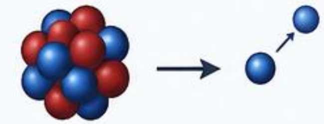
↓

Nuclear reaction
$^{40}Ar(n,2n)^{39}Ar$ reactions are recorded



OUTPUT

^{39}Ar production via $^{40}Ar(n,2n)^{39}Ar$



Reaction threshold 10.12 MeV
Neutron energy = 14.1 MeV

RESULTS

Fraction of emitted DT-neutrons producing ^{39}Ar via (n, 2n):

$1.5 - 3.4 \times 10^{-3}$

(for high- to low-altitude tests)

$\approx 2.0 \times 10^{-3}$
(loosely et al., 1968)

For 8×10^{28} emitted neutrons (all tests):

$1.2 \times 10^{26} - 2.7 \times 10^{26}$

anthropogenic ^{39}Ar atoms

$\approx$ 20% of atmospheric cosmogenic ^{39}Ar inventory

GEANT4 simulates the transport of 14.1 MeV neutrons in the atmosphere and quantifies ^{39}Ar production via the $^{40}Ar(n, 2n)^{39}Ar$ reaction, enabling a reliable estimate of the anthropogenic contribution from thermonuclear tests.

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- First experimental determination of the $^{40}Ar(n,2n)^{39}Ar$ reaction cross section and ^{39}Ar production in Earth's atmosphere
  - Experimental details for 40Ar(n,2n)39Ar reaction
  - Noble Gas Accelerator Mass Spectrometry (NOGAMS)
  - ^{39}Ar cosmogenic production at different altitudes
  - ^{39}Ar anthropogenic production through thermonuclear bomb
- **Thermal $^{41}Ar(n,\gamma)^{42}Ar$ reaction cross section**
  - Introduction
  - ^{42}Ar production with the radiative capture process
  - Measuring $^{41}Ar(n,\gamma)^{42}Ar$ cross section
- Summary

Background

^{42}Ar: a “rare” nuclide

R.W. Stoenner, O.A. Schaeffer, S. Katcoff, Science 148, 1325 (1965)

Half-Lives of Argon-37, Argon-39, and Argon-42

Abstract. *The half-lives of three argon isotopes have been carefully determined, with the following results: Ar^{37}, 35.1 ± 0.1 days; Ar^{39}, 269 ± 3 years; Ar^{42}, 32.9 ± 1.1 years. By combining the Ar^{42} value with earlier data, a cross section of 0.5 ± 0.1 barn is calculated for the reaction, with thermal neutrons, $Ar^{41}(n,\gamma)Ar^{42}$.*

Sc39 (7/2-)	Sc40 182.3 ms 4- ECp,ECα,...	Sc41 596.3 ms 7/2- EC	Sc42 681.3 ms 0+ * EC	Sc43 3.891 h 7/2- EC	Sc44 3.927 h 2+ * EC	Sc45 7/2- * 100	Sc46 83.79 d 4+ * β-	Sc47 3.3492 d 7/2- β-
Ca38 440 ms 0+ EC	Ca39 859.6 ms 3/2+ EC	Ca40 0+ 96.941	Ca41 1.03E+5 y 7/2- EC	Ca42 0+ 0.647	Ca43 7/2- 0.135	Ca44 0+ 2.086	Ca45 162.61 d 7/2- β-	Ca46 0+ 0.004
K37 1.226 s 3/2+ EC	K38 7.636 m 3+ * EC	K39 3/2+ 93.2581	K40 1.277E+9 y 4- EC,β- 0.0117	K41 3/2+ 6.7302	K42 12.360 h 2- β-	K43 22.3 h 3/2+ β-	K44 22.13 m 2- β-	K45 17.3 m 3/2+ β-
Ar36 0+ 0.337	Ar37 35.04 d 3/2+ EC	Ar38 0+ 0.063	Ar39 269 y 7/2- β-	Ar40 0+ 99.600	Ar41 109.34 m 7/2- β-	Ar42 32.9 y 0+ β-	Ar43 5.37 m (3/2,5/2) β-	Ar44 11.87 m 0+ β-
Cl35 3/2+ 75.77	Cl36 3.01E+5 y 2+ EC,β-	Cl37 3/2+ 24.23	Cl38 37.24 m 2- * β-	Cl39 55.6 m 3/2+ β-	Cl40 1.35 m 2- β-	Cl41 38.4 s (1/2,3/2)+ β-	Cl42 6.8 s β-	Cl43 3.3 s β-

^{42}Ar is extremely rare in nature

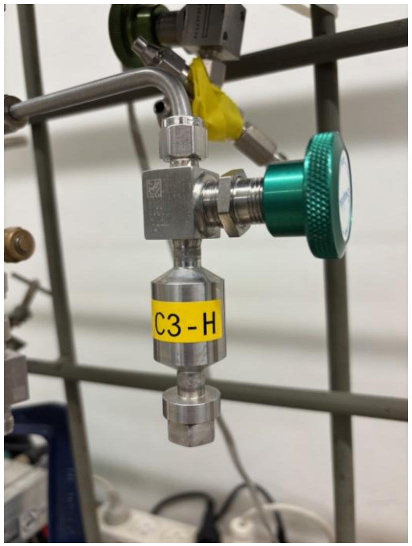
^{42}Ar/Ar in Earth atmosphere: ^{42}Ar/Ar= $(6.10 \pm 0.54) \times 10^{-21}$

[Z. F. Wan Nature Physics 22 (2026) 665]

