Neutron-Induced Reactions in the High-Density NIF Plasma and Their Nuclear Astrophysics Nexus

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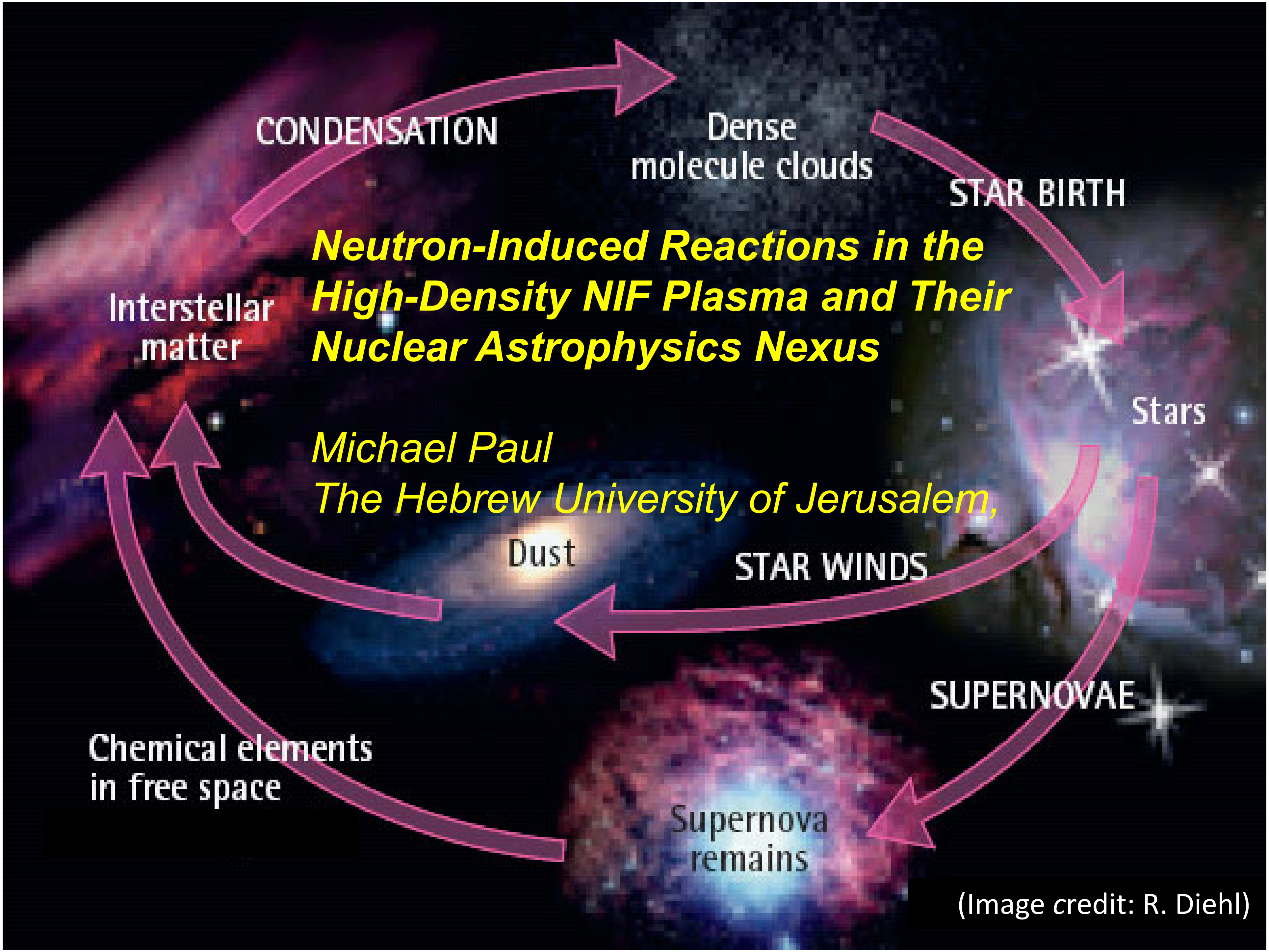
The Hebrew University of Jerusalem,



(Image credit: R. Diehl)

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UNIVERSITY OF NOTRE DAME

NEUTRONS FOR SOCIETY

TUD

HZDR HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

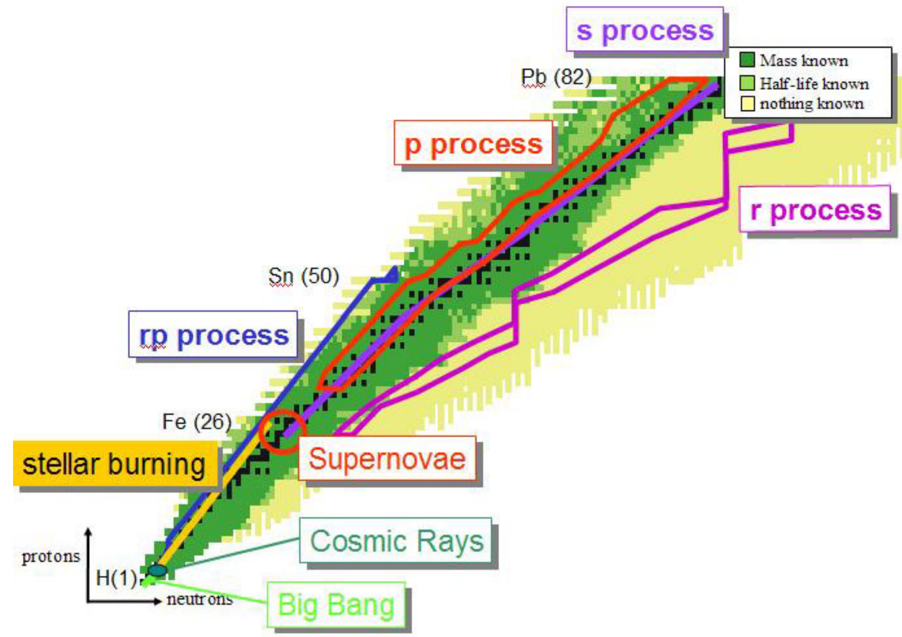
u b UNIVERSITÄT BERN

Introduction:

