Neutron-Induced Reactions in a High-Density Inertial Confinement Plasma and Their Nuclear Astrophysics Nexus

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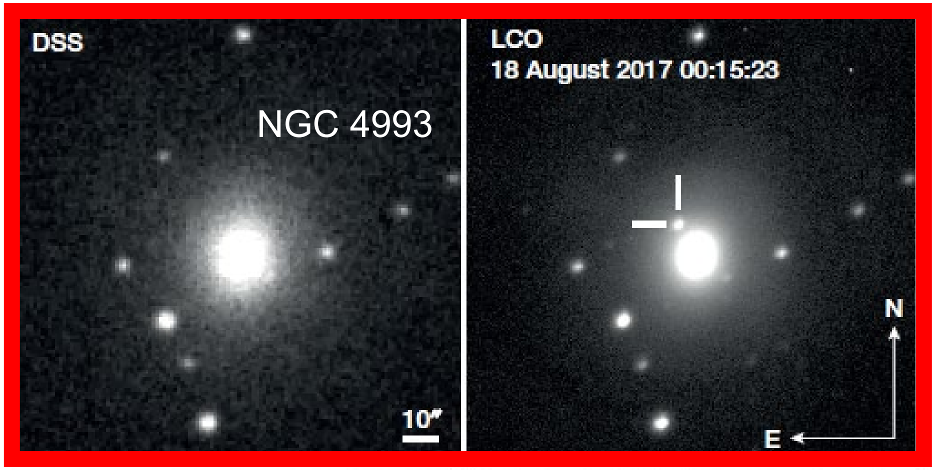
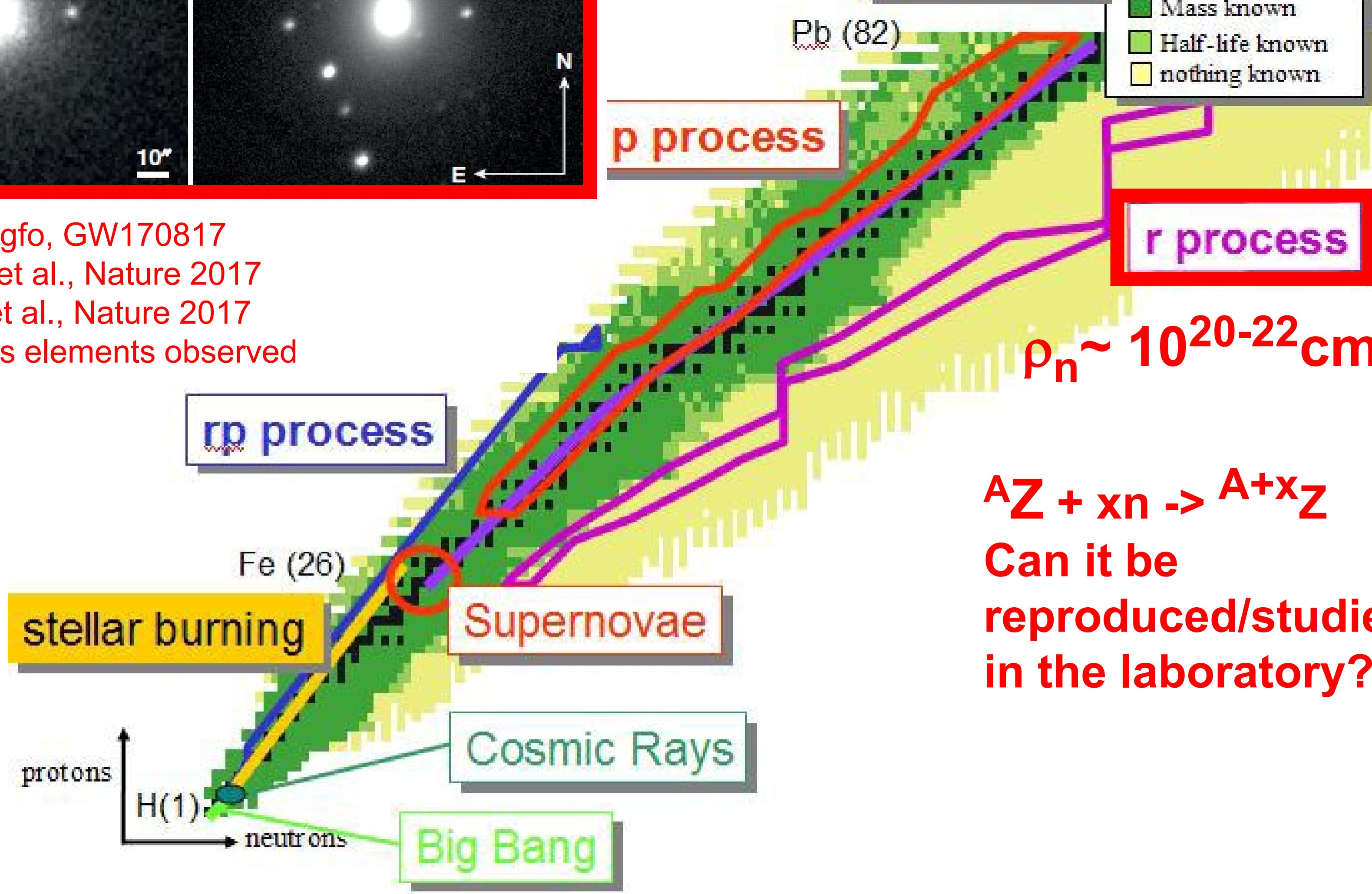
J. McLain[3], R. C. Pardo[3], K. E. Rehm[3], R. Scott[3], I. Tolstukhin[3], R. Vondrasek[3],
M. Tessler[4], S. Vaintraub[4], T. Bailey[5], L. Callahan[5], A. M. Clark[5], P. Collon[5],
Y. Kashiv[5], D. Robertson[5], U. Koester[6], H.F.R. Hoffmann[7],M. Pichotta[7],
K. Zuber[7], T. Doering[8], R. Schwengner[8], R. Purtschert[9],



AT 2017 gfo, GW170817
I. Arcavi et al., Nature 2017
E. Pian et al., Nature 2017
r- process elements observed



$\rho_n \sim 10^{20\text{-}22} cm^{-3}$

$^{A}Z + xn \rightarrow {}^{A+x}Z$

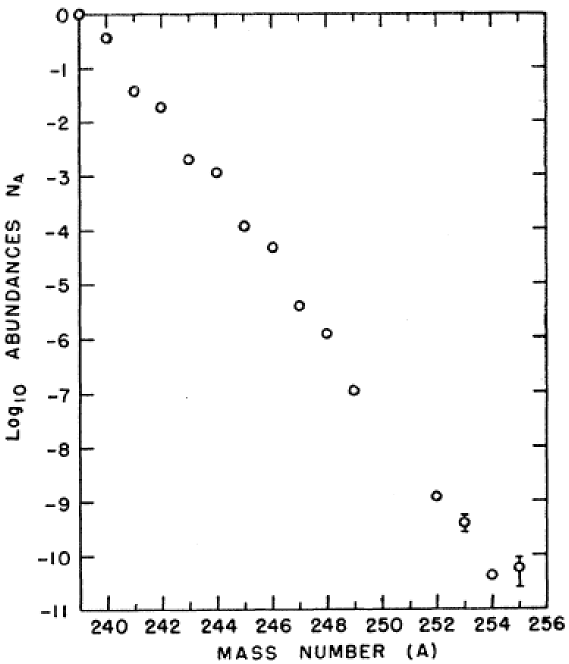
Can it be reproduced/studied in the laboratory?

Ivy Mike thermonuclear test (1952)

MULTIPLE NEUTRON CAPTURE IN THE MIKE FUSION EXPLOSION[1]

A. G. W. CAMERON

Can. J. Phys. Vol. 37 (1959)



a man-made *r*-process

PHYSICAL REVIEW VOLUME 119, NUMBER 6 SEPTEMBER 15, 1960

Heavy Isotope Abundances in Mike Thermonuclear Device*

H. DIAMOND, P. R. FIELDS, C. S. STEVENS, M. H. STUDIER, S. M. FRIED, M. G. INGHRAM, D. C. HESS, G. L. PYLE†, J. F. MECH, AND W. M. MANNING
Argonne National Laboratory, Lemont, Illinois

AND

A. GHIORSO, S. G. THOMPSON, G. H. HIGGINS, AND G. T. SEABORG
Radiation Laboratory and Department of Chemistry, University of California, Berkeley, California

AND

C. I. BROWNE, H. L. SMITH, AND R. W. SPENCE
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

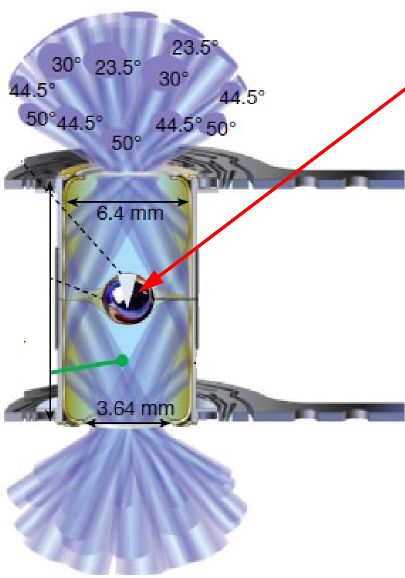
(Received May 2, 1960)

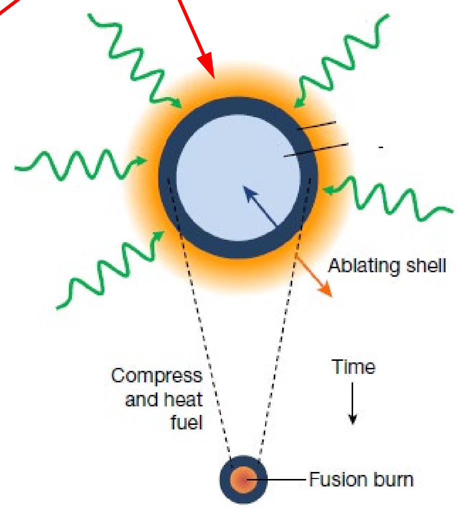
The High-Density Plasma at National Ignition Facility

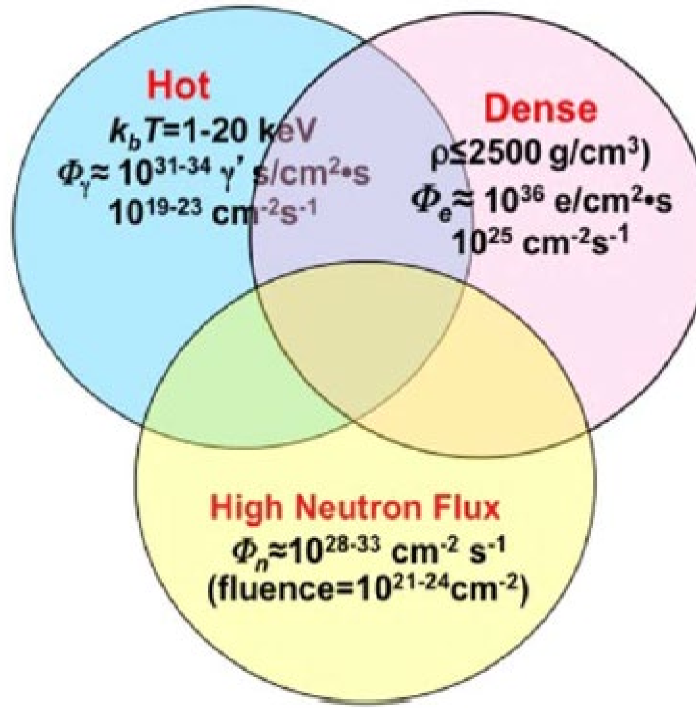
The closest analog to *explosive stellar conditions* in the laboratory and in particular the closest laboratory *neutron analog to astrophysical r-process*

192 laser beams, 351 nm
1.9 MJ, 500 TW peak

deuterium-tritium
(DT) filled capsule





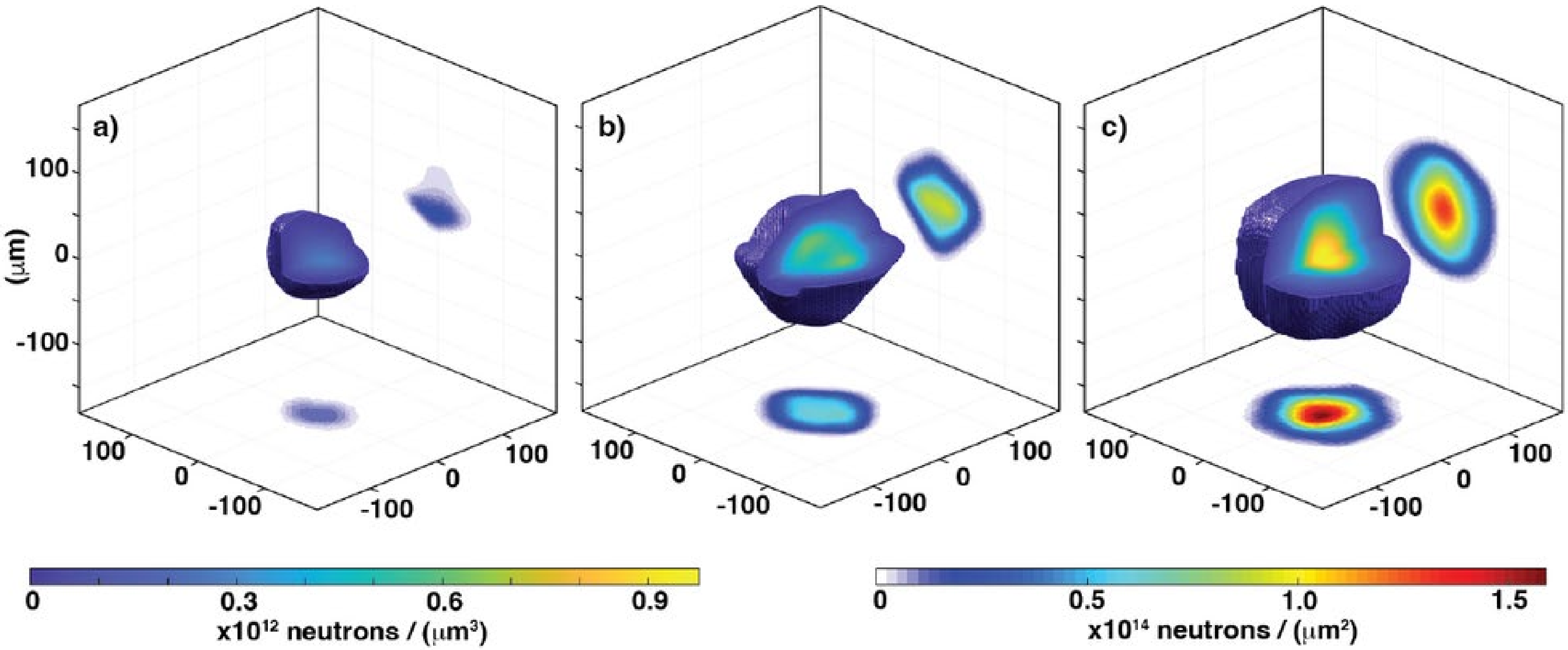


A. Zylstra et al. (2022)
H. Abu-Shawareb et al (2024)

Ch. J. Cerjan et al. (2018)

N221204: ignition achieved
3.1 MJ fusion yield / 2.05 MJ 351nm laser light

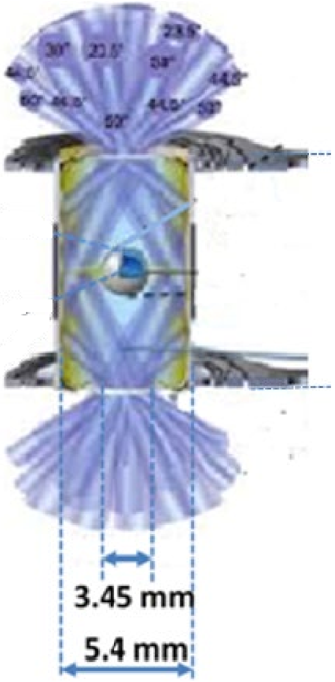
experimental neutron tomographic reconstruction