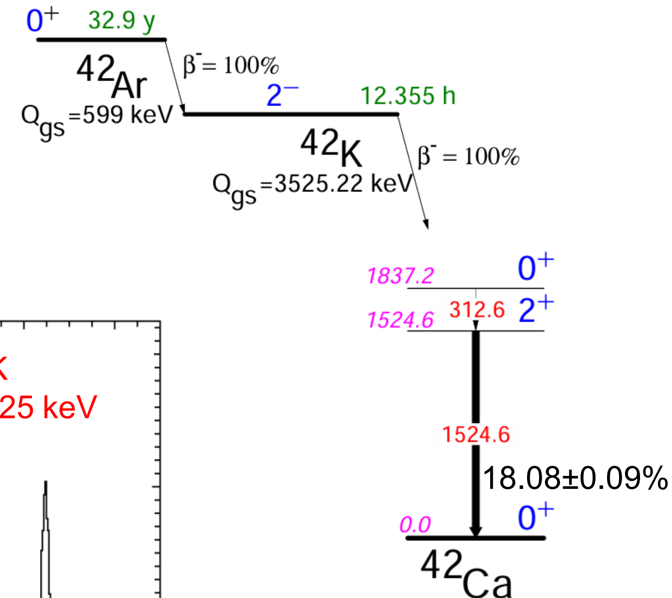
A unique ^{42}Ar calibration sample: produced at the high-flux reactor of Institut Laue-Langevin (Grenoble, France) at $\Phi_{thermal}$= 0.86 × 10^{15} cm^{-2} s^{-1}

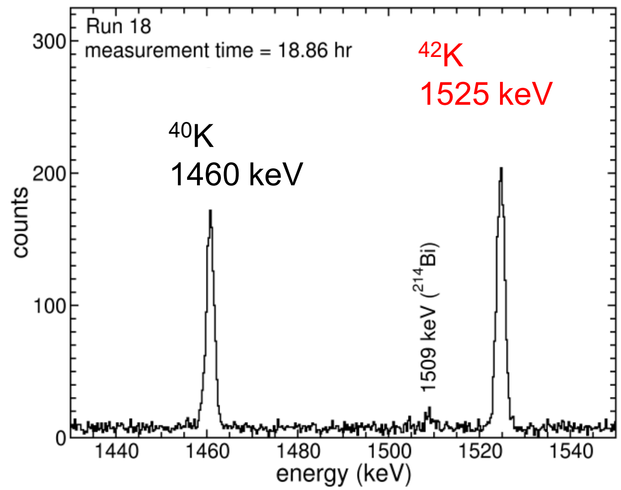
4.7 days irradiation in a quartz ampoule: $^{40}Ar(n,\gamma)^{41}Ar(n,\gamma)^{42}Ar$(32.9 y)

99.92% ^{40}Ar

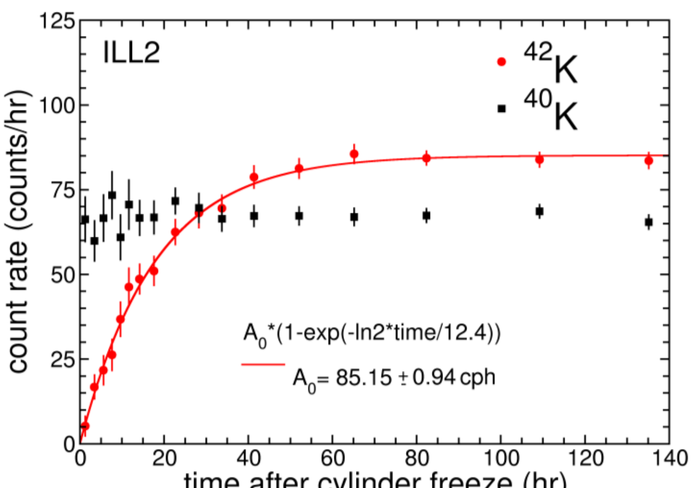


NEUTRONS FOR SOCIETY





(manuscript in preparation)



Growth curve

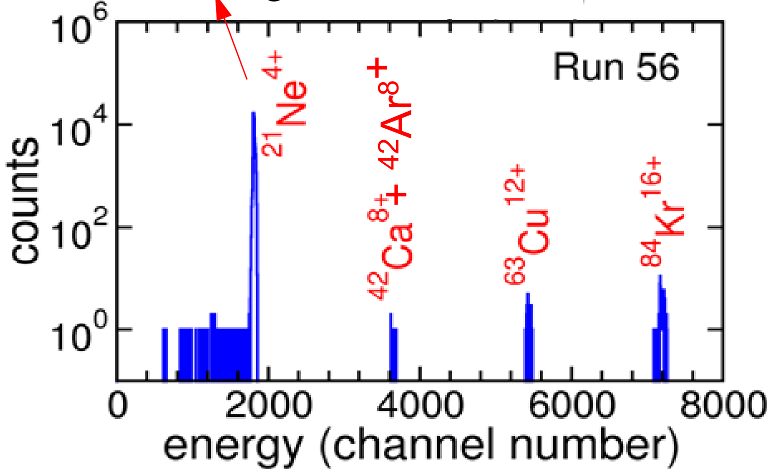
Activity: (8.48 ± 0.54) Bq

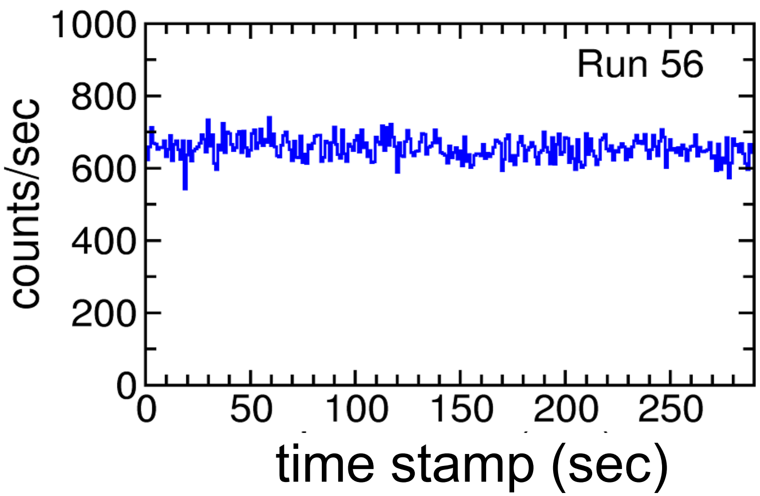
$\sigma_{th}(^{41}Ar(n,\gamma)^{42}Ar)$= 621±65 mb (first measurement)