Neutron capture:

Elements beyond ^{56}Fe are mainly produced by neutron capture reactions:

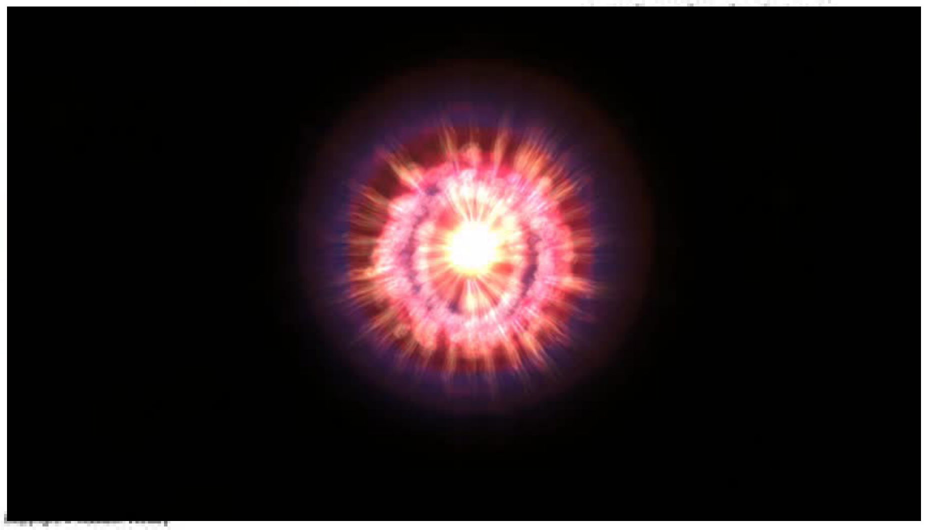
$$n + {}^{A}_{Z}X \rightarrow {}^{A+1}_{Z}X^{*} + \gamma$$



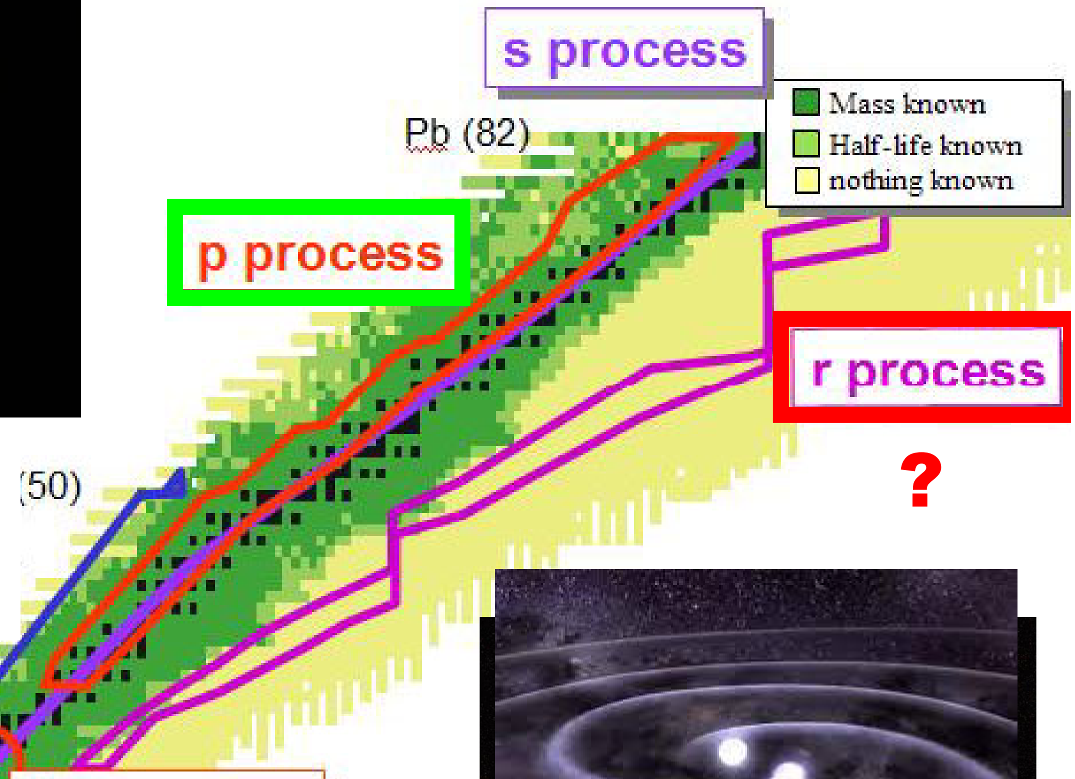
1. Slow neutron capture(s-process)
   - n-capture rate < β–decay constant
   - n-density ~ $10^{7\text{-}13}$ cm^{-3} , T ~ 0.1- 0.3 GK
   - Isotopes along ß-stability valley
   - Massive stars, AGB stars (0.5 - 8 $M_{\odot}$)