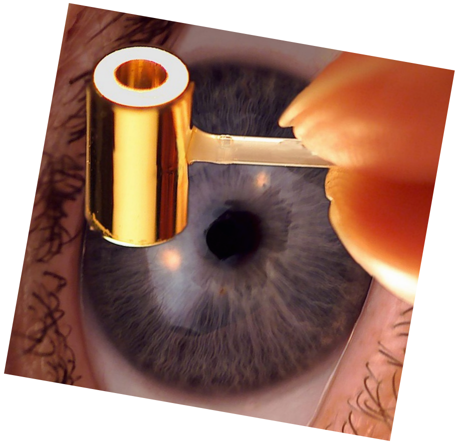


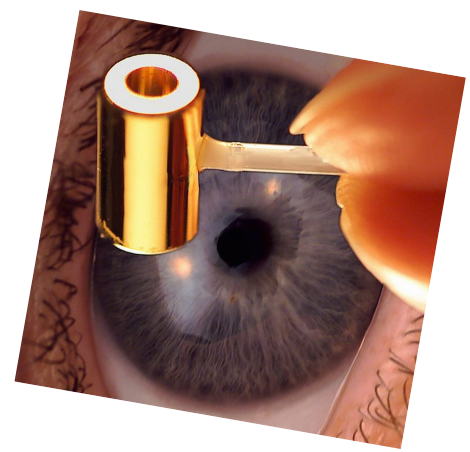
(10^{24} n/cm^3)

(10^{26} n/cm^2)

Abu-Shawareb et al., PRL (2024)


3.45 mm
5.4 mm



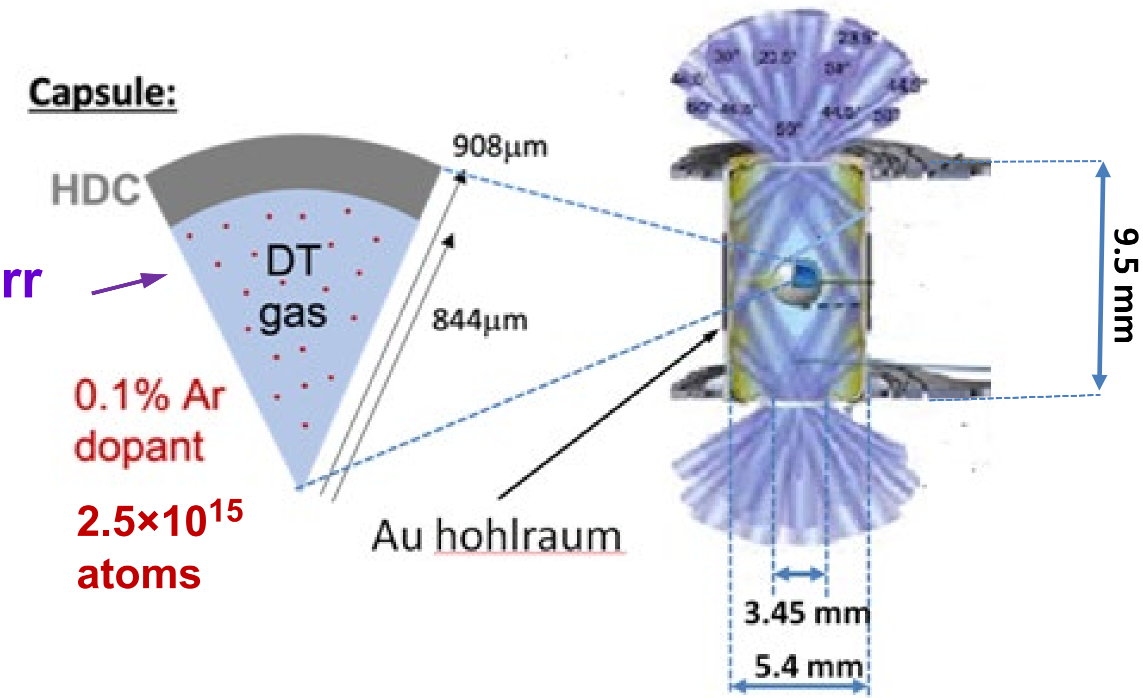


Discovery Science proposal P-000523: "A noble-gas accelerator mass spectrometry platform at NIF for nuclear astrophysics" :

➡ **introduce seeds of Ar in DT fuel and observe (*n*,2*n*) and neutron capture reactions**

Shot N221002
192 laser beams
1.2 MJ, 390 TW

3624 Torr
75 K



2.5×10^{15} atoms

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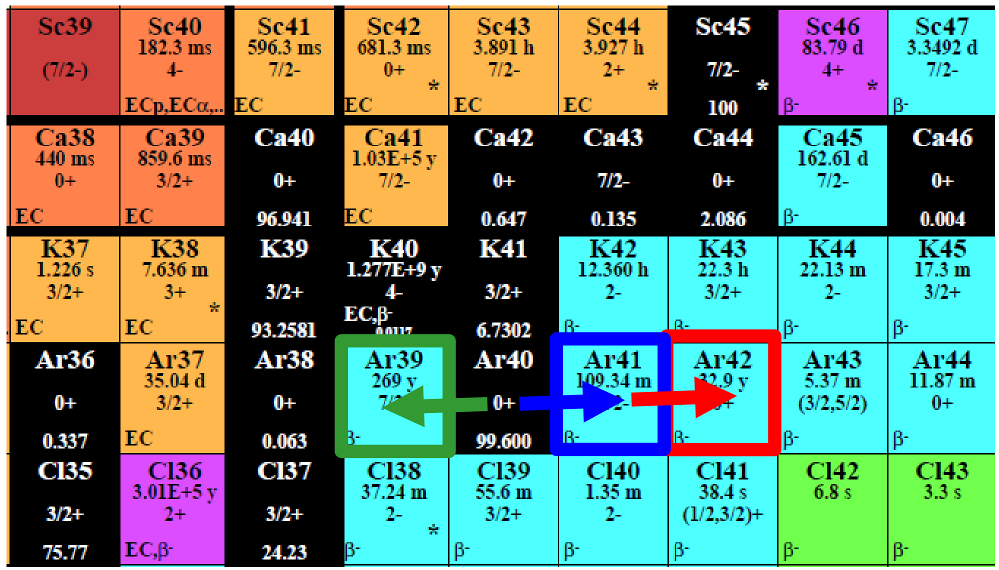


^{42}**Ar** motivation:
^{40}Ar(2n,γ)^{42}Ar,
a "mini-r" process

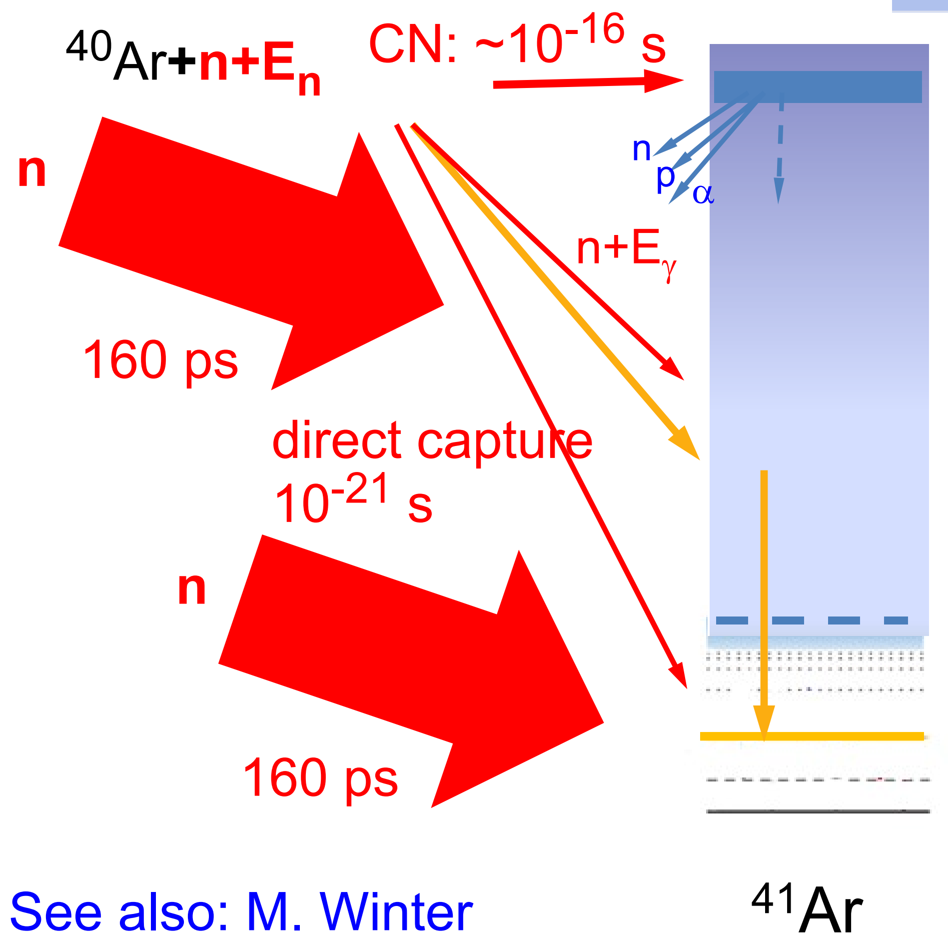
Choice of Ar:

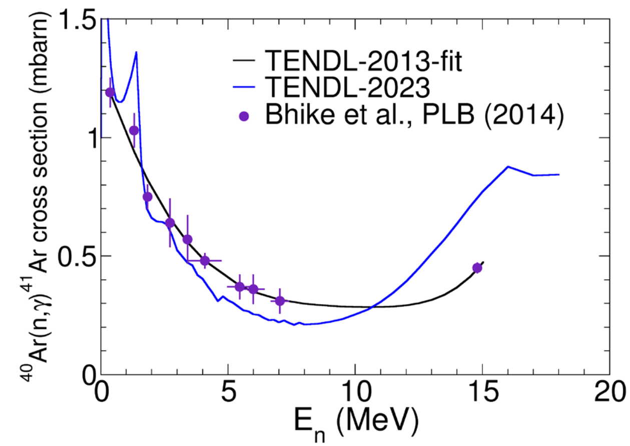
- three **long-lived** neutron induced products: **^{39}Ar(268 y)**, **^{41}Ar(110 min)**, **^{42}Ar(33y)**
- Ar is **a noble gas:** can be reliably collected using **a stable ^{38}Ar carrier**
- **^{39,42}Ar** detection at ultra-high sensitivity by **atom counting**

A hypothesis: could neutron capture occur on an excited/isomeric state?

E(level) (keV)	XREF	J^{π}(level)	$T_{1/2}$(level)	E(γ) (keV)
0	ABCDEFG	7/2-	109.61 m 4 % β^- = 100	
167.11 9	ABCDEFG	5/2-	315 ps 15	167.1 1
515.77 15	ABCD FG	3/2-	0.26 ns 8	348.7 2 516.0 3
1033.94 16	ABCD FG	3/2+	5 ps +28-3	517.9 3 866.7 2

^{41}Ar low-lying levels

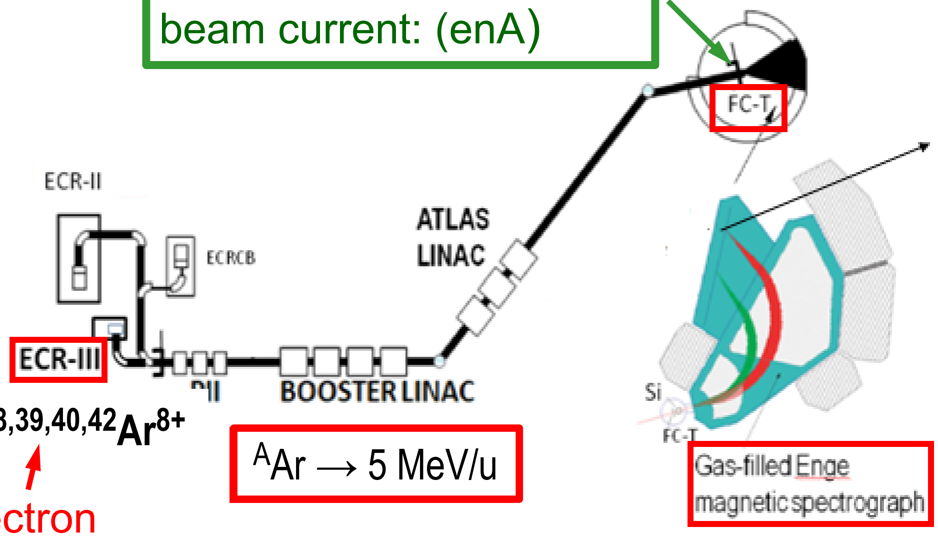




See also: M. Winter MSc Thesis (2024), U. Jyvaskyla.

***Atom counting with noble gas accelerator mass spectrometry** (NOGAMS) at ATLAS (Argonne): a brief*

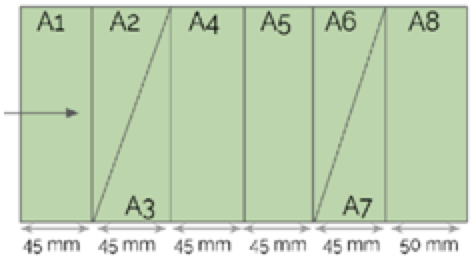
abundant isotope
beam current: (enA)



$^{38,39,40,42}Ar^{8+}$

$^{A}Ar \rightarrow 5$ MeV/u

N_2 10 Torr



ionization chamber

CF_4 39.5 Torr

rare ion counting and identification: < 1 h^-1

electron cyclotron resonance ion source: **highly-charged** positive ions sequentially injected

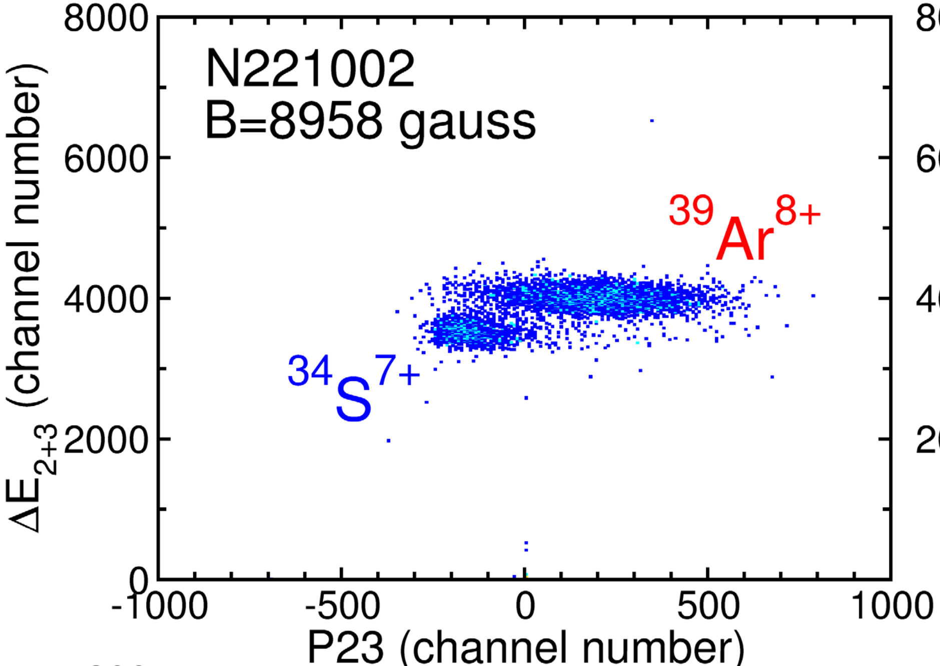
linear acceleration (superconductive RF cavities): a m/q filter