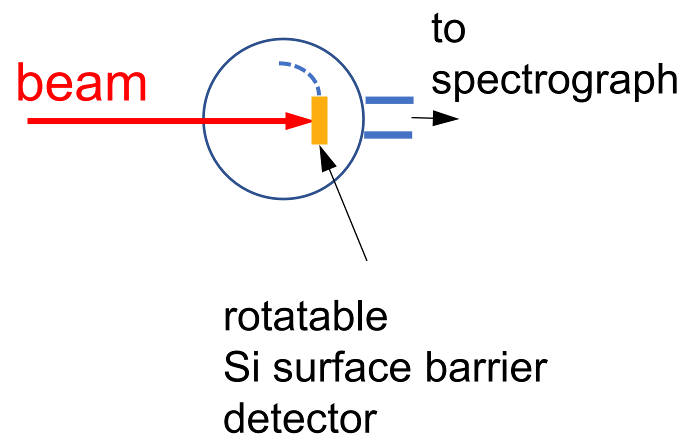
Previous estimate: 0.5 ± 0.1 b (Stoenner et al., 1965)

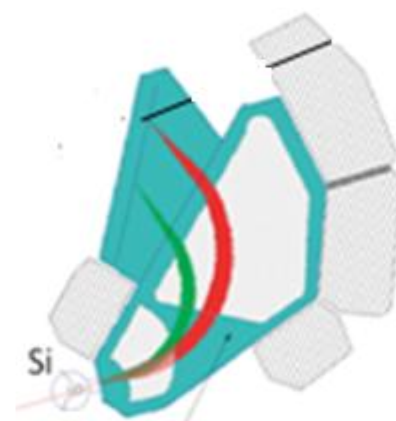
ILL2 sample at Argonne: ^{42}Ar tuning

Ne/air= 18 ppm, ^{21}Ne (0.27%), from ion source residual gas as 10^{-7} Torr





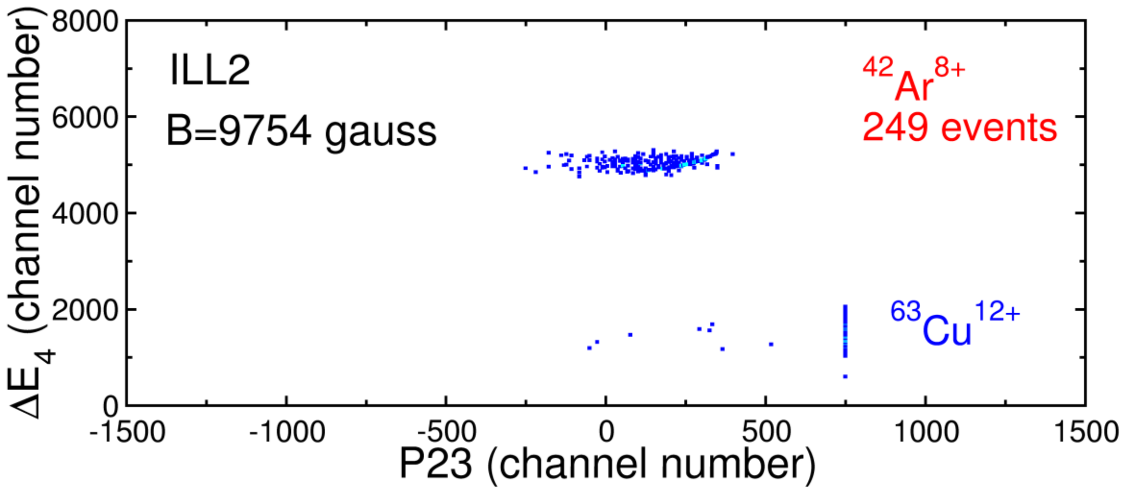


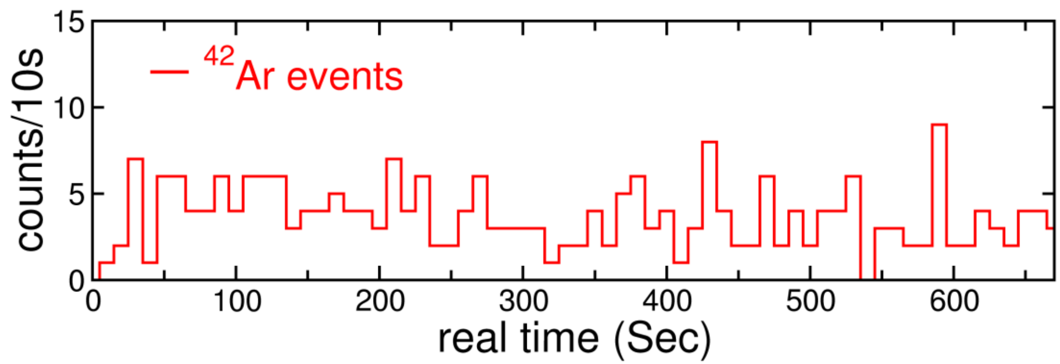


beam diagnostics

ILL2: ^{42}Ar NOGAMS calibration sample (2023)