2. Rapid neutron capture (r-process)
   - n-capture rate > β–decay constant
   - n-density ≳ 10^{24} cm^{-3} , T ~ 1 GK
   - Isotopes along the neutron drip line
   - Supernova explosion, neutron star merger and black hole accretion disk

- Cameron, A. G.W., “Stellar evolution, nuclear astrophysics, and nucleogenesis,” Report No. CRL-41 (Chalk River) (1957)
- Burbidge, E. M., G. R. Burbidge, W. A. Fowler, and F. Hoyle, “Synthesis of the elements in stars,” Rev. Mod. Phys. 29, 547–650 (1957)



Heavy elements (A>56) are mainly produced via neutron captures



SN1998aa

The High-Density NIF Plasma

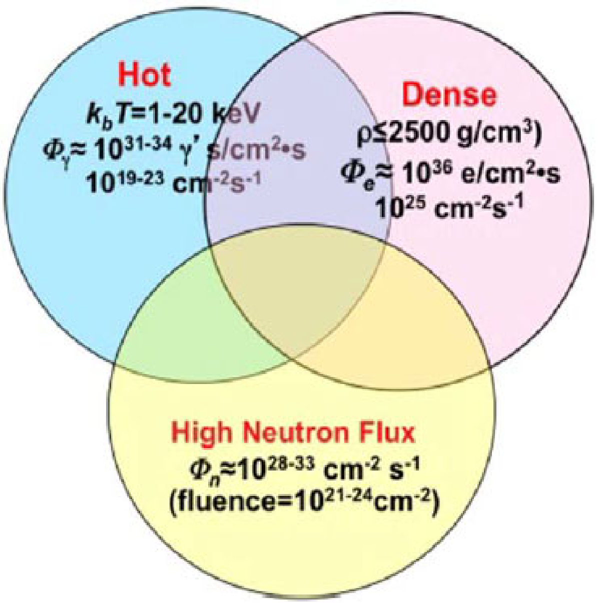
The closest analog to explosive stellar conditions in the laboratory and the closest neutron analog

$\rho_n \sim 10^{19\text{-}22}$ n cm^{-3}

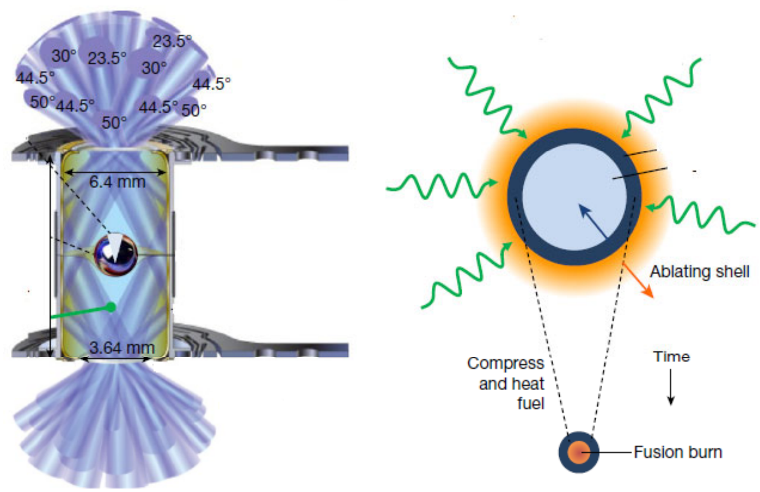
$\Phi_n \Delta t \sim 10^{21\text{-}24}$ n cm^{-2}

to astrophysical

r-process: $\rho_n = 10^{24}$ n cm^{-3}



from: Ch. J. Cerjan et al. (2018)



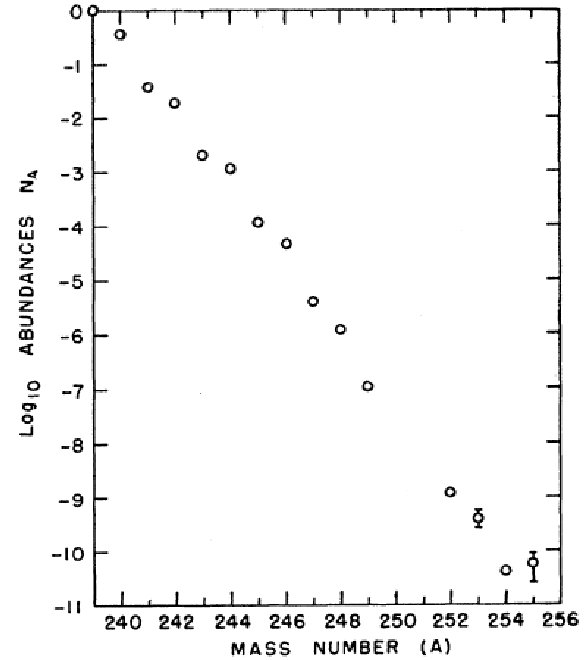
from: A. Zylstra et al. (2022)