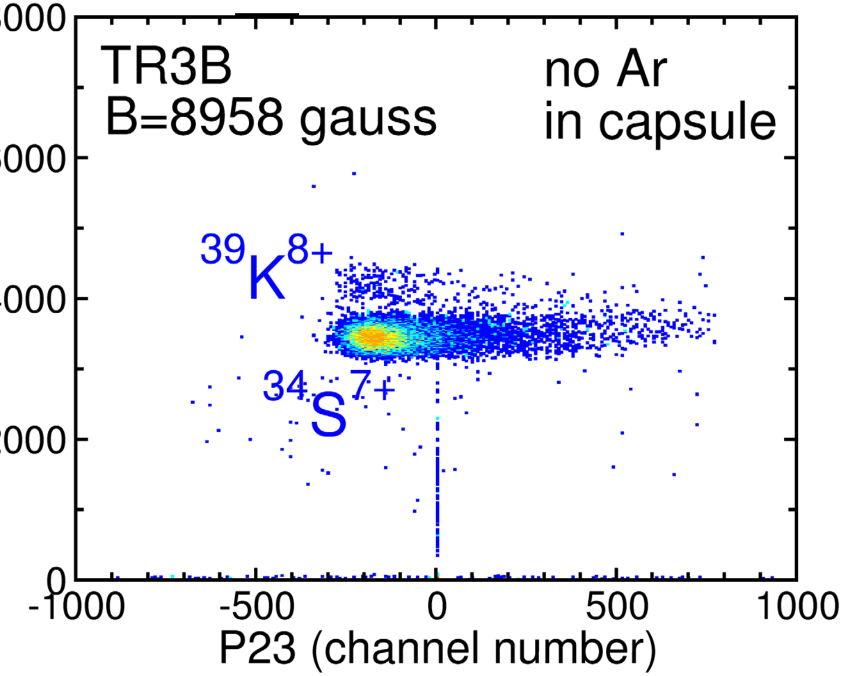
dispersion by <q>: separation of isobars and parasitic ions

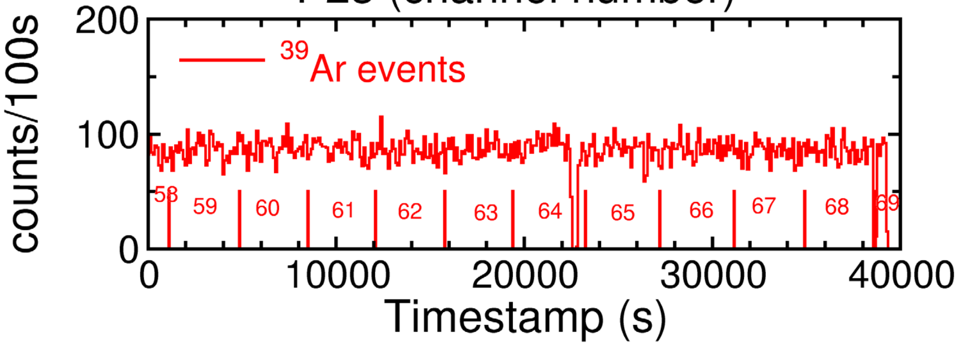
The technique measures an ***absolute* isotopic ratio**:
r = rare/abundant
number of rare atoms =
N(rare) = *r* × *N(abundant)*

NIF shot N221002: 22 Oct 2022

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







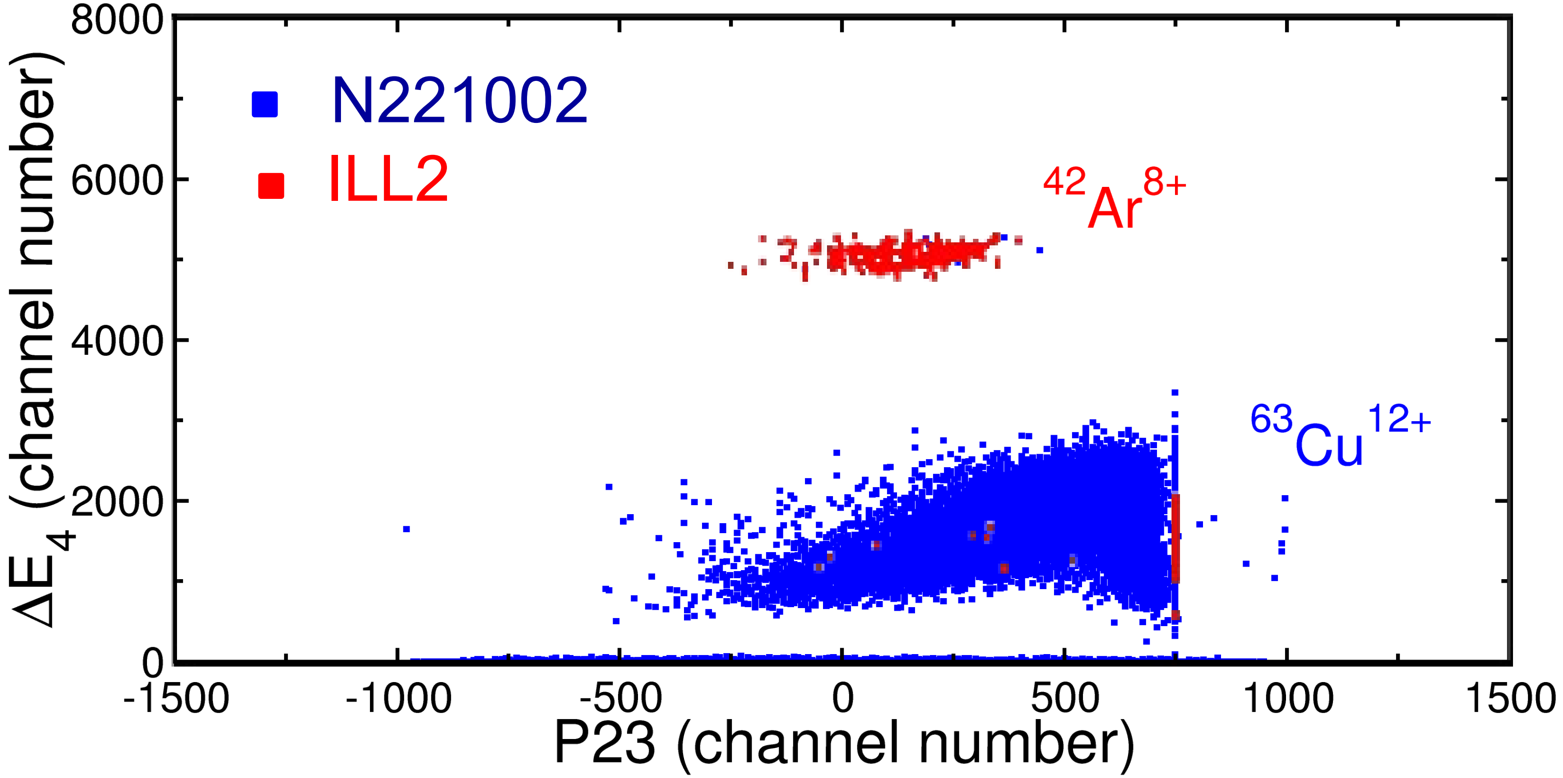
$^{40}Ar(n,2n)^{39}Ar$(268 y)

$^{39}Ar/^{38}Ar = 1.76 \pm 0.06 \times 10^{-10}$

Yield : $(2.8 \pm 0.1) \times 10^{10}$ ^{39}Ar atoms

NIF shot N221002: 22 Oct 2022

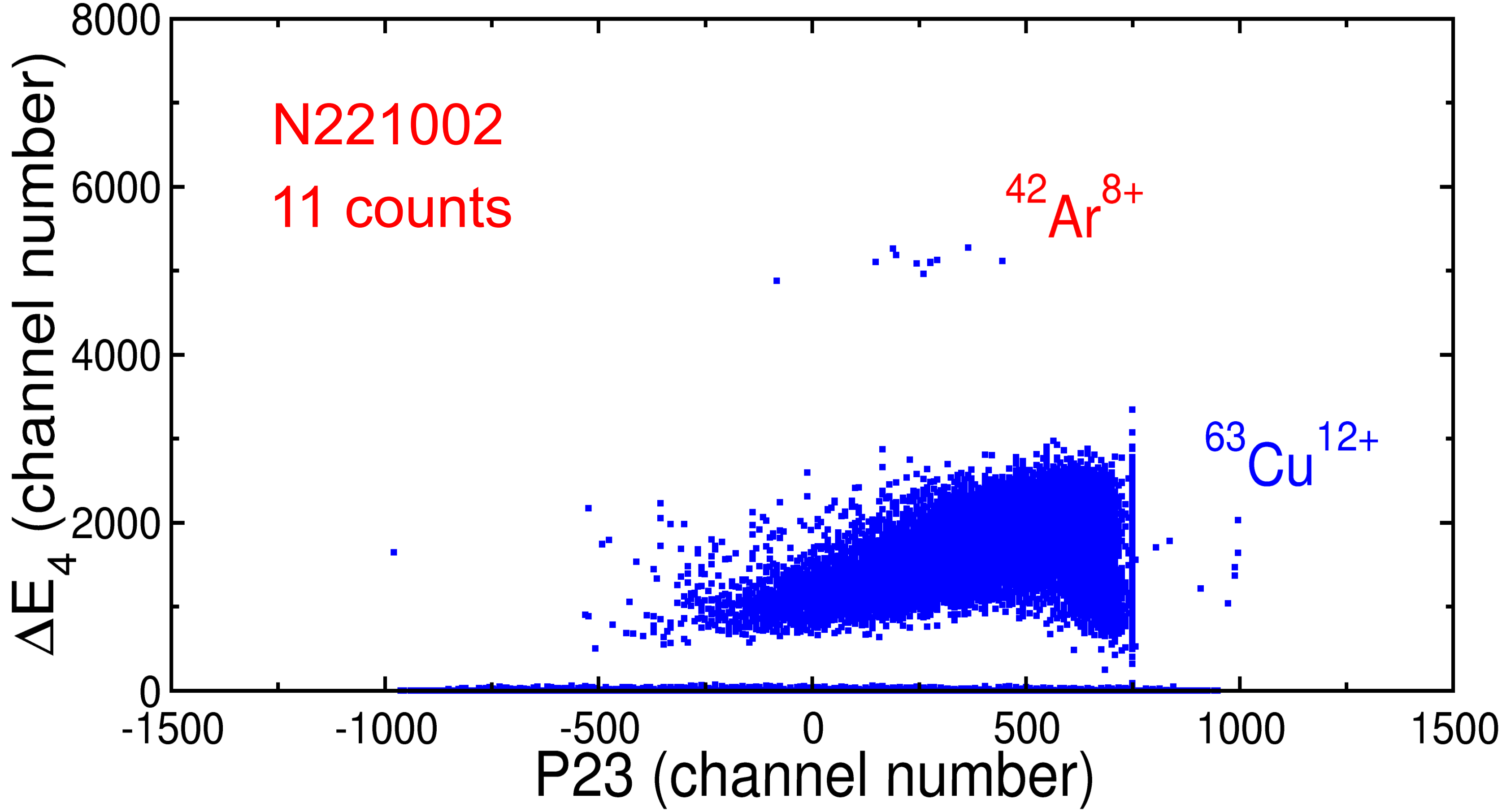
^{42}Ar detected (Nov 2024)

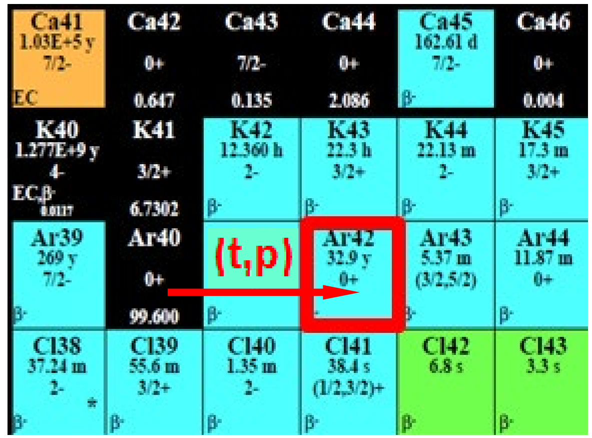


$^{42}Ar/^{38}Ar = (1.0 \pm 0.3) \times 10^{-14}$

$^{42}Ar = (1.6 \pm 0.5) \times 10^{6}$ atoms ??

$^{41}Ar = 2.0 \times 10^{7}$ atoms





E_B (t,p) ~ 400 keV
T_{ion} = 4.3 keV

Presently considered scenario:
tertiary reaction in flight (within 160 ps)

D +T -> n + α: E_n ~ 14 MeV

n + T -> T + n : E_T ~ 10 MeV

T + ^{40}Ar -> p + ^{42}Ar : ^{40}Ar(t,p) ^{42}Ar

σ(TALYS 2.03)) ~ 20 mb (not experimentally measured)

Present scenario: tertiary reaction in flight (within 160 ps)

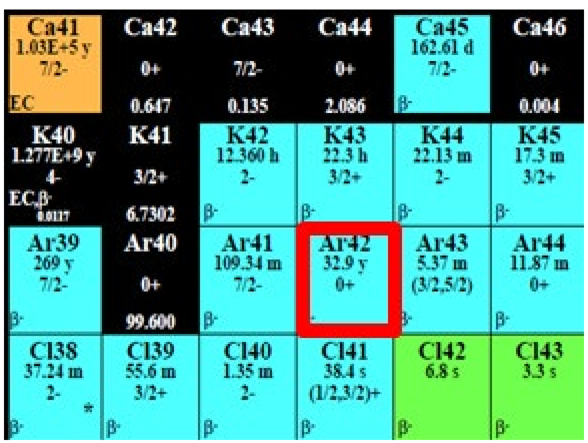
D + T -> n + α: E_n ~ 14 MeV

n + T -> t + n : E_T ~ 10 MeV

T + ^{40}Ar -> p + ^{42}Ar : ^{40}Ar(t,p)^{42}Ar

preliminary

	new-HYDRA	expt.
T:H:D	50:00:50	
DT-n Yield	2.01E+15	1.49e15 (NIF monitors)
38Ar	4.64E+04	
39Ar	1.20E+10	2.8 e10 (NOGAMS)
41Ar	7.73E+06	2.0 e7 (γ spect., NIF)
42Ar	8.45E+05	1.6 e6 (NOGAMS)
40K	3.88E+07	
41K	1.39E+07	
42K	5.96E+06	
39Cl	1.71E+05	
40Cl	2.71E+08	
37S	1.31E+08	



Summary

1. Quantitative determination of neutron induced reaction yields on ^{40}Ar seeds in a stellar-like high-density plasma
2. The origin of the ^{42}Ar events observed is attributed *mainly* to a charged-particle reaction in flight, first time observed:

$$d(t,\alpha)n(t,n)t(^{40}Ar,p)^{42}Ar$$

3. The implosion of a pure DD capsule is considered to search for a two-neutron capture reaction.

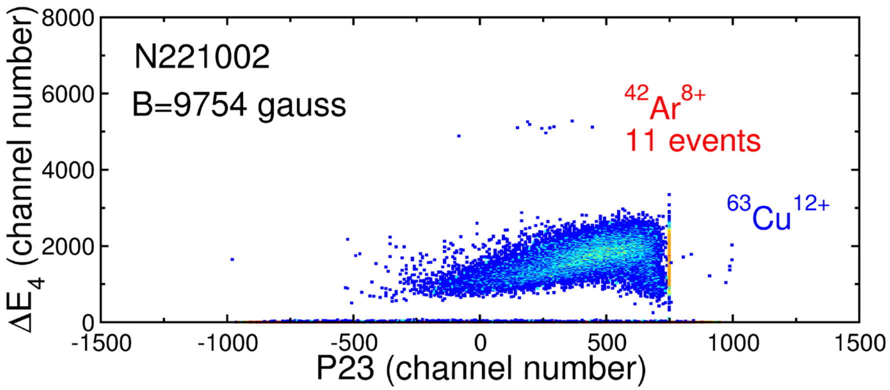
Thank you for your attention.