^{42}Ar/Ar (ILL2) = $(1.09 \pm 0.12) \times 10^{-11}$
^{42}Ar/Ar (activity+dilution) = $(1.12 \pm 0.06) \times 10^{-11}$





preliminary results

$t_{1/2}(^{42}Ar)$ (AMS)= 32.0 ± 2.5 yr
$t_{1/2}(^{42}Ar)$ (1965)= 32.9 ± 1.1 yr

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  - ^{39}Ar anthropogenic production through thermonuclear bomb
- Thermal $^{41}Ar(n,\gamma)^{42}Ar$ reaction cross section
  - Background
  - ^{42}Ar production with the radiative capture process
  - Measuring $^{41}Ar(n,\gamma)^{42}Ar$ cross section
- **Summary**

Summary

- First experimental determination of the $^{40}Ar(n,2n)^{39}Ar$ cross section with possible impact on estimates of ^{39}Ar cosmogenic atmospheric production or cosmogenic neutron production: confirmation of TENDL23 theoretical result.

- The steady state $^{39}Ar/Ar$ ratio from neutron-induced production in the atmosphere up to an altitude of 20 km is $(5.9 \pm 1.8)\times10^{-16}$, indicating that 73% of ^{39}Ar is produced by cosmic-ray induced neutrons.

- The contribution of the thermonuclear tests of the 1960's to ^{39}Ar in the atmosphere is estimated to be 20% of the ^{39}Ar atmospheric inventory.

- Measured the total thermal cross section $^{41}(n,\gamma)^{42}Ar$ reaction.

- The half-life of ^{42}Ar is very close to the previous measurement.

Acknowledgement

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SOREQ Soreq Nuclear Research Center

Argonne NATIONAL LABORATORY

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THANK YOU

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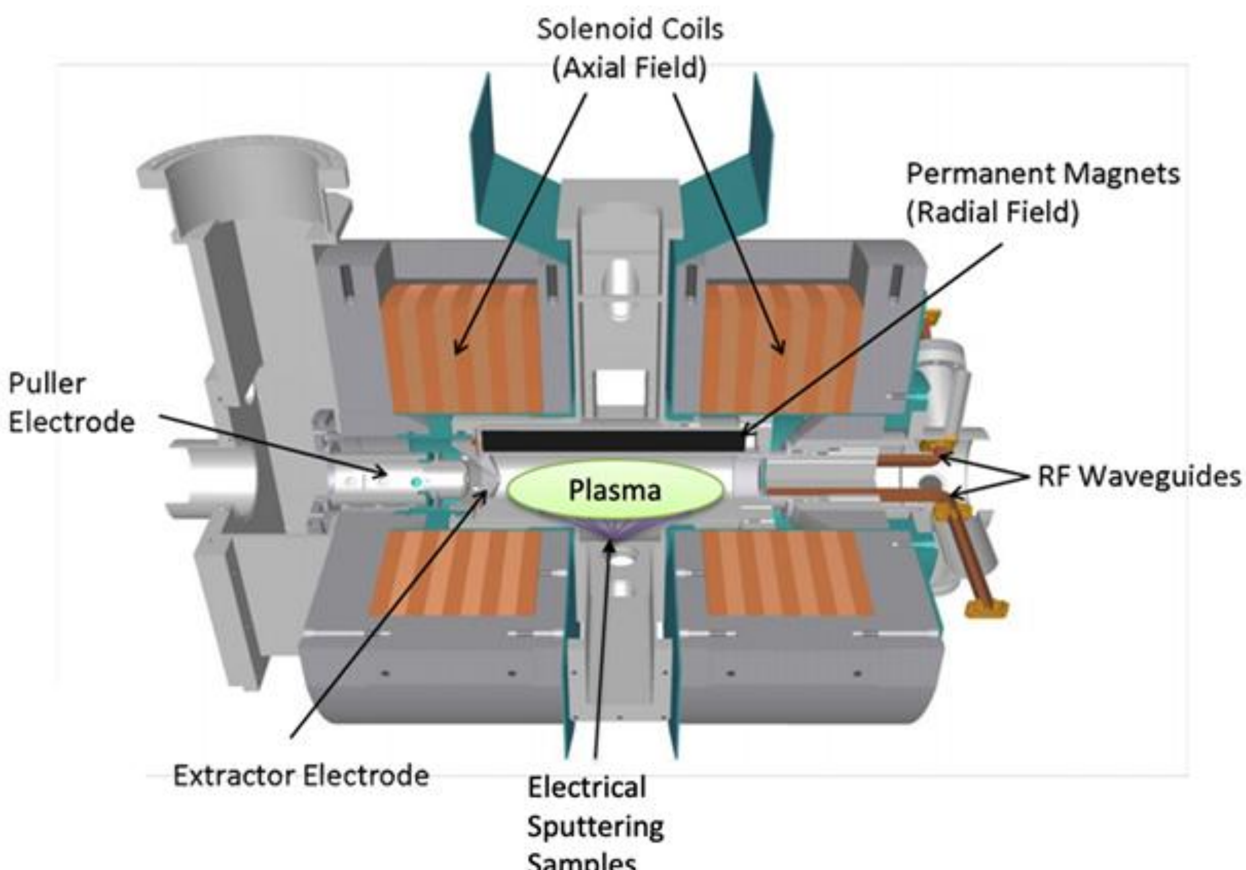
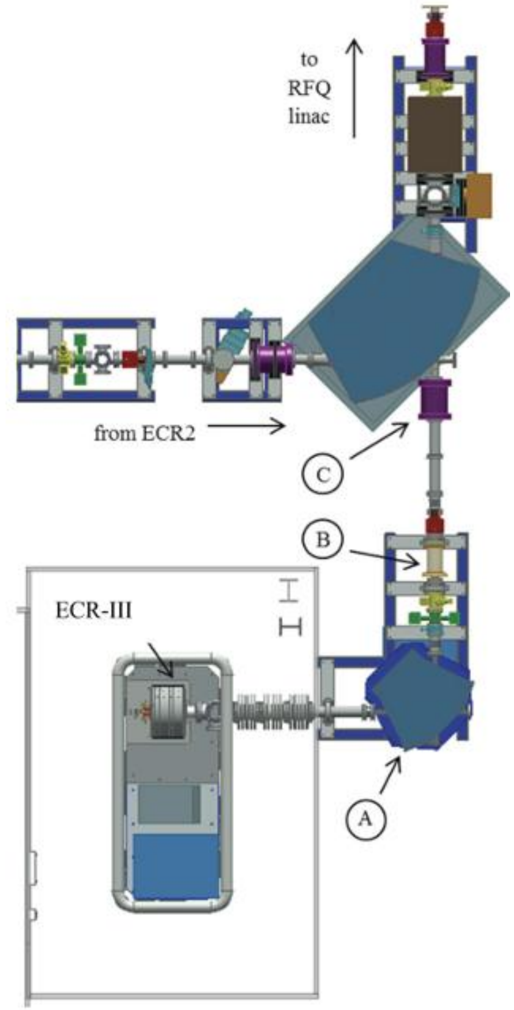
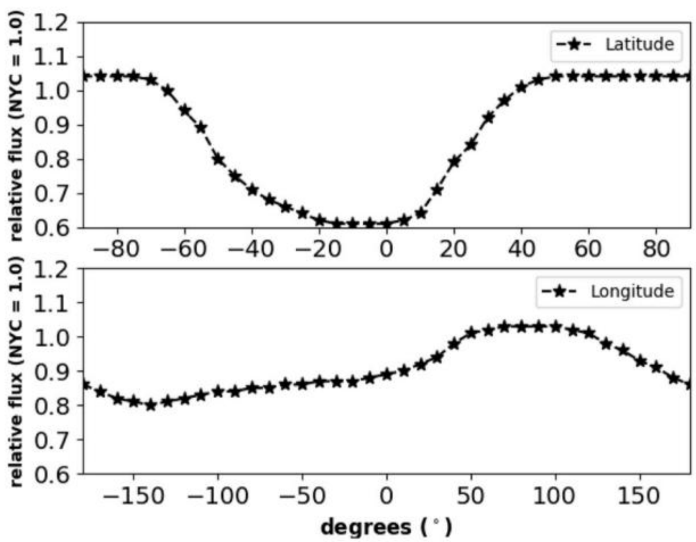
Study of noble gas memory effect of ECR3 at ATLAS