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

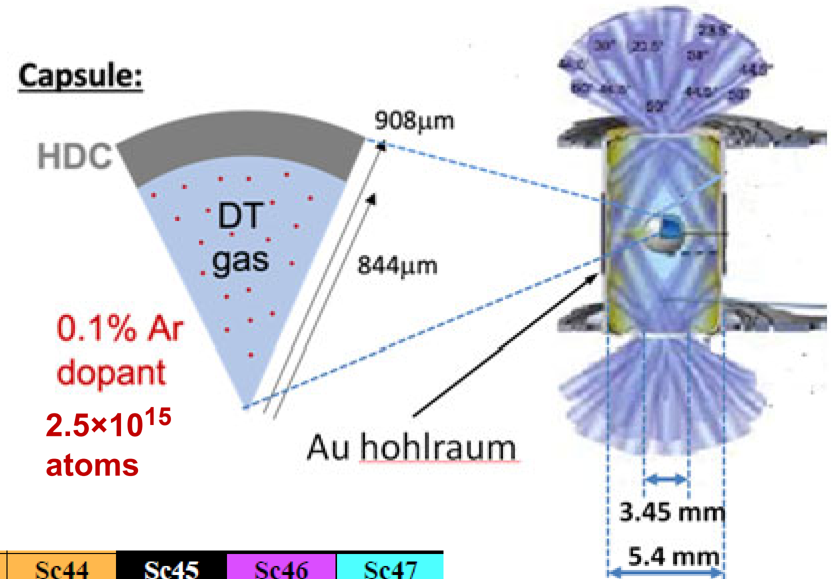
and

C. I. Browne, H. L. Smith, and R. W. Spence
Los Alamos Scientific Laboratory, Los Alamos, New Mexico

(Received May 2, 1960)

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

Choice of Ar:
- noble gas for reliable collection
- three long-lived isotopes
  search for ^{39,41,42}**Ar** reachable by
  neutron-induced reactions:
- ^{41}**Ar: γ spectromtery**
- ^{39,42}**Ar: accelerator mass spec (AMS)**
- use rare ^{38}**Ar as tracer**
  for collection of Ar isotope
  products

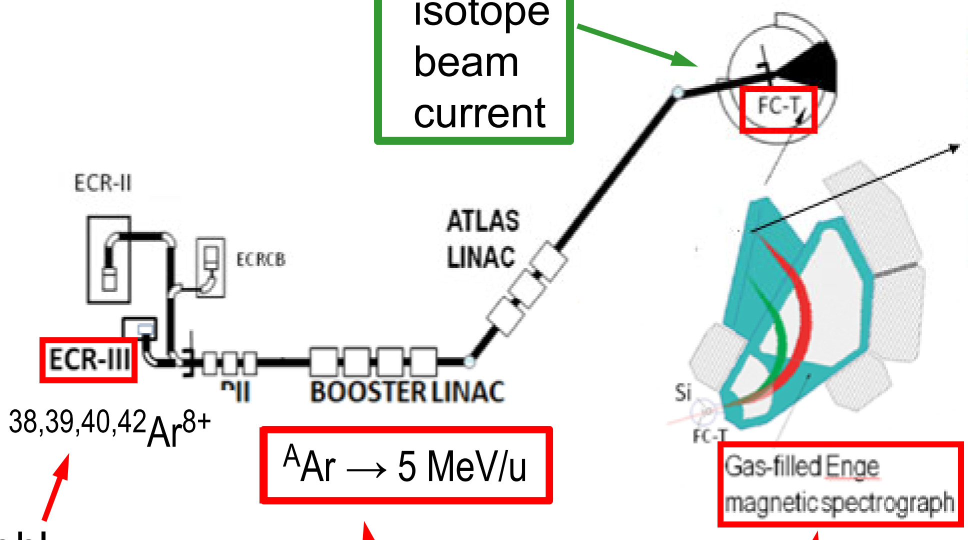


Sc39 (7/2-)	Sc40 182.3 ms 4- ECp,ECα,...	Sc41 596.3 ms 7/2- EC	Sc42 681.3 ms 0+ * EC	Sc43 3.891 h 7/2- EC	Sc44 3.927 h 2+ * EC	Sc45 7/2- * 100	Sc46 83.79 d 4+ * β-	Sc47 3.3492 d 7/2- β-
Ca38 440 ms 0+ EC	Ca39 859.6 ms 3/2+ EC	Ca40 0+ 96.941	Ca41 1.03E+5 y 7/2- EC	Ca42 0+ 0.647	Ca43 7/2- 0.135	Ca44 0+ 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-	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-

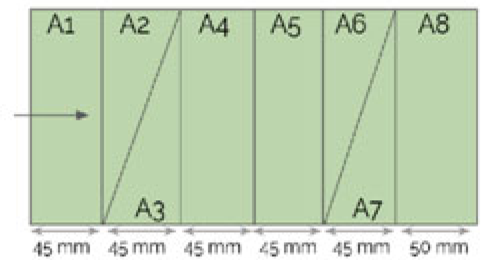
^{42}**Ar** motivation:
^{40}Ar(2n,γ)^{42}Ar,
a “mini-r process”