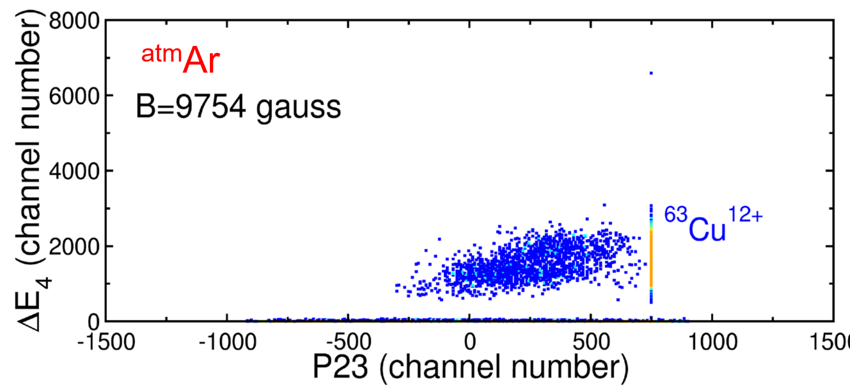
Preliminary results: N221002

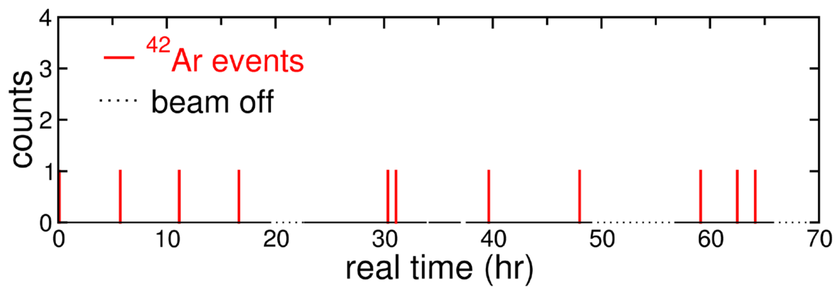
$^{42}Ar/^{38}Ar = (1.0 \pm 0.3) \times 10^{-14}$

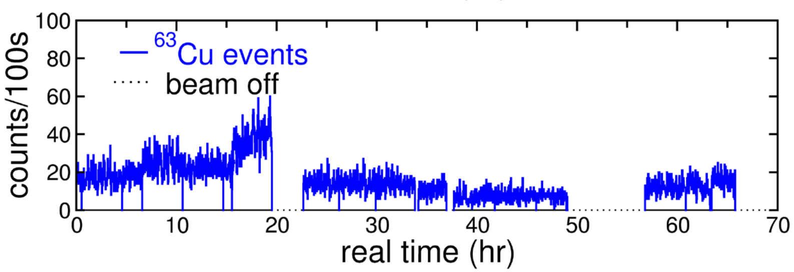
$N(^{42}Ar) = 1.6 \pm 0.5 \times 10^{6}$ atoms

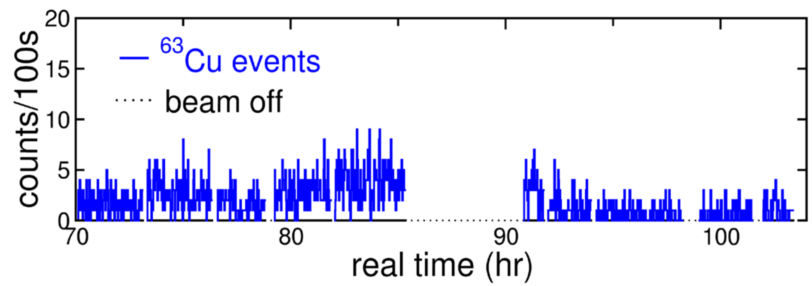
- 11 counts of ^{42}Ar from TR5 sample during a 53.5-hour run: **(1.0±0.3) ct/5 h**
- 0 ^{42}Ar counts for ^{atm}Ar during a 25.9-hour run: **< 0.2 ct/5 h**







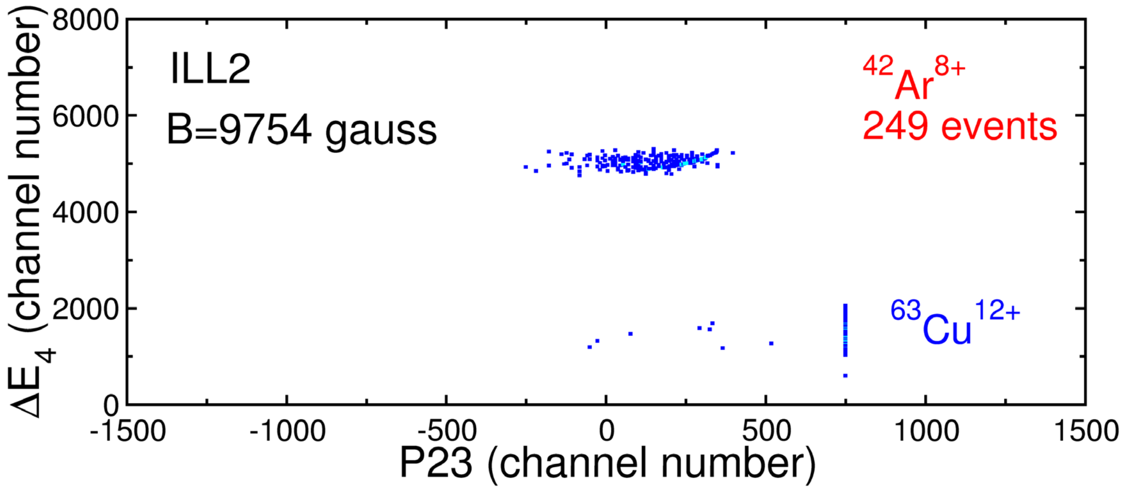


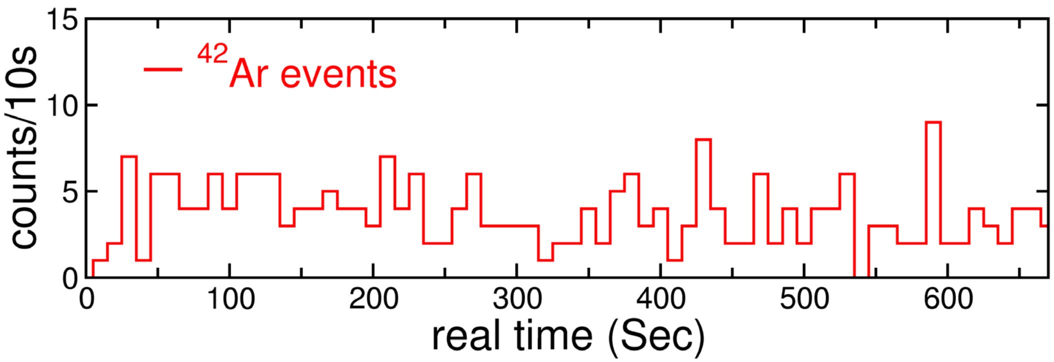


^{atm}Ar: $^{42}Ar/^{38}Ar < 2 \times 10^{-15}$

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

^{42}Ar/Ar (NOGAMS) = $(1.09 \pm 0.12) \times 10^{-11}$
^{42}Ar/Ar (activity+dilution) = $(1.16 \pm 0.05) \times 10^{-11}$





preliminary

$t_{1/2}(^{42}Ar)$ (AMS)= 30.8 ± 4.9 yr
$t_{1/2}(^{42}Ar)$ (1965)= 32.9 ± 1.1 yr

$\sigma_{th}(^{41}Ar(n,\gamma)^{42}Ar)$= 402±48 mb
(first measurement)
Previous estimate: 0.5 ± 0.1 b
(Stoenner et al., 1965)

(manuscript in preparation)

Best-to-date two-dimensional half-sphere HYDRA simulation for N221002 (DT-gas loaded Ar)

N221002 Subscale Symcap	Experiment	Simulation
DT-n yield	1.49E+15	3.34E+15
Peak Burn (ns)	6.87	6.87
DSR (%)	0.52	0.67
T_{ion} (keV)	4.31	4.02
Burnwidth (ps)	NA	162
Ar in gas fill	2.520E+15	2.522E+15
39Ar	~~4.00E+10~~ 2.8(1)e+10	3.28621E+10
41Ar	2.00E+07	7.80998E+06
40Cl	NA	4.70612E+08
42Ar	1.6(5)e+6 NA	0.0755 (i.e. 0)
38Ar	NA	2.21030E+05
37S	NA	2.29266E+08
39Cl	NA	3.13837E+05

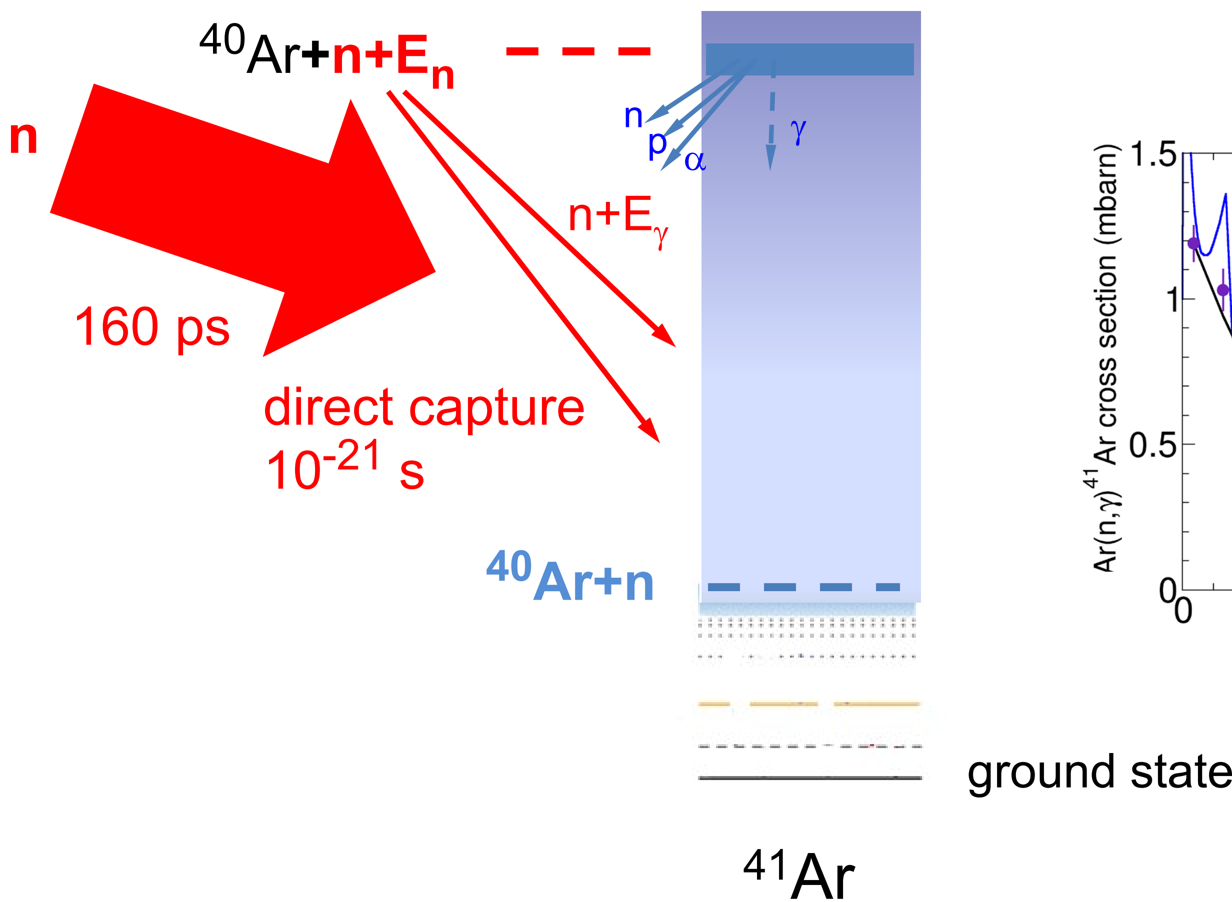
incompatible with neutron capture unless σ ~ few 100b

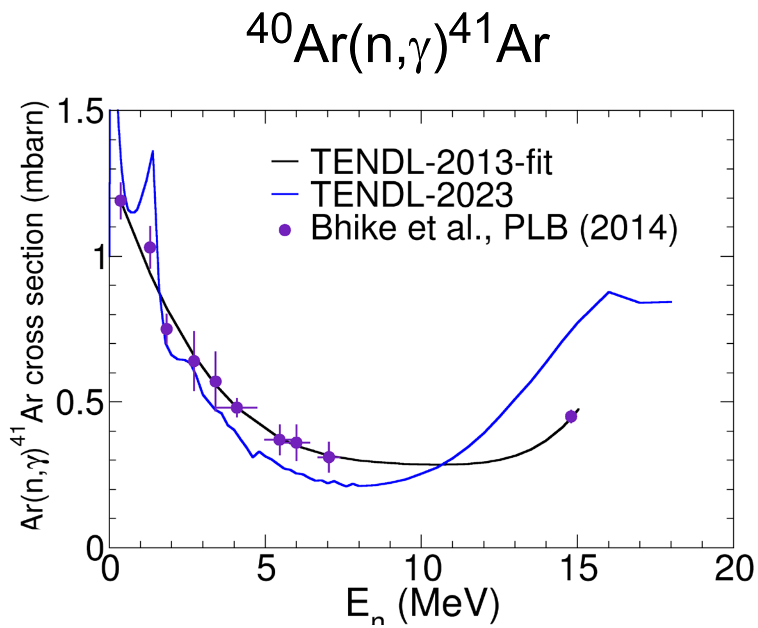
new-HYDRA simulations: T/D ratio study

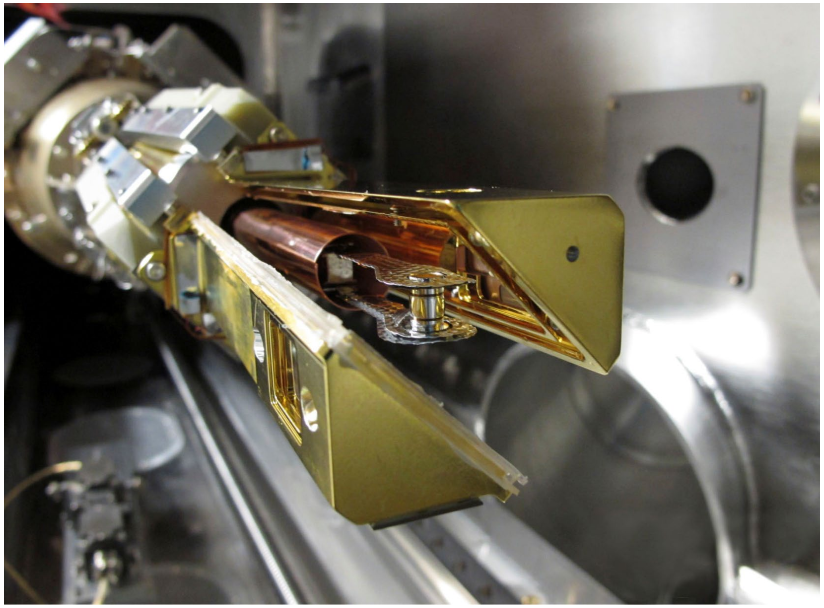
	N221002 Exp	N221002	T/D			
	T/D=50/50	50/0/50	80/20	70/30	20/80	30/70
DT-n Yield	1.49E+15	2.01E+15	1.49E+15	1.69E+15	1.76E+15	2.43E+15
39Ar	2.8(1)E+10	1.20E+10	9.35E+09	1.04E+10	1.03E+10	1.46E+10
41Ar	2.00E+07	7.73E+06	6.23E+06	9.34E+05	6.82E+06	9.70E+06
42Ar	1.6(5)E+06	8.45E+05	1.01E+06	6.55E+06	3.31E+05	7.21E+05

our next shot
Fall 2025,
we'll be back…

D + T -> α + n(~14 MeV)
14 MeV neutron capture on ^{40}Ar

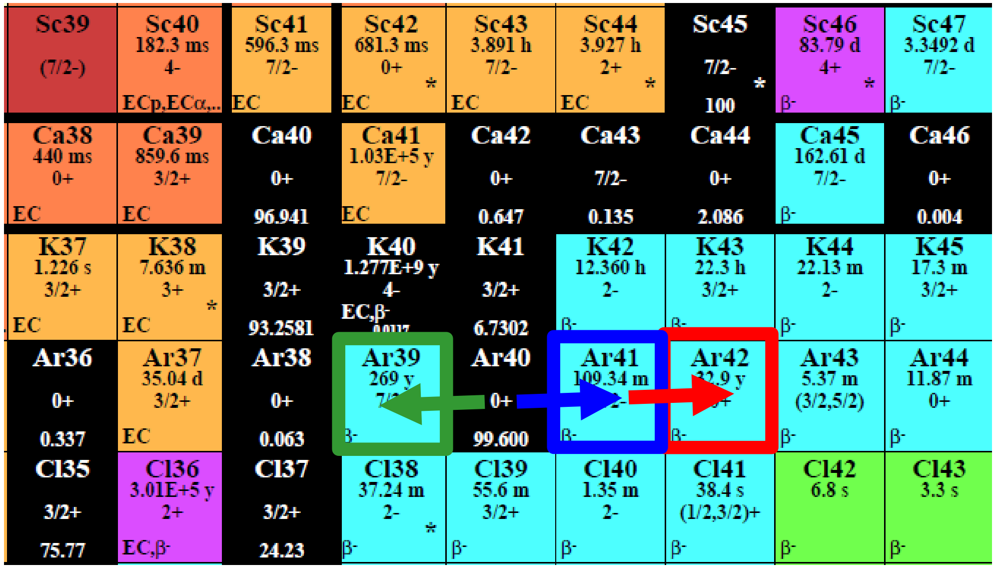






Discovery Science proposal P-000523: “A noble-gas accelerator mass spectrometry platform at NIF for nuclear astrophysics” :

introduce seeds of Ar in DT fuel and observe (*n*,2*n*) and neutron capture reactions