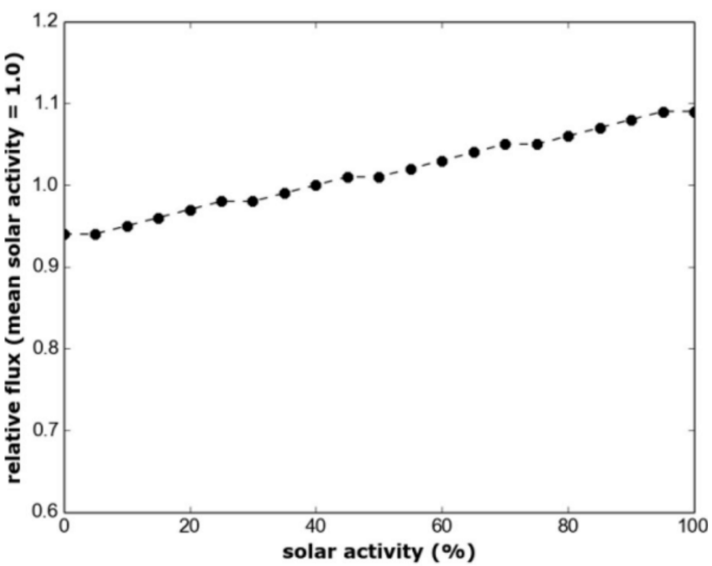
Monday, September 16, 2024 5:00 PM (1h 30m)





^{39}Ar production rate at different altitude z





The average $P(z)$ values extracted from the flux data of taken at different locations and times using the latitude, longitude and solar activity dependence of the neutron flux

$$\dot{P}(z) = \int_{-90}^{90} f(\theta) R^2 cos\theta d\theta \int_{-180}^{180} f(\phi) d\phi \int_{0}^{E_{max}} N_{Ar} \times 86400 \frac{d\phi(E,z)}{dE} \sigma(E) dE$$

$f(\theta)$ and $f(\phi)$ are the correction factor calculated from Ref [a].

The average altitude-dependent ^{39}Ar production rate $\dot{P}(z)$ (atoms/kg$_{Ar}$/day) in an air column of 1 cm^2 cross section

$$\frac{d\dot{P}39_{Ar}}{dS} = \int_{sea\ level}^{H_{max}} \dot{P}(z)\, mf\ \rho_{air}(z)\, dz$$

m_f is the mass fraction of argon in air,
$\rho_{air}(z)$ is the air density at altitude z(cm)