Noble gas accelerator mass spectrometry (NOGAMS) at ATLAS (Argonne): a brief

stable isotope beam current



N$_2$ 10 Torr



ionization chamber

CF_4 39.5 Torr

ion counting and identification by multiple ΔE measurements

highly-charged positive ions

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

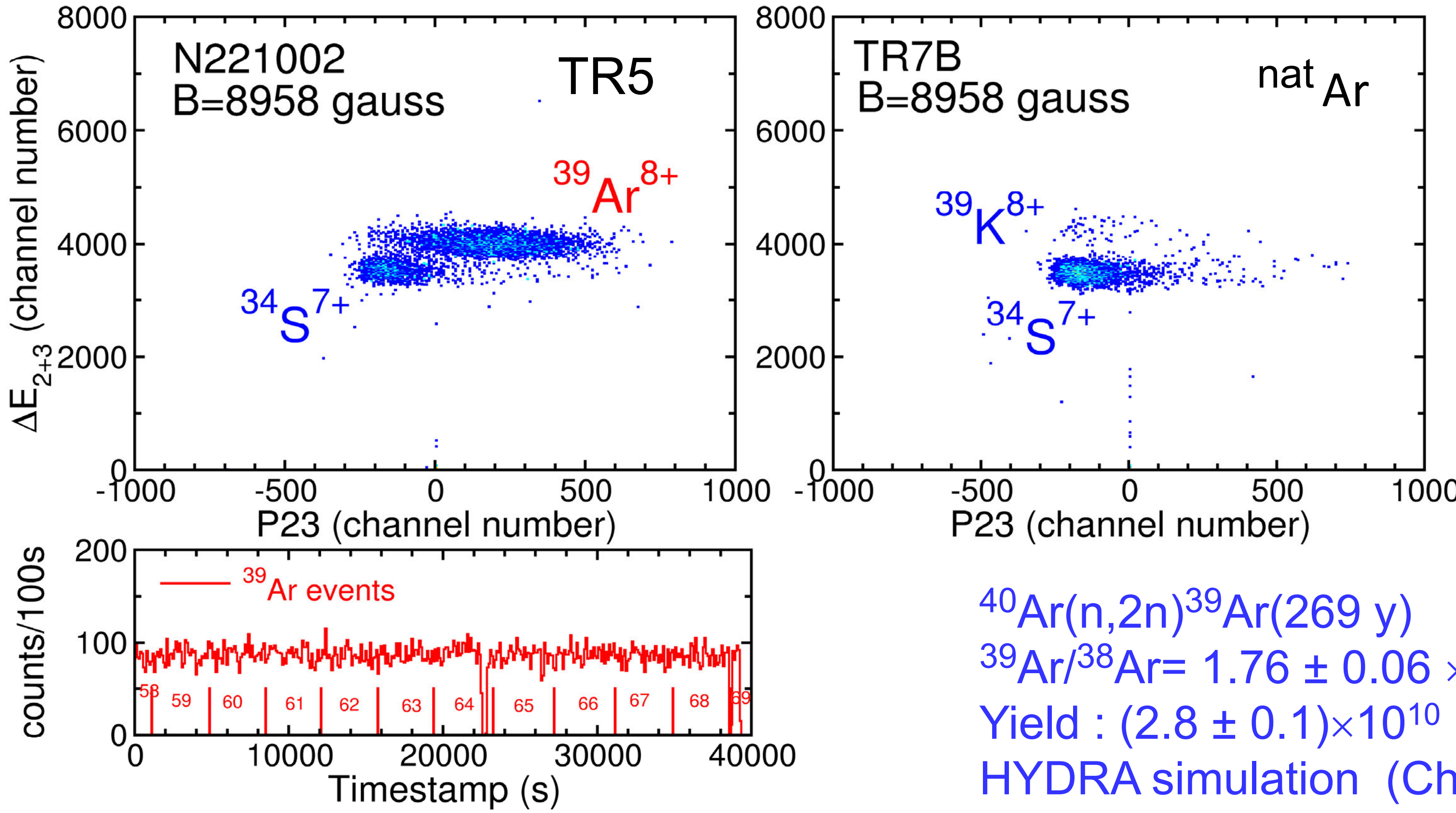
dispersion by <q>: separation of isobars and parasitic ions

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

Shot N221002

Oct '23 experiment: the $^{40}Ar(n,2n)^{39}Ar$ reaction

$Y_n = 1.5\times10^{15}$



$^{40}Ar(n,2n)^{39}Ar$(269 y)

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

Yield : $(2.8 \pm 0.1)\times10^{10}$ ^{39}Ar atoms

HYDRA simulation (Ch. Cerjan):

3.3×10^{10} ^{39}Ar atoms.

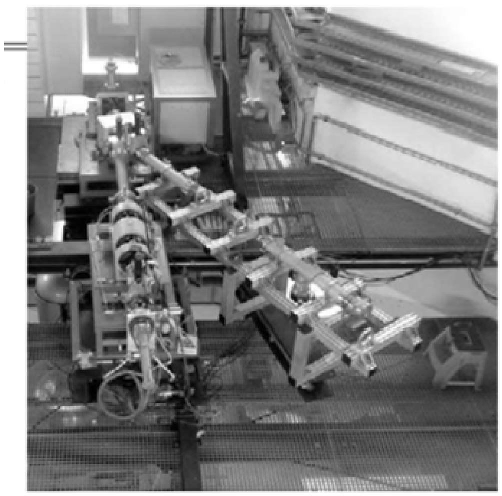
Auxilliary experiments: - production of ^{39}Ar by ^{38}Ar(n_{th},g)^{39}Ar
- ^{40}Ar(n,2n)^{39}Ar first cross section measurement (14 MeV)