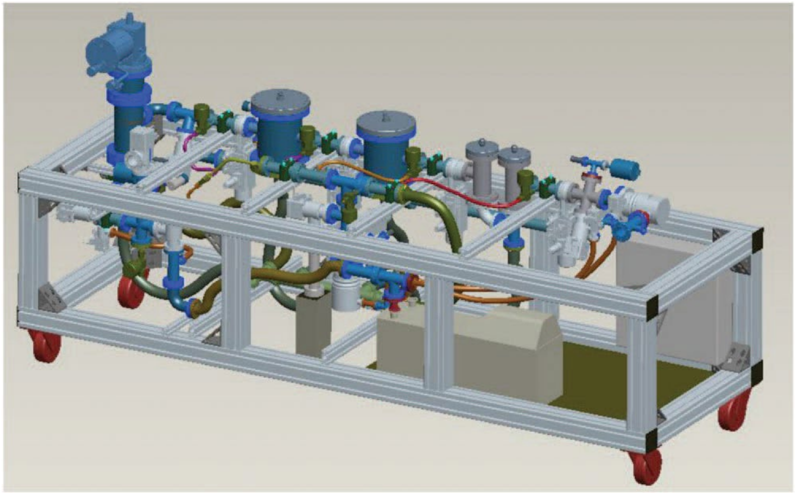


Collection of reaction product atoms:

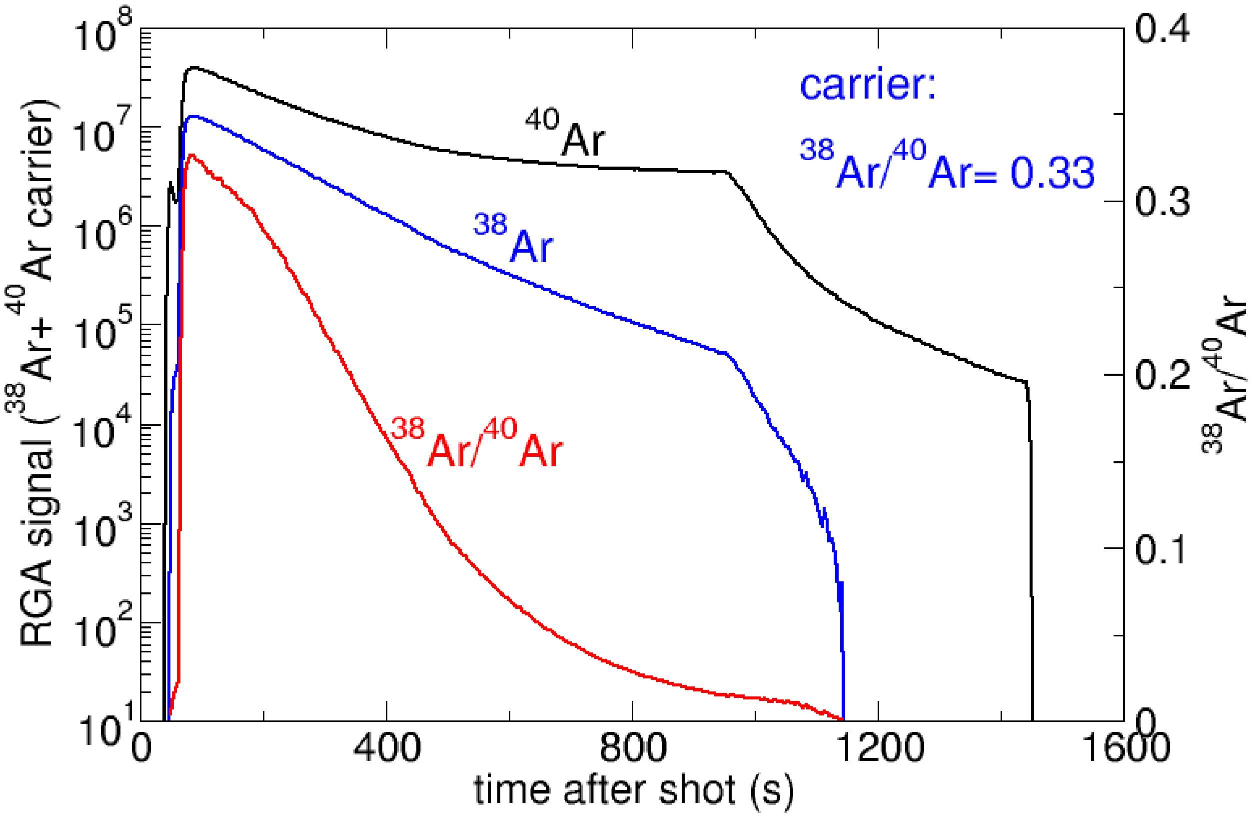
- inject a known volume of ^{38}**Ar** carrier in NIF chamber just after shot, pump chamber into a cryogenic trap system to separate Ar

(Radiochemical Analysis of Gaseous Samples (RAGS) apparatus

The Radiochemical Analysis of Gaseous Samples (RAGS) apparatus



N221002-001-999 RAGS FLTR RGA
DT HDC Au, stable and rad carriers



N221002 Ar sample

HYDRA simulation for a Ar-doped DT implosion at high power
Ch. Cerjan, LLNL, private comm.

39Ar	2.706E+12
37S	1.931E+10
41Ar	7.204E+08
39Cl	2.236E+08
40Cl	3.858E+10
38Ar	3.696E+09
36S	2.080E+08
38Cl	2.456E+07
42Ar	1.550E+03

HYDRA simulations: Ch. Cerjan (LLNL)

- **The primary implosion experiment simulation tool used for NIF experimental design and analysis.**
  - **ALE (Adaptive Lagrange-Euler)**
  - **Finite element based (quadrilateral in 2D or hexahedral elements in 3D)**
  - **Massively parallel**
  - **PYTHON user scripts may be readily linked.**
- **Physics capabilities are extensive.**
  - **Consistent numerical treatment of the hydrodynamic equations, diffusive radiation transport, and diffusive electron conduction.**
  - **Substantial flexibility exists for different EOS and conductivity model choices.**
  - **Implicit Monte Carlo photon transport.**
  - **Particle Monte Carlo neutron, charged particle, and gamma-ray generation and transport.**
  - **In-line or post-processing radiochemistry available (KUDU).**
- **A static three-dimensional model exists that correlates implosion diagnostics and quantifies the stagnation properties.**

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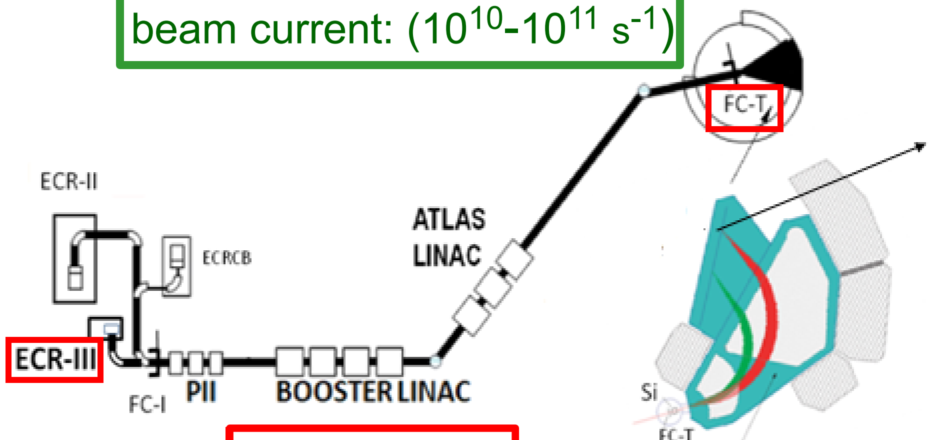
Atom counting with noble gas accelerator mass spectrometry (NOGAMS) at ATLAS (Argonne): a brief

abundant isotope
beam current: (10^{10}-10^{11} s^{-1})

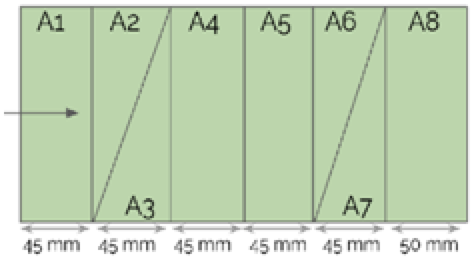


$^{38,39,40,42}Ar^{8+}$

$^{A}Ar \rightarrow 5$ MeV/u

Gas-filled Enge magnetic spectrograph

N_2 10 Torr



ionization chamber

CF_4 39.5 Torr

electron cyclotron resonance ion source: highly-charged positive ions sequentially injected

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

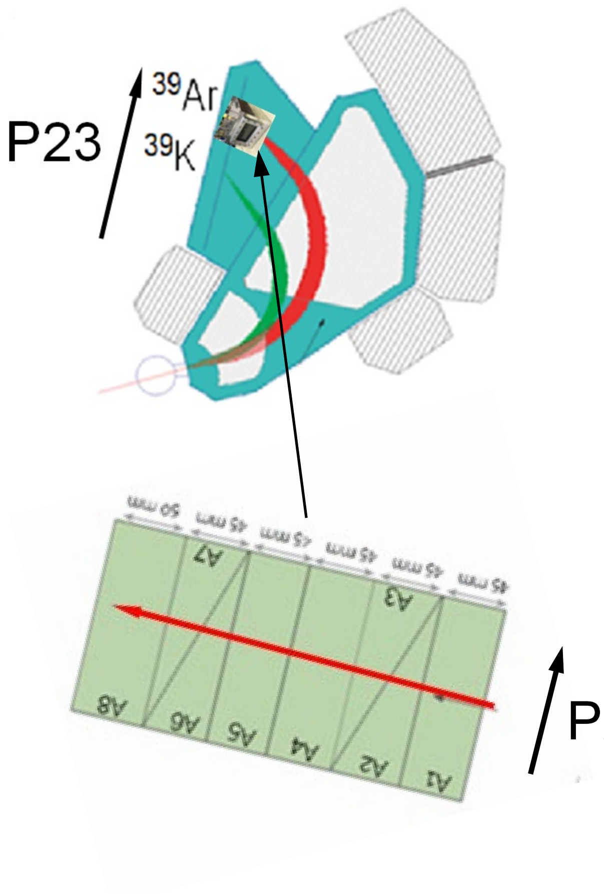
dispersion by <q>= f(Z) separation of isobars and parasitic ions

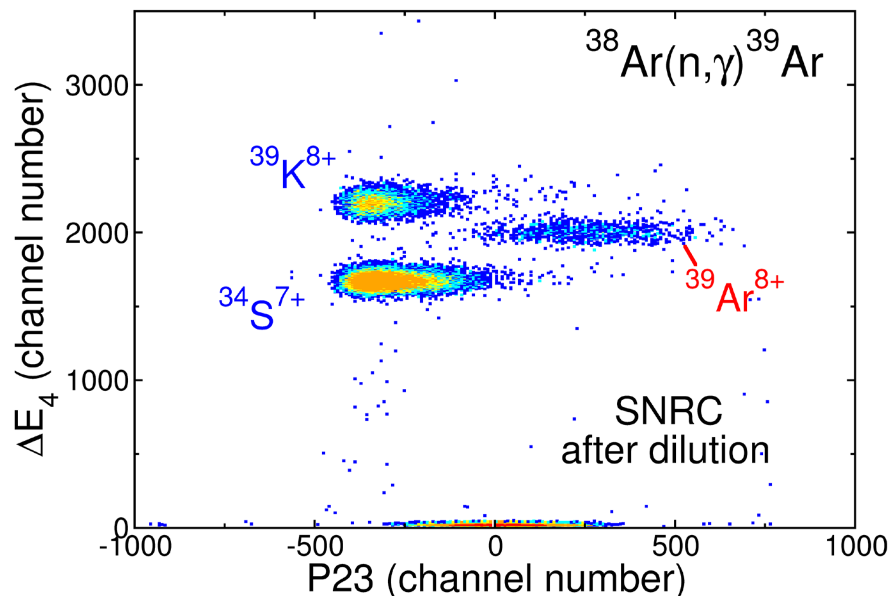
rare ion counting and identification: < 0.1-1 h^-1

The technique measures an *absolute* isotopic ratio:
r = rare/abundant
number of rare atoms =
N(rare) = *r* × *N(abundant)*

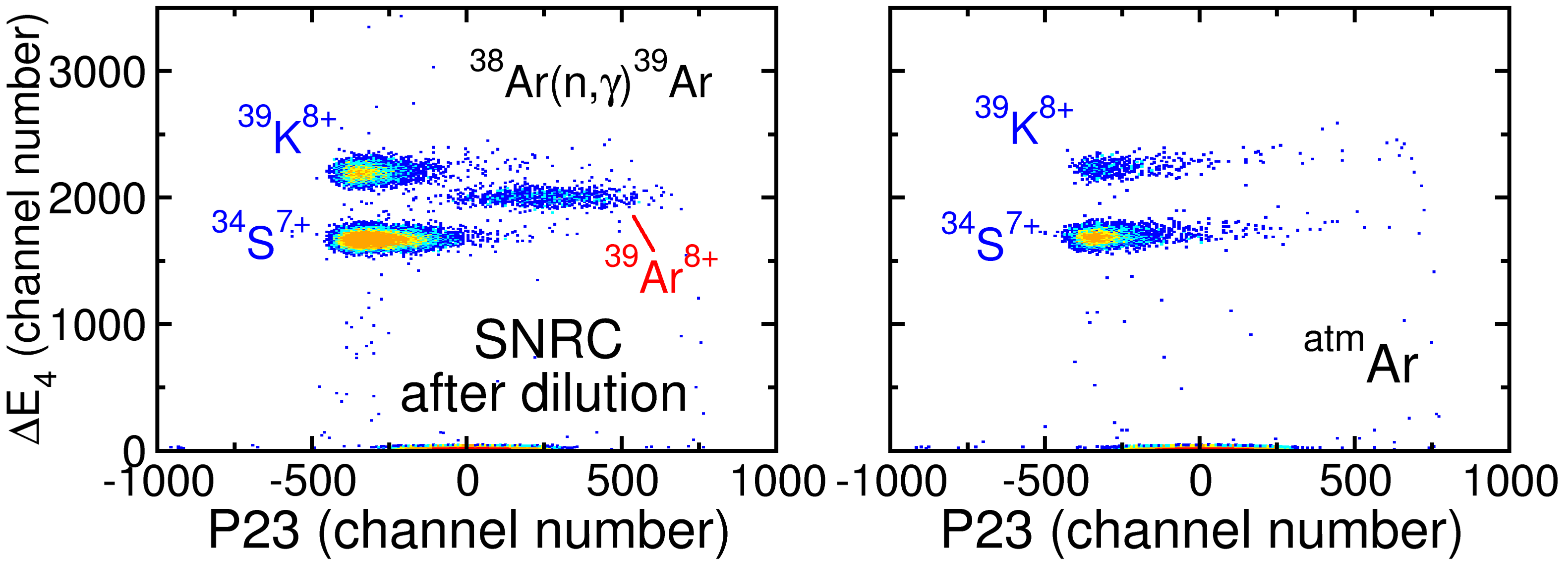
2

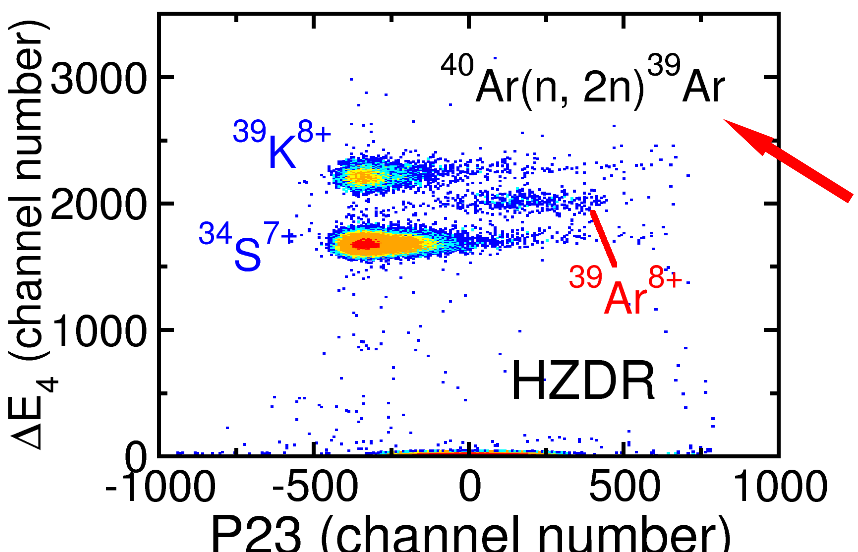
A test experiment: ^{39}Ar detection
$^{38}Ar(n,\gamma)^{39}Ar$ with thermal neutrons from Soreq nuclear reactor