The steady-state ^{39}Ar/Ar ratio is expressed as:

$$\frac{^{39}Ar}{Ar} = \frac{(d\dot{P}39_{Ar}/dS)/\lambda}{dn_{Ar}/dS}$$

λ is the decay constant of ^{39}Ar in day^{-1} and dn_{Ar}/dS denotes the number of Ar atoms per cm^2 of air column

$$\frac{dn_{Ar}}{dS} = \frac{N_A\, mf\ \rho_{air}(z)}{M_{Ar}}\ dz$$

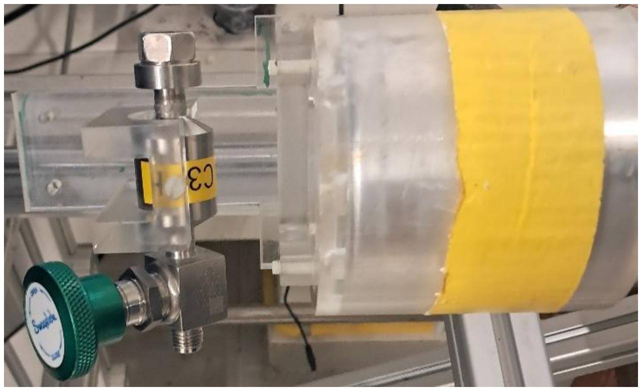
N_A denotes Avogadro's constant,
M_{Ar} is the molar mass of argon (in kg)

AMS measurement

Sample	**HZDR**	**HZDR**	**HZDR23**
NOGAMS			
Ave. FC $^{40}Ar^{8+}$ (nA)	1.8(1)	1.75(3)	2.6(1)
$^{40}Ar^{8+}$ attenuation factor	26.7(8)	26.8(8)	28.0(8)
Ave. ^{39}Ar rate-gross (cpm)	0.96(5)	0.92(4)	1.56(7)
Ave. ^{39}Ar rate-net (cpm)	0.70(4)	0.89(4)	1.50(7)
^{39}Ar fractionation correction	1.13(10)	1.08(11)	1.03(5)
R_net (10^{-13}) – NOGAMS	3.5(3)	4.4(5)	4.6(4)
Cross section (mb) – NOGAMS	510(50)	640(80)	590(70)
LLC			
Sample count rate-gross (cpm)	0.455(5)	—	0.532(9)
Sample count rate-net (cpm)	0.319(6)	—	0.409(9)
Atmosphere-net (cpm)	0.059(9)	—	0.058(6)
R_net(sample)/R^a_net(atmosphere)	460(70)	—	727(60)
R_net(count. gas)/R^a_net(atmosphere)	5.5(8)	—	7.1(7)
R_net (10^{-13}) – LLC	3.7(6)	—	5.9(4)
Cross section (mb) – LLC	540(90)	—	760(80)

A unique ^{42}Ar calibration sample: produced at the high-flux reactor of Institut Laue-Langevin (Grenoble, France) at $\Phi_{\mathbf{thermal}} = 0.86 \times 10^{15}\ \mathrm{cm^{-2}\ s^{-1}}$

4.7 days irradiation in a quartz ampoule: $^{40}\mathrm{Ar}(n,\gamma)^{41}\mathrm{Ar}(n,\gamma)^{42}\mathrm{Ar}(32.9\ \mathrm{y})$



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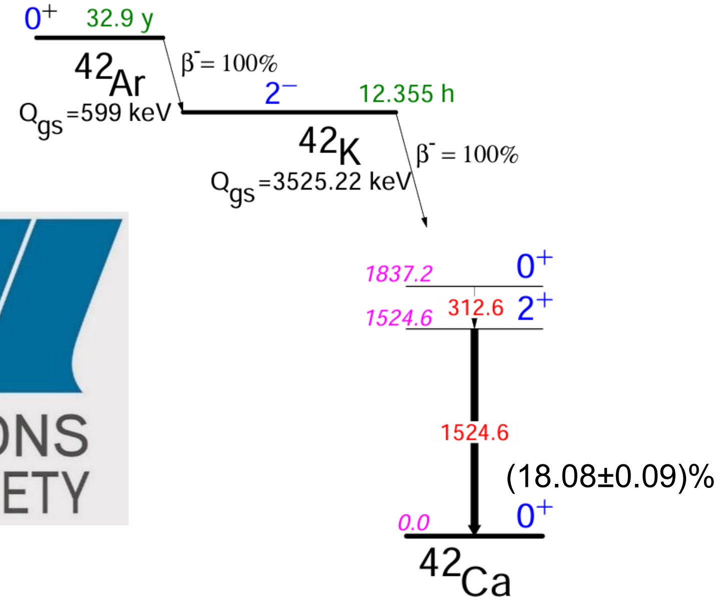
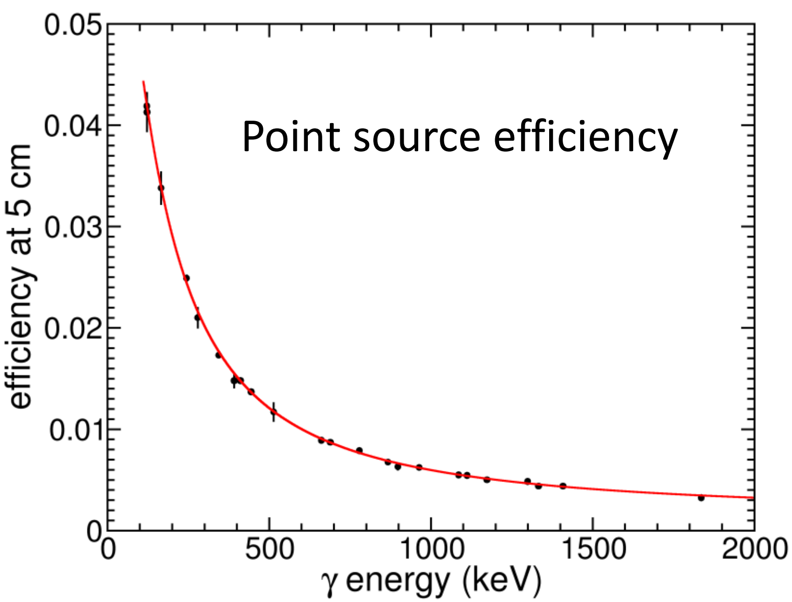
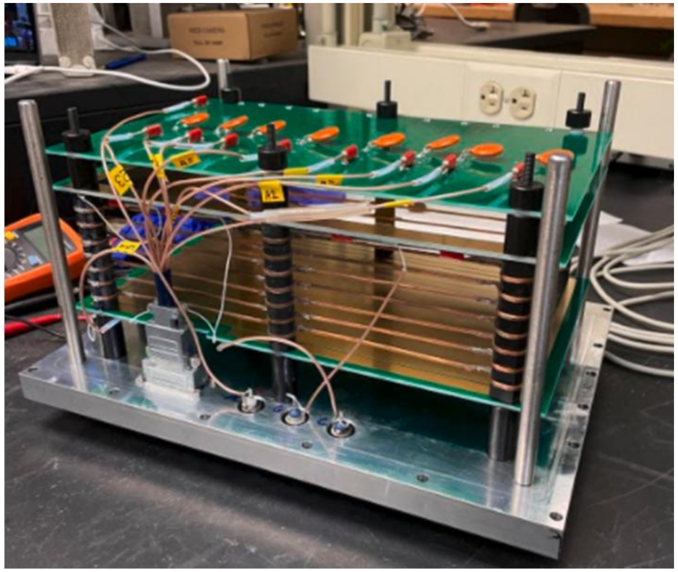