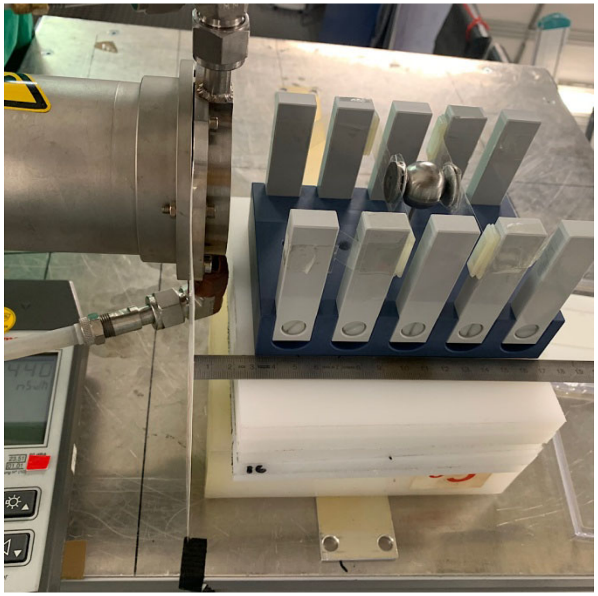
^{38}Ar(n_{th},γ)^{39}Ar, thermal neutrons at Soreq NRC (Israel)
^{40}Ar(n,2n)^{39}Ar, 14 MeV neutrons, TU Dresden/Helmholtz Zenter Dresden Rossendorf (HZDR)

T(D,n)^{4}He reaction at HZDR
~ 6.6(1)×10^{11} n/cm^2
4.5 hours

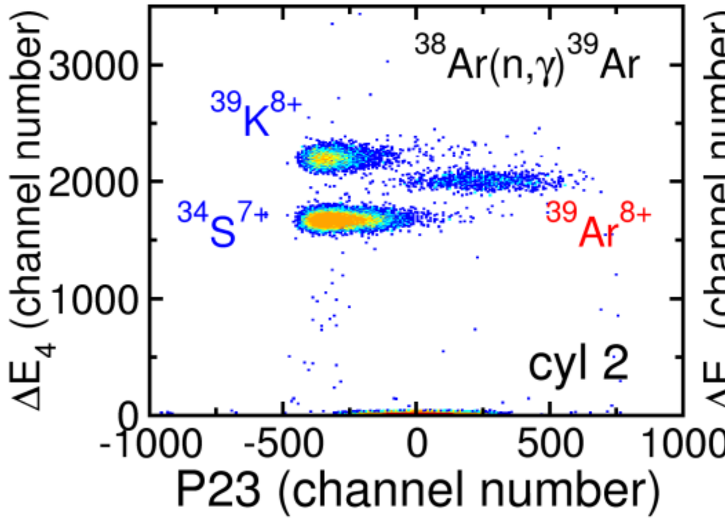
sphere: stainless steel
volume: 4.18 cm^3
content : ^{40}Ar (5N) gas
pressure: 20 bar