$$P23 = \frac{A3-A2}{A3+A2}$$





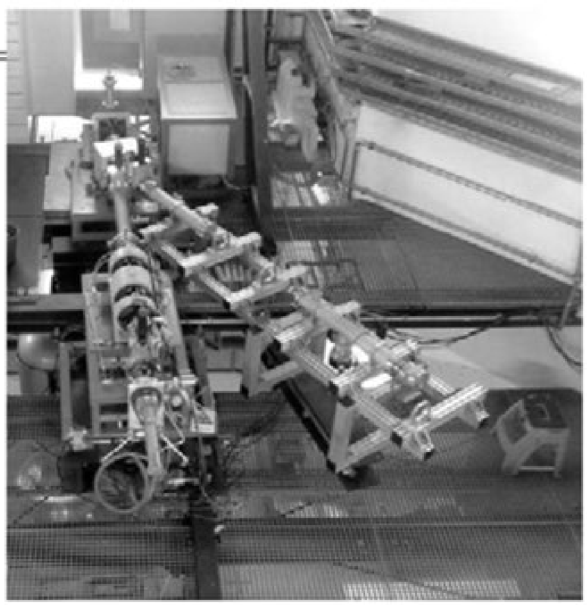
A digression: 14 MeV neutron from a DT generator (TU Dresden-Rossendorf (Germany)

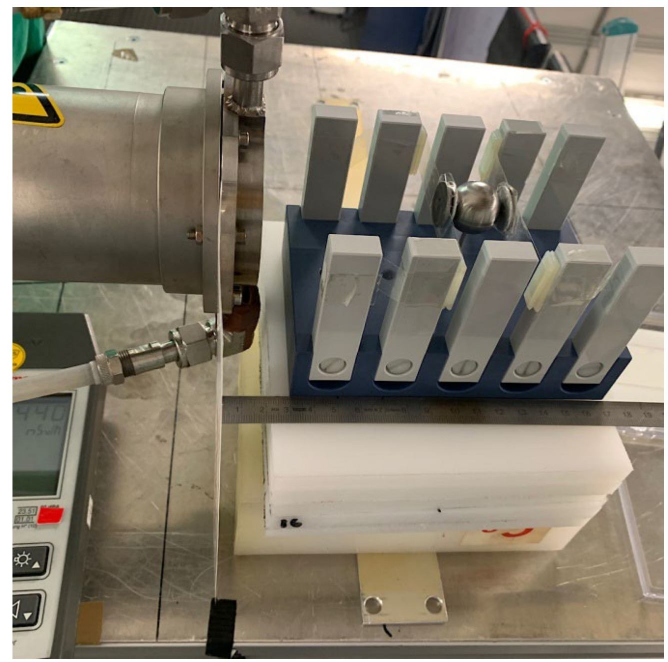
Auxilliary experiment: $^{40}Ar(n,2n)^{39}Ar$ first cross section measurement (14 MeV) at TU Dresden/Helmholtz Zenter Dresden Rossendorf

$T(D,n)^4He$ reaction at Rossendorf (HZDR)
~$6.6(1)\times10^{11}$ 14 MeV ncm^{-2}
4.5 hours

sphere: stainless steel
volume: 4.18 cm^3
content : ^{40}Ar (5N) gas
pressure: 20 bar

fast-neutron monitors:
^{27}Al, ^{93}Nb





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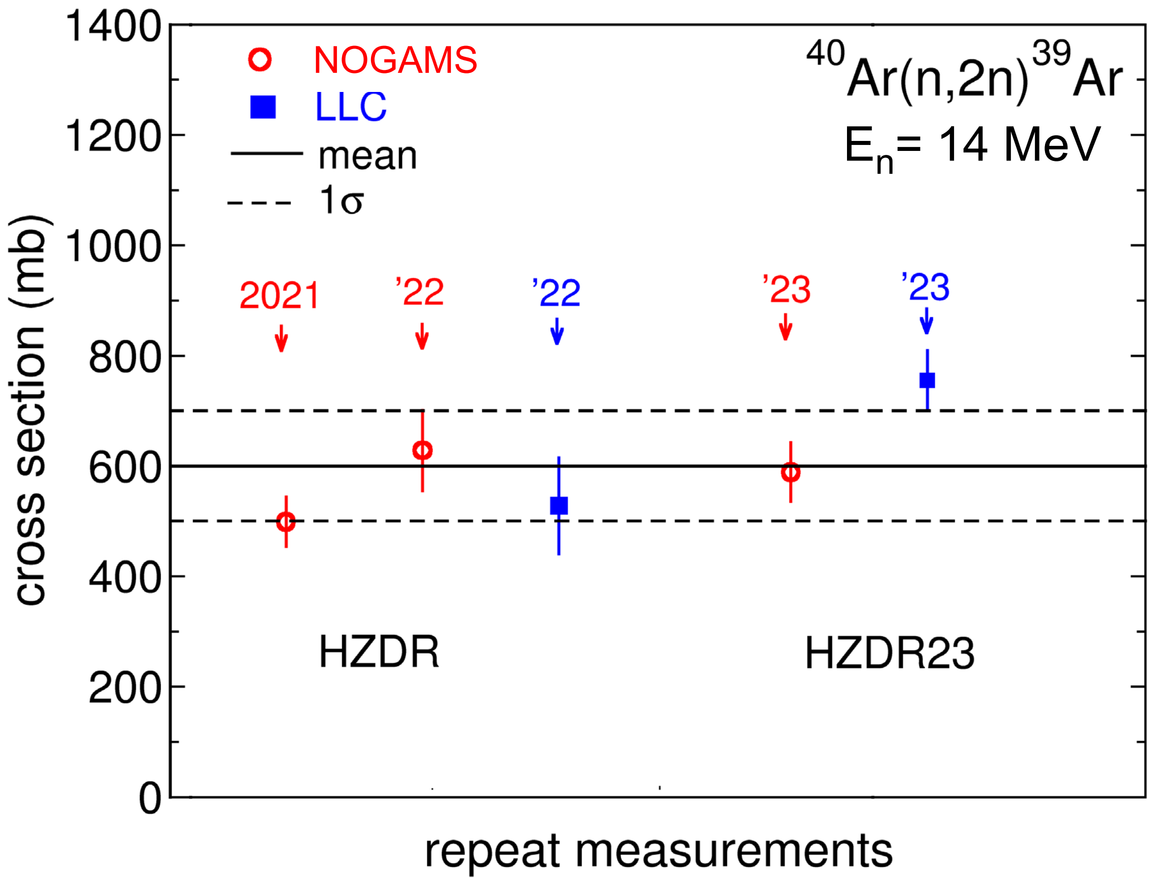


NOGAMS (Argonne)

Low-Level β Counting (LLC) at Bern University

$^{40}Ar(n,2n)^{39}Ar$.
E_n= 14 MeV

First determination of total cross section:
σ= 600 ±100 mb

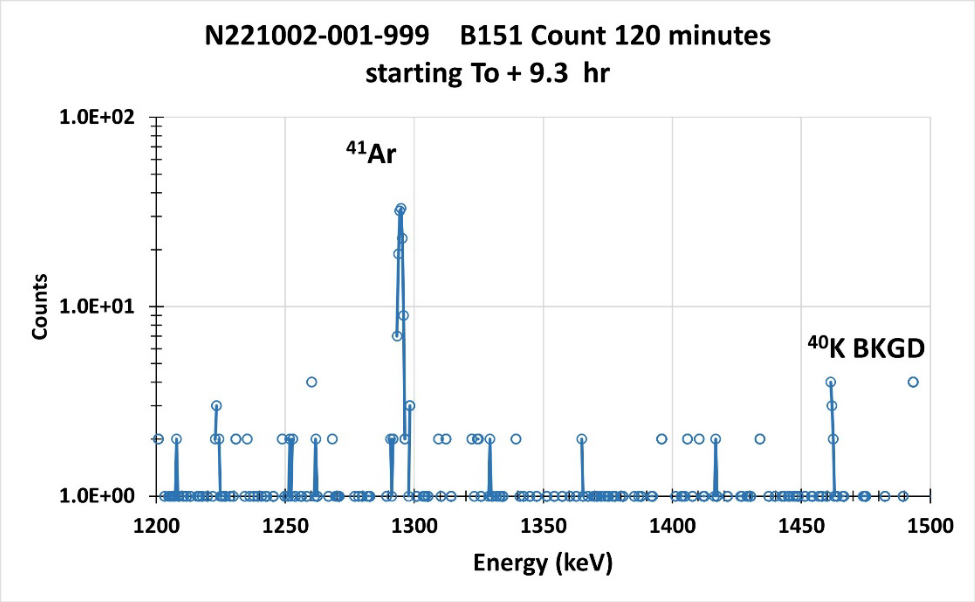
TENDL23: 579 mb

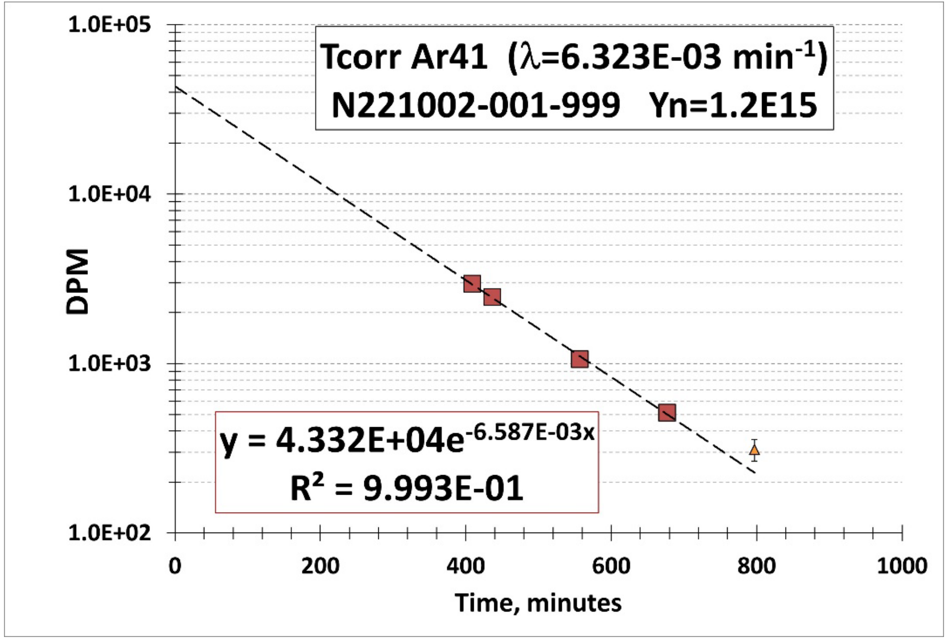
manuscript in preparation

Best-to-date two-dimensional half-sphere HYDRA simulation for N221002 (DT-gas loaded Ar)

N221002 Subscale Symcap	Experiment	Simulation
DT-n yield	1.49E+15	3.34E+15
Peak Burn (ns)	6.87	6.87
DSR (%)	0.52	0.67
T_{ion} (keV)	4.31	4.02
Burnwidth (ps)	NA	162
Ar in gas fill	2.520E+15	2.522E+15
39Ar	~~4.00E+10~~ 2.8(1)e+10	3.28621E+10
41Ar (β^-,110 min)	2.00E+07	7.80998E+06
40Cl		4.70612E+08
42Ar		0.0755 (i.e. 0)
38Ar		2.21030E+05
37S		2.29266E+08
39Cl		3.13837E+05

measured by γ spect, after shot, 41K line at 1294 keV

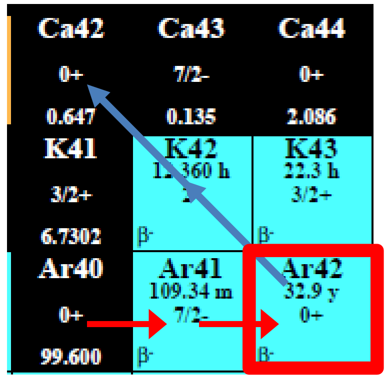

N221002-001-999 B151 Count 120 minutes
starting To + 9.3 hr
41Ar
40K BKGD
Counts
1.0E+02
1.0E+01
1.0E+00
1200
1250
1300
1350
1400
1450
1500
Energy (keV)

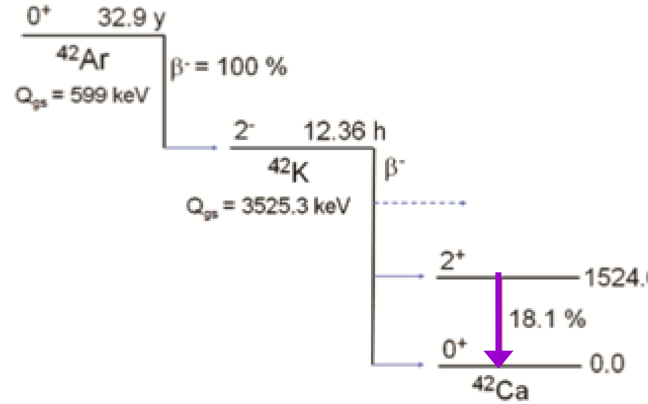

Tcorr Ar41 (λ=6.323E-03 min-1)
N221002-001-999 Yn=1.2E15
y = 4.332E+04e-6.587E-03x
R2 = 9.993E-01
DPM
1.0E+05
1.0E+04
1.0E+03
1.0E+02
0
200
400
600
800
1000
Time, minutes

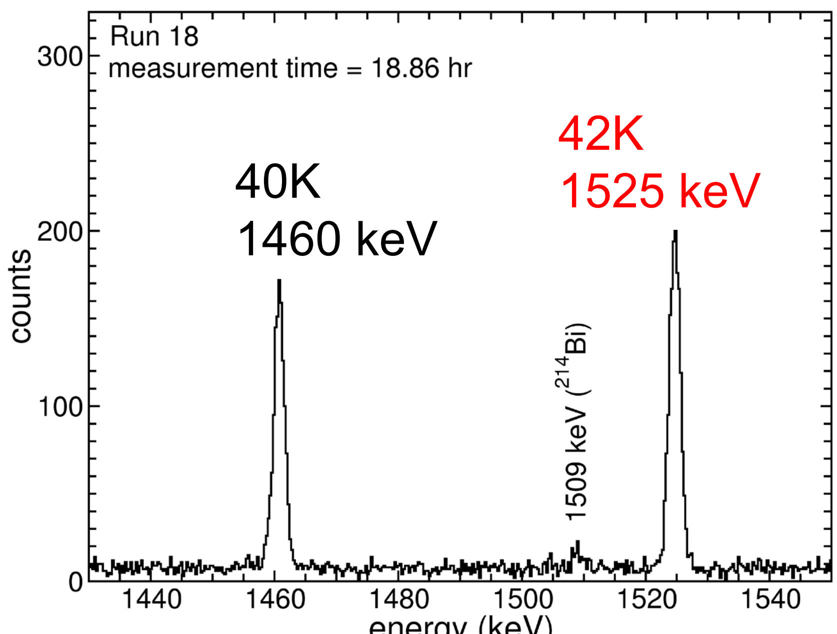
A unique ^{42}Ar calibration sample: produced at the high-flux reactor of Institut Laue-Langevin (Grenoble, France) at $\Phi_{thermal}$= 1.1 × 10^{15} cm^{-2} s^{-1}