- ✓ True coincidence summing correction using GEANT4 simulation for ^{152}Eu point source at 5 cm
- ✓ The geometry factor used for the multi-gamma source was transferred to the point-source configuration. Show the final efficiency at 5cm for a point source
- ✓ GEANT4 simulation for cylindrical geometry : Correction factor = 0.8384 ± 6 % (relative)

Multi-anode Ionization Chamber (MONICA)



- Gas: CF_4 gas with Pressure 31 Torr/39 Torr
- Bias voltage : +275/-300 V,
- Mylar window used with 6.8 um.
- The dimension of anode

8 cm (H) × 15cm (W) × 45 mm (thickness)
(except A8 anode)

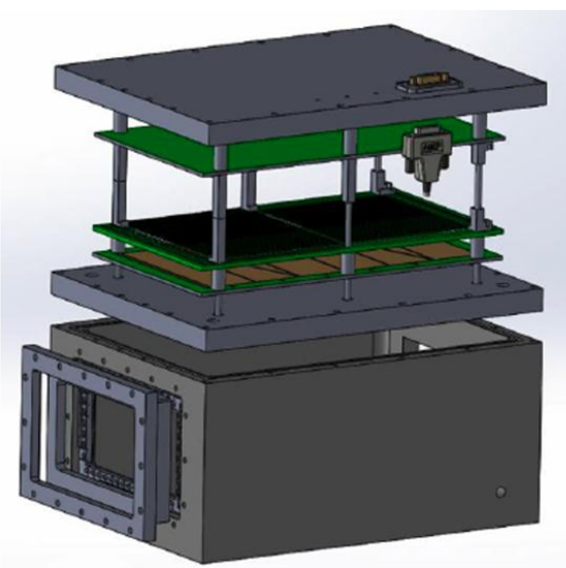
Last A8 anode dimension

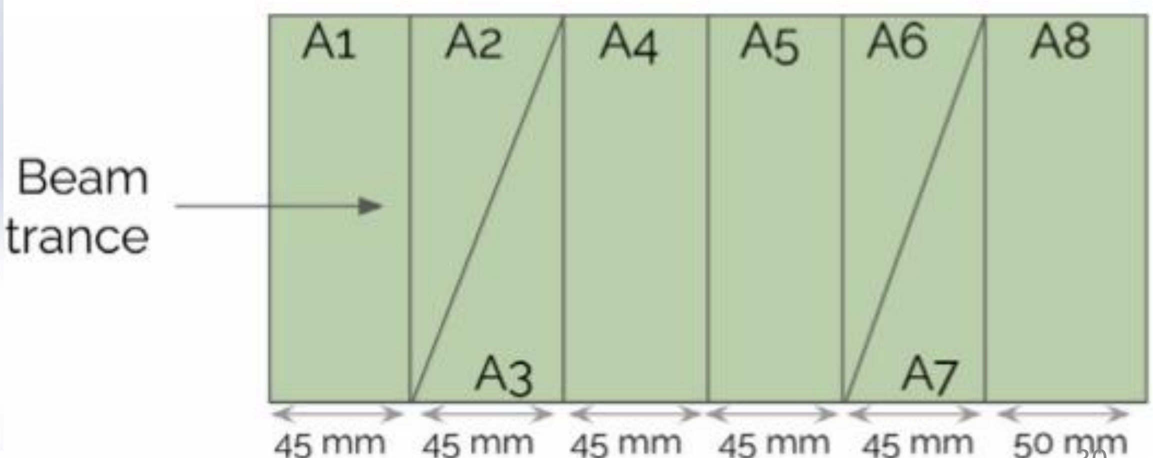
8 cm (H) × 15cm (W) × 50 mm (thickness)

- Placed at 125 cm far from the Gas Filled Magnetic spectrograph.
- 2 & 3 and 6 & 7 are spilt anode used for determine the position of ion w.r.t focal plane.