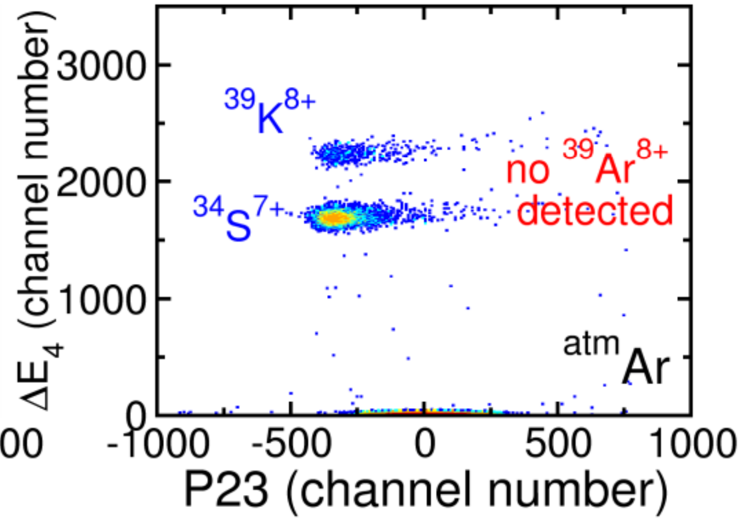
fast-neutron monitors:
^{27}Al, ^{93}Nb

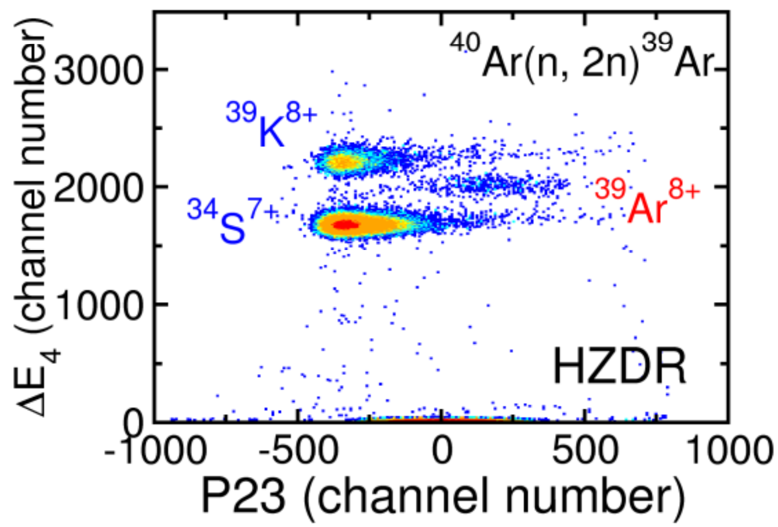


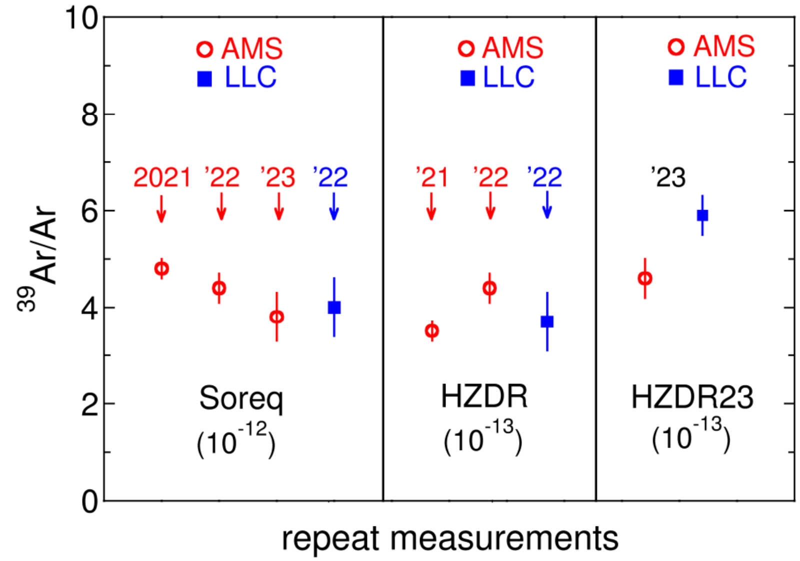


Auxilliary experiments: production of ^{39}Ar by $^{38}Ar(n_{th},g)^{39}Ar$
$^{40}Ar(n,2n)^{39}Ar$ cross section measurement (14 MeV)

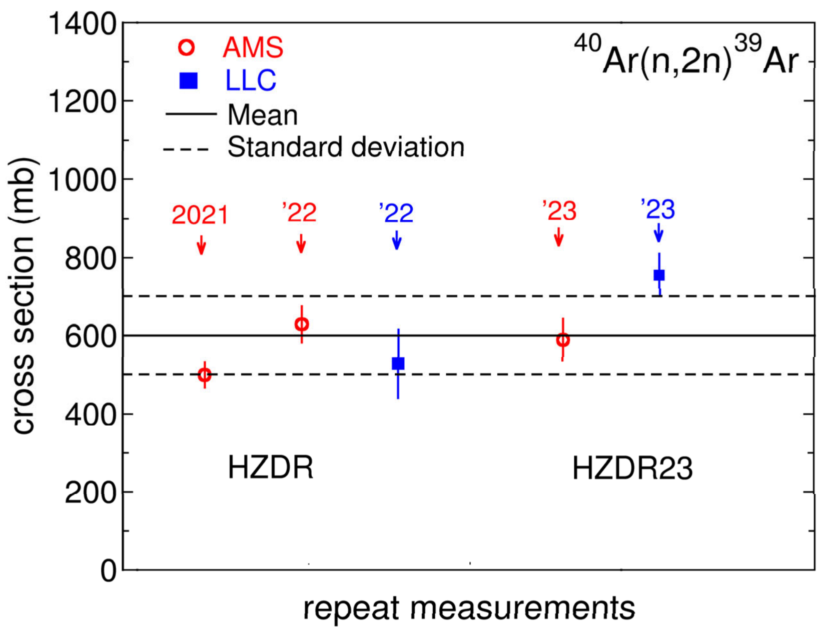








LLC: Low-Level Counting,
U. of Bern



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

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

TENDL23: 579 mb

^{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

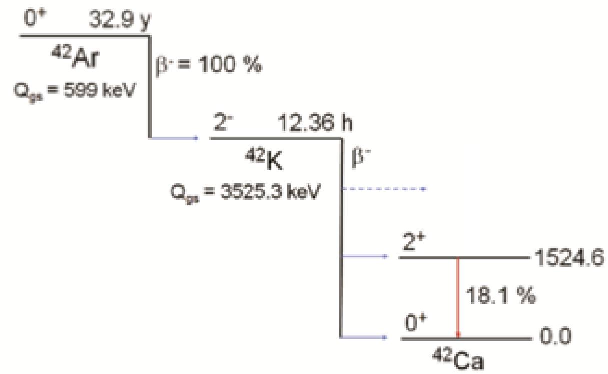
Abstract. *The half-lives of three argon isotopes have been carefully determined, with the following results: Ar^{37} 35.1 ± 0.1 days; Ar^{39}, 269 ± 3 years; Ar^{42}, 32.9 ± 1.1 years. By combining the Ar^{42} value with earlier data, a cross section of 0.5 ± 0.1 barn is calculated for the reaction,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

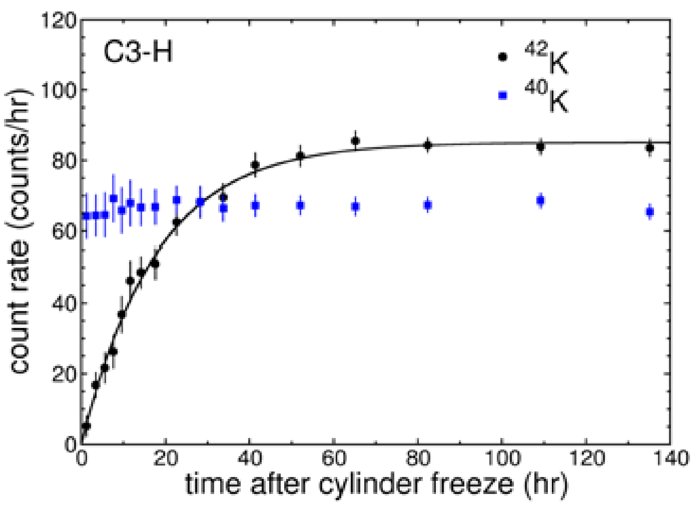
Sc39 (7/2-)	Sc40 182.3 ms 4- ECp,ECα,...	Sc41 596.3 ms 7/2- EC	Sc42 681.3 ms 0+ * EC	Sc43 3.891 h 7/2- EC	Sc44 3.927 h 2+ * EC	Sc45 7/2- * 100	Sc46 83.79 d 4+ * β-	Sc47 3.3492 d 7/2- β-
Ca38 440 ms 0+ EC	Ca39 859.6 ms 3/2+ EC	Ca40 0+ 96.941	Ca41 1.03E+5 y 7/2- EC	Ca42 0+ 0.647	Ca43 7/2- 0.135	Ca44 0+ 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-