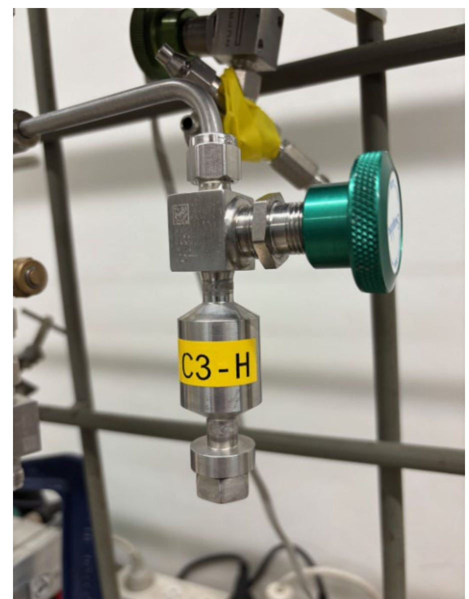
4.7 days irradiation in a quartz ampoule: $^{40}Ar(n,\gamma)^{41}Ar(n,\gamma)^{42}Ar$(32.9 y)

99.92% ^{40}Ar









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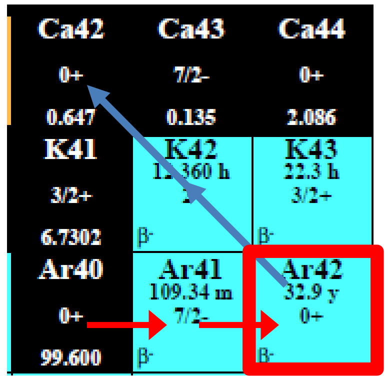

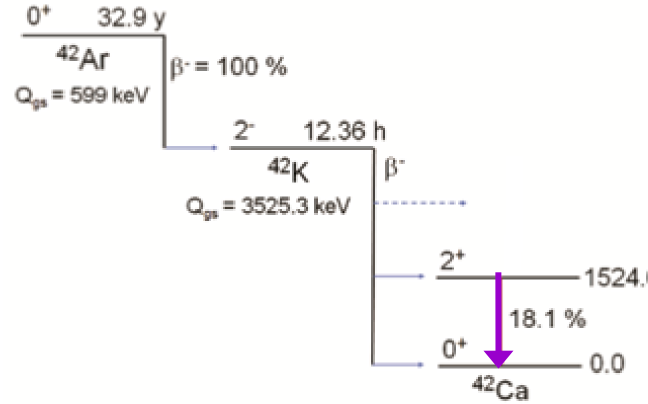

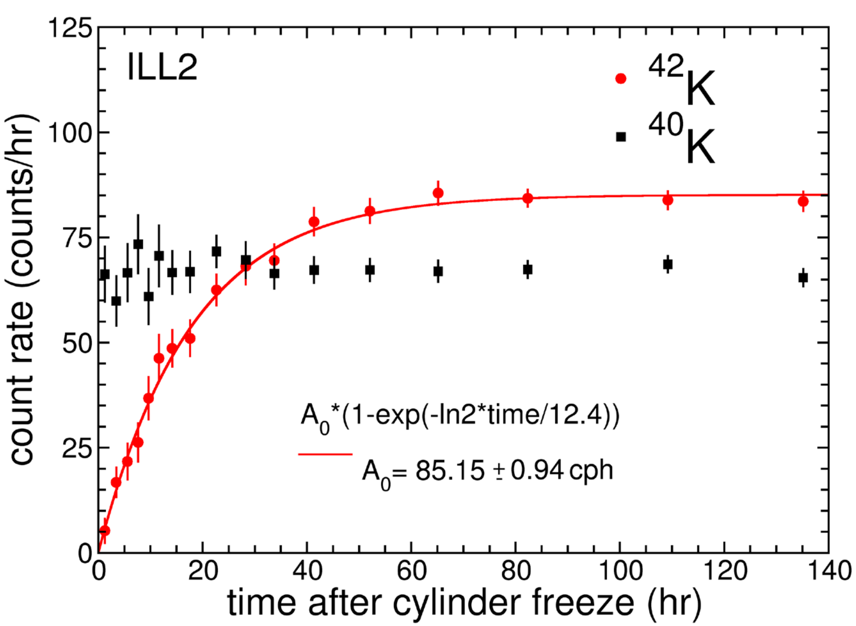

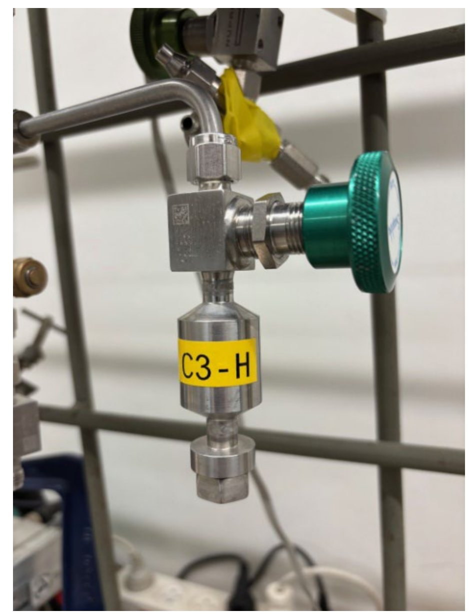

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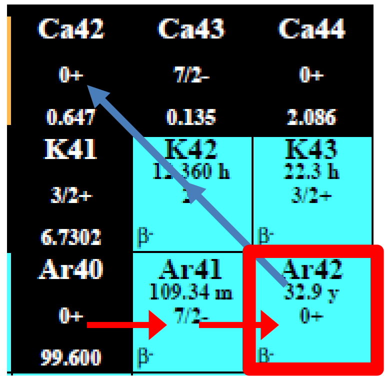

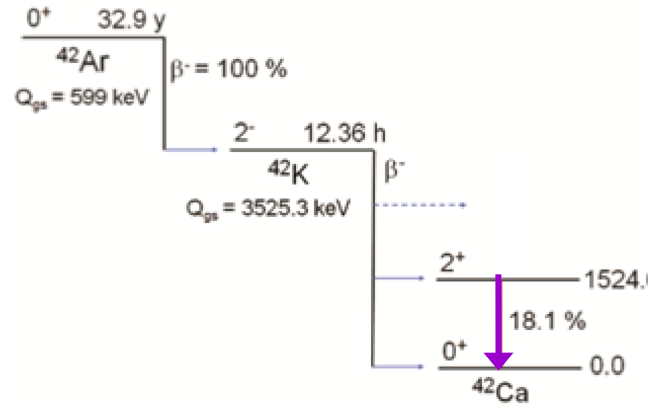

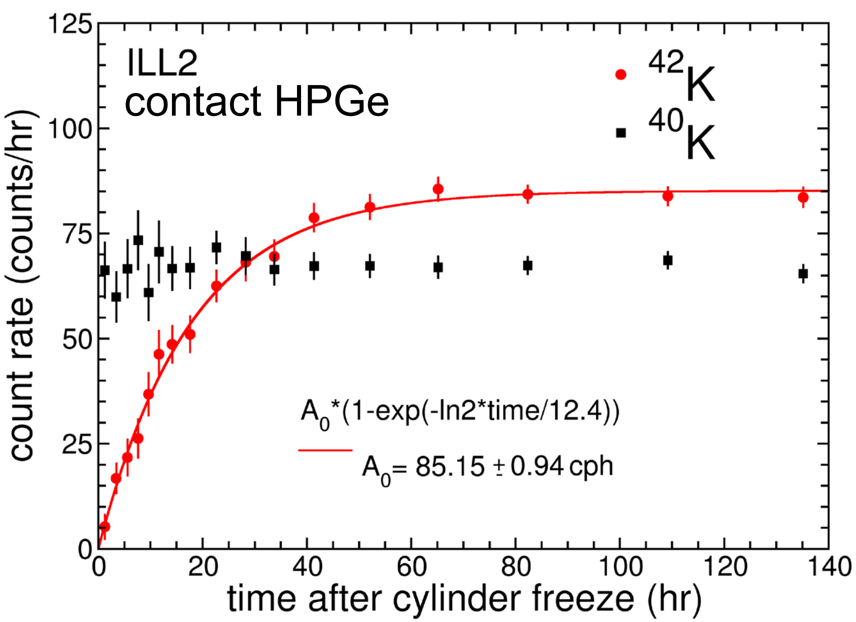

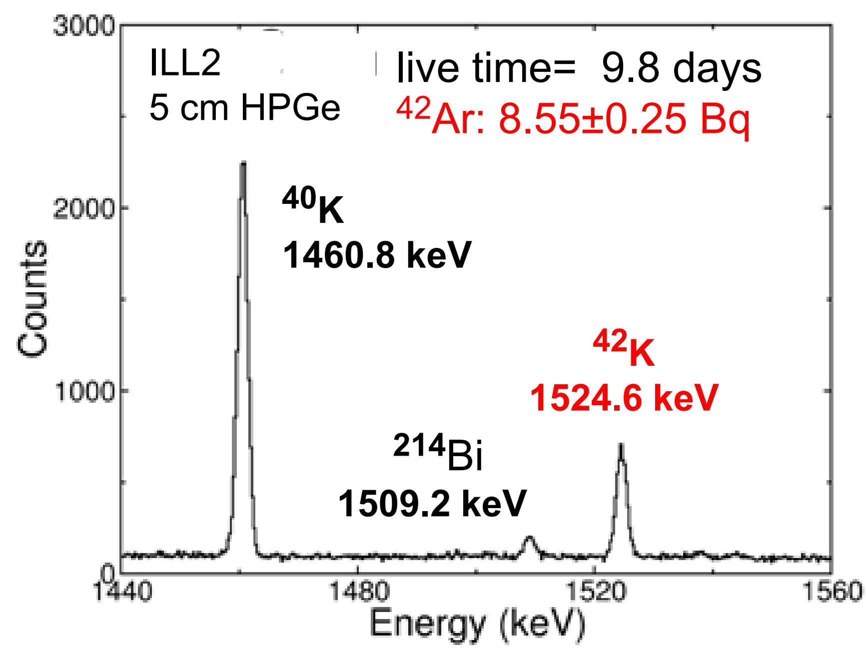

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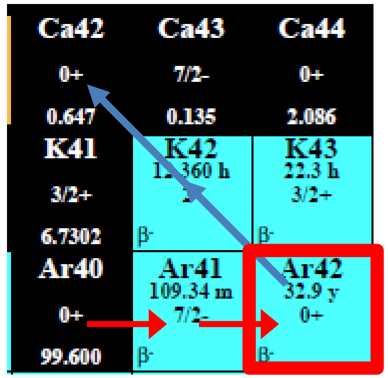
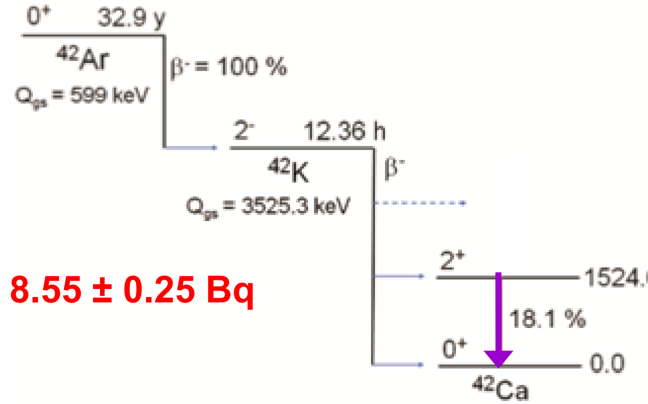




^{42}Ar= 8.55 ± 0.25 Bq

after quantitative dilution with ^{nat}Ar:

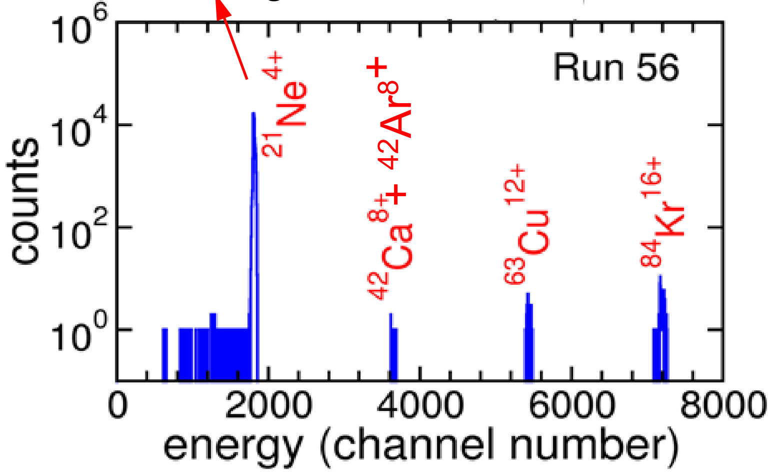
^{42}Ar/^{40}Ar (ILL2 calibration sample):