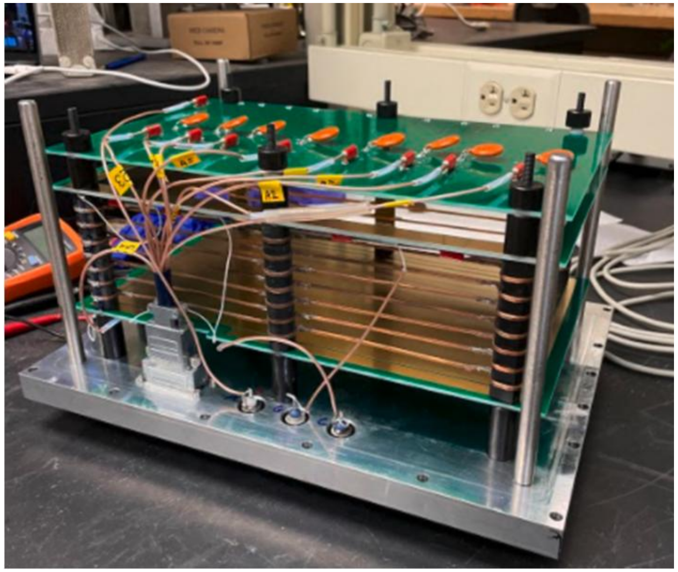
$P23 = (\Delta E3 - \Delta E2)/(\Delta E3 + \Delta E2)$ and

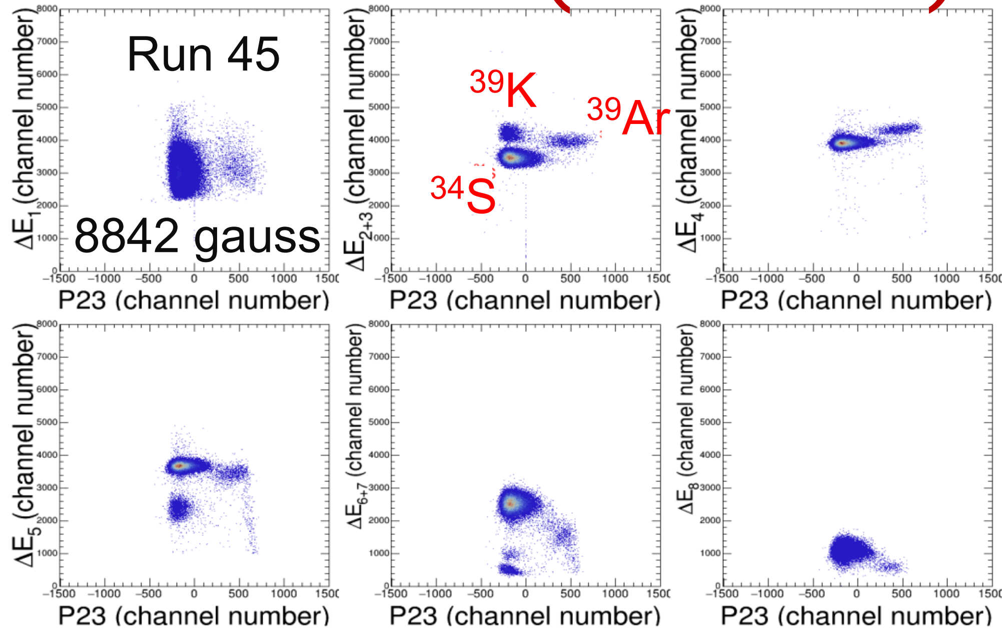
$P67 = (\Delta E7 - \Delta E6)/(\Delta E6 + \Delta E7)$



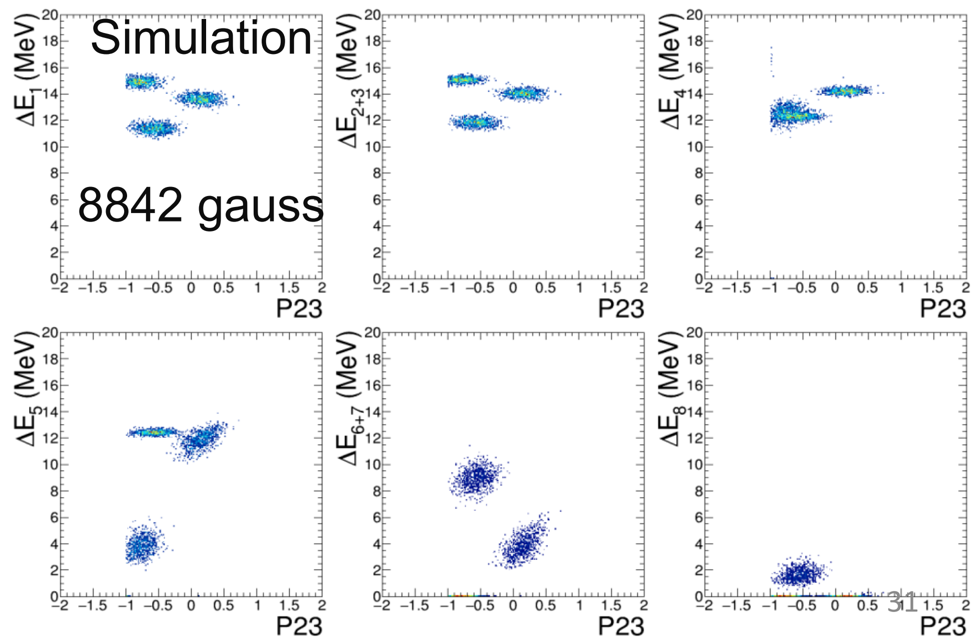


Multi-anode Ionization Chamber (MONICA)





program RAYTRACE + GEANT4 simulation



- We used Cyl-2 sample (calibration) to check
- Energy Consideration:
  - ^{39}Ar =205.7 MeV.
  - ^{39}K =205.7 MeV.
  - ^{34}S =179.35 MeV.

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North-Holland, Amsterdam

HEAVY ION SEPARATION WITH A GAS-FILLED MAGNETIC SPECTROGRAPH

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Received 27 December 1988

The average charge $\bar{q}$ of the ion depends on atomic number Z and roughly proportional to its velocity.
Magnetic rigidity $\langle B\rho \rangle \propto mv/\bar{q}$