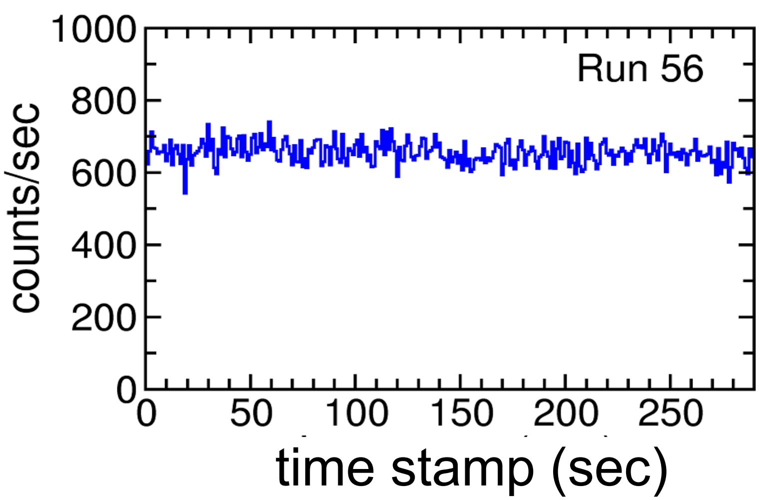
= $(1.16 \pm 0.05) \times 10^{-11}$

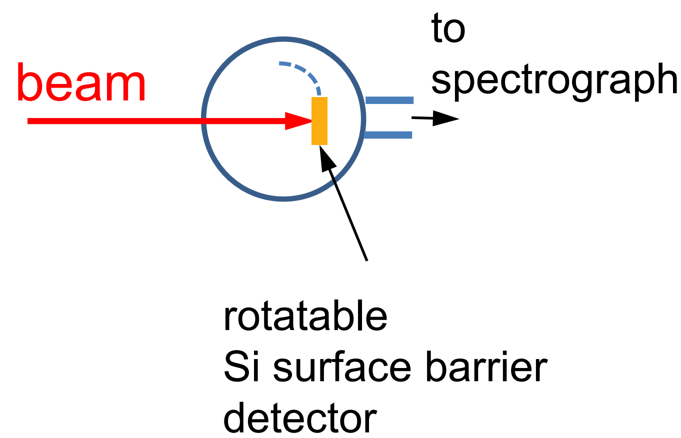
ILL2 shipped to Argonne for NOGAMS

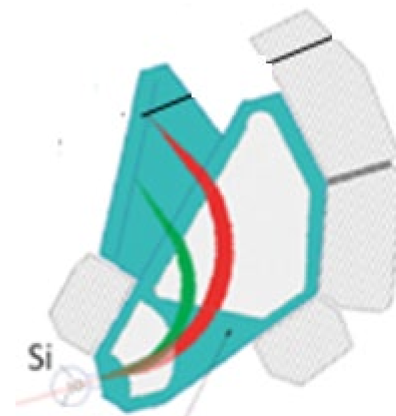
ILL2 sample at Argonne: ^{42}Ar tuning

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

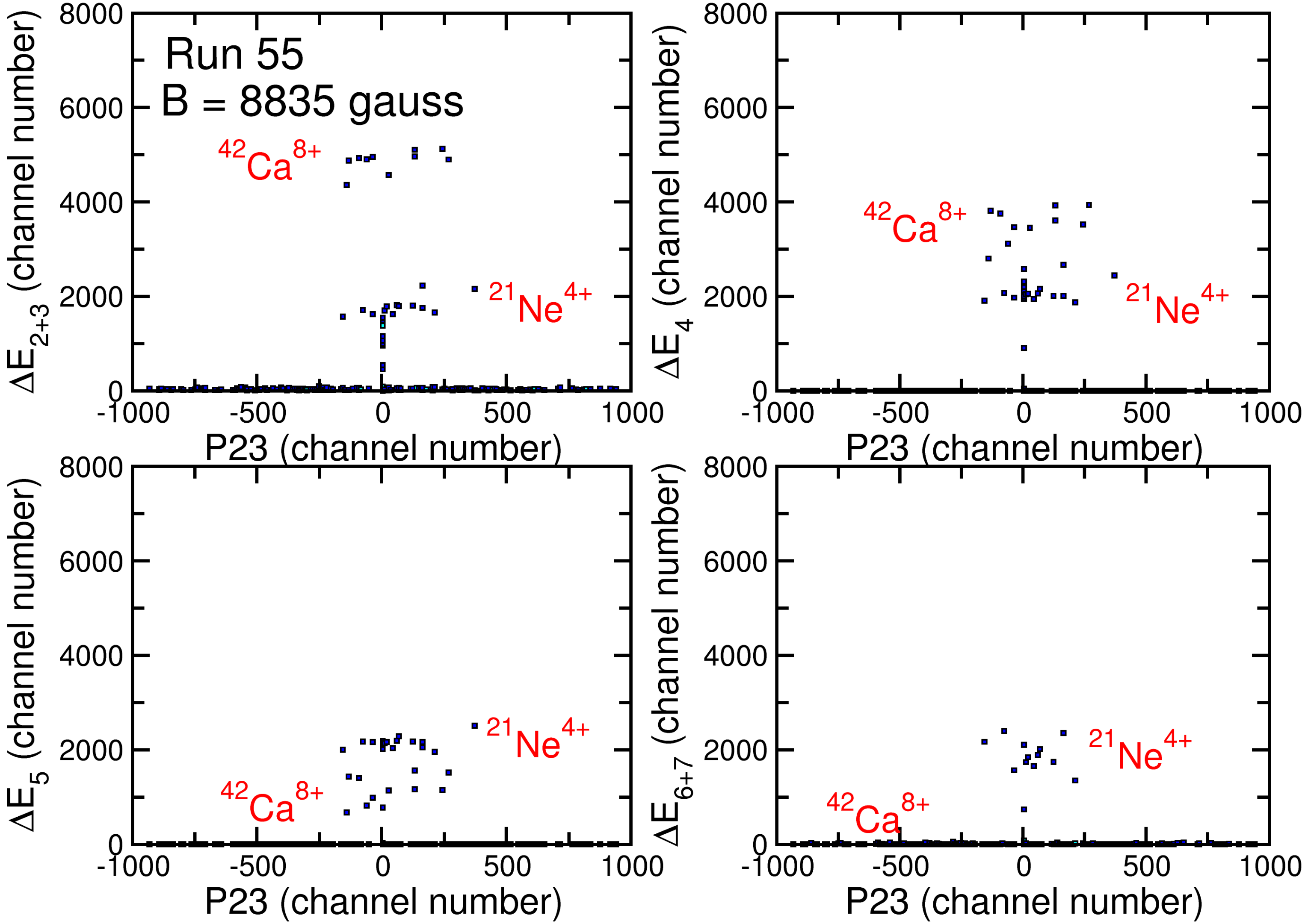






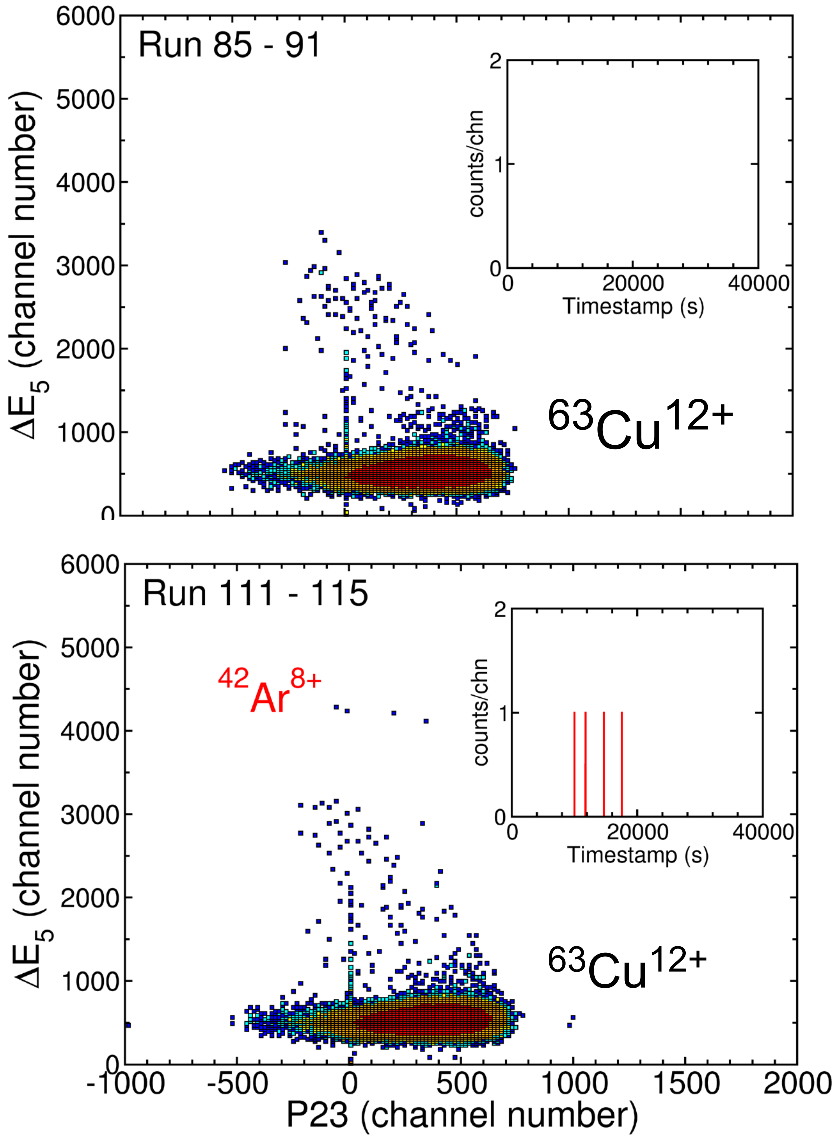


beam diagnostics



Run 55
B = 8835 gauss
42Ca8+
21Ne4+
ΔE2+3 (channel number)
ΔE4 (channel number)
ΔE5 (channel number)
ΔE6+7 (channel number)
P23 (channel number)
0
2000
4000
6000
8000
-1000
-500
0
500
1000

NIF sample N221002: 2023 experiment, same ^{42}Ar setting



Nov ‘24 experiment: dedicated to ^{42}Ar search

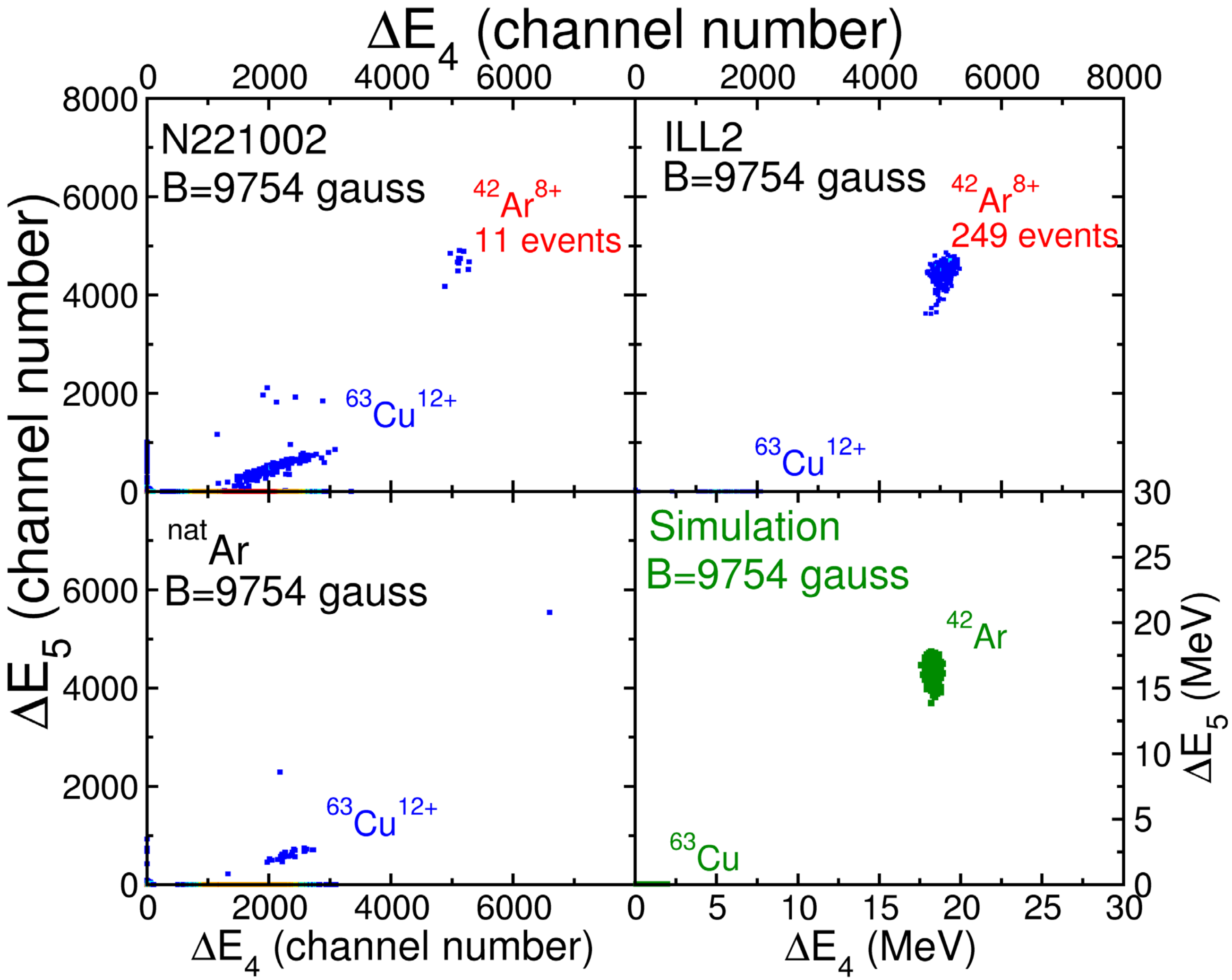
Timeline:

-11/11-20: Ion source was run with UHP (Ultra-High Purity) Ar gas and $^{40}Ar^{8+}$ monitored at ECR3 cup

-11/20-24: sample TR5B (NIF N221002), ^{42}Ar running, 53.5 h

-11/24-26: sample ^{nat}Ar (see below), ^{42}Ar running, 25.9 h

-11/26: ILL2 ^{42}Ar calibration sample, ^{21}Ne , ^{42}Ar running.



ΔE4 (channel number)
ΔE5 (channel number)
N221002
B=9754 gauss
42Ar8+
11 events
63Cu12+
ILL2
B=9754 gauss
42Ar8+
249 events
63Cu12+
natAr
B=9754 gauss
63Cu12+
Simulation
B=9754 gauss
42Ar
63Cu
ΔE4 (channel number)
ΔE4 (MeV)
ΔE5 (MeV)

Preliminary results summary

- ^{42}Ar unambiguously identified in sample N221002:

  $^{42}Ar/^{38}Ar = (1.0 \pm 0.3) \times 10^{-14}$

  $N(^{42}Ar) = 1.6 \pm 0.5 \times 10^{6}$ atoms

Extraneous presence of ^{42}Ar or crosstalk effects are ruled out.

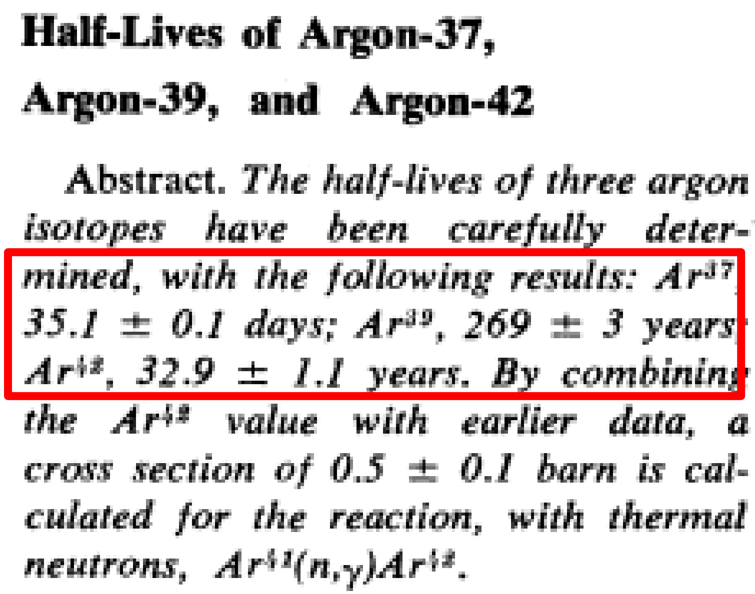
- ^{42}Ar calibration sample ILL2 OK:

  calibration (activity+dilution): $^{42}Ar/^{40}Ar = (1.17 \pm 0.05) \times 10^{-11}$

  NOGAMS: $^{42}Ar/^{40}Ar = (1.09 \pm 0.12) \times 10^{-11}$

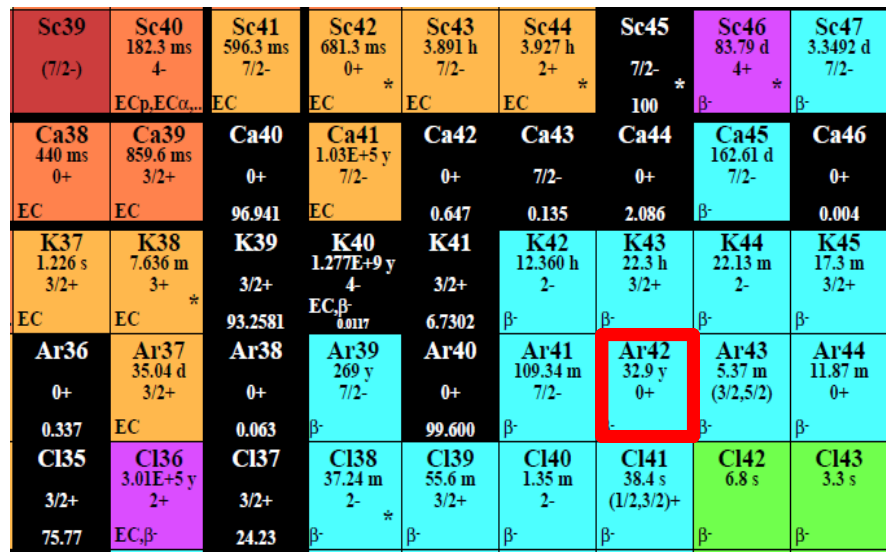
^{42}Ar: a “rare” nuclide

R. W. Stoenner, O. A. Schaeffer, S. Katcoff, Science (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, $Ar^{41}(n,\gamma)Ar^{42}$.*



^{42}A is extremely rare in nature

^{42}Ar/Ar in Earth atmosphere: ^{42}Ar/Ar= $9.2^{+2.2}_{-4.6} \times 10^{-21}$ (Barabash et al., 2016)

Neutron-induced reactions in a high-density inertial confinement plasma at National Ignition Facility

- *neutrons?*
- *high-density plasma?*
- *National Ignition Facility?*

- *proposal, experiment, results: a progress report*