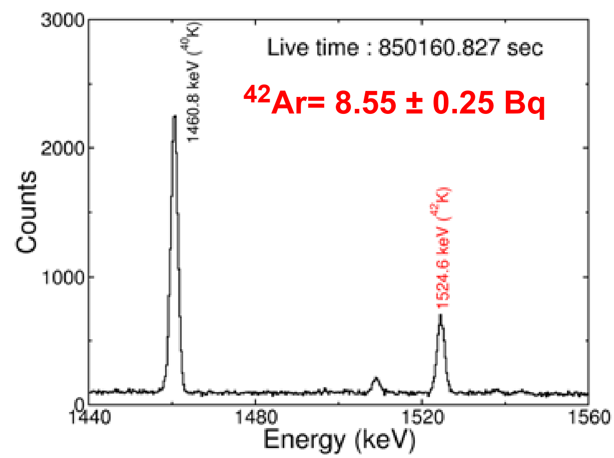
^{42}A is extremely rare in nature

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

A unique ^{42}Ar calibration sample was produced at the high-flux reactor of Institut Laue-Langevin (Grenoble, France) at $\Phi_n = 1.0 \times 10^{15}$ cm^{-2} s^{-1}
4.7 days irradiation in a quartz ampoule: ^{40}Ar(n,γ)^{41}Ar(n,γ)^{42}Ar(32.9 y)





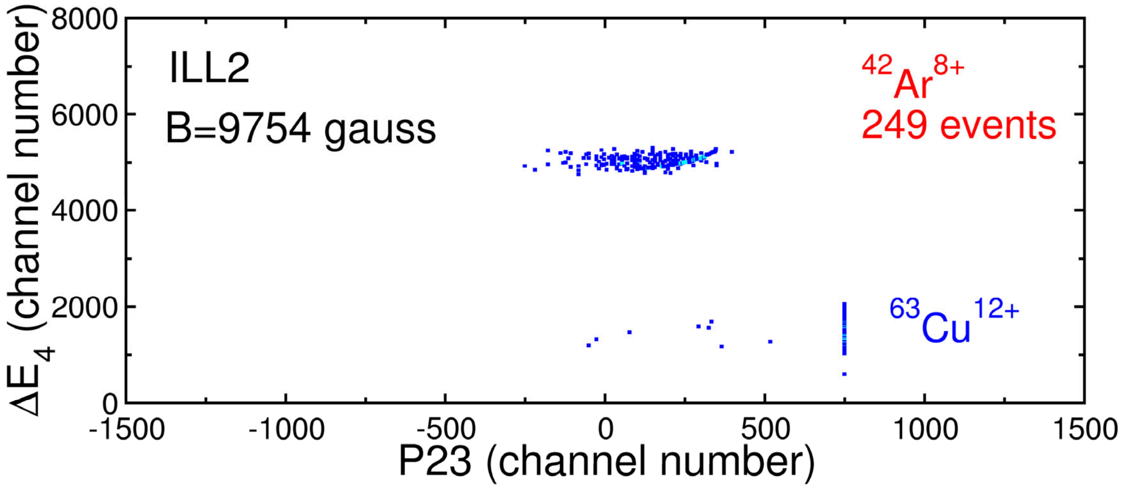


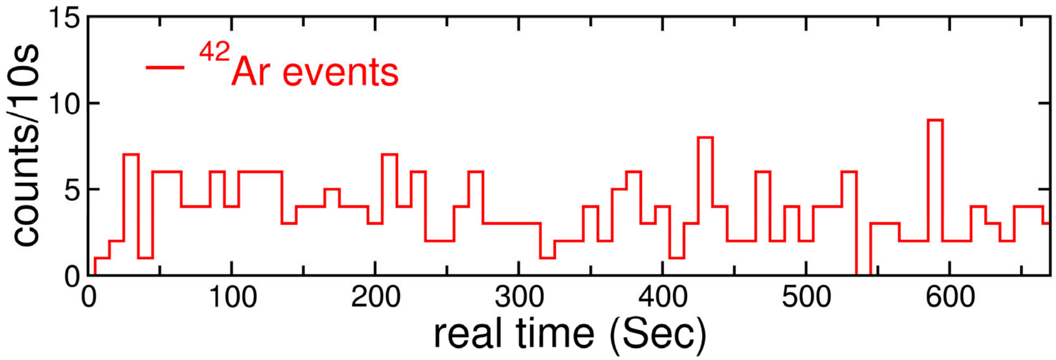
after quantitative dilution with ^{nat}Ar:
^{42}Ar/^{40}Ar (ILL2 calibration sample):
$(1.17 \pm 0.05) \times 10^{-11}$

ILL2: ^{42}Ar NOGAMS calibration sample

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

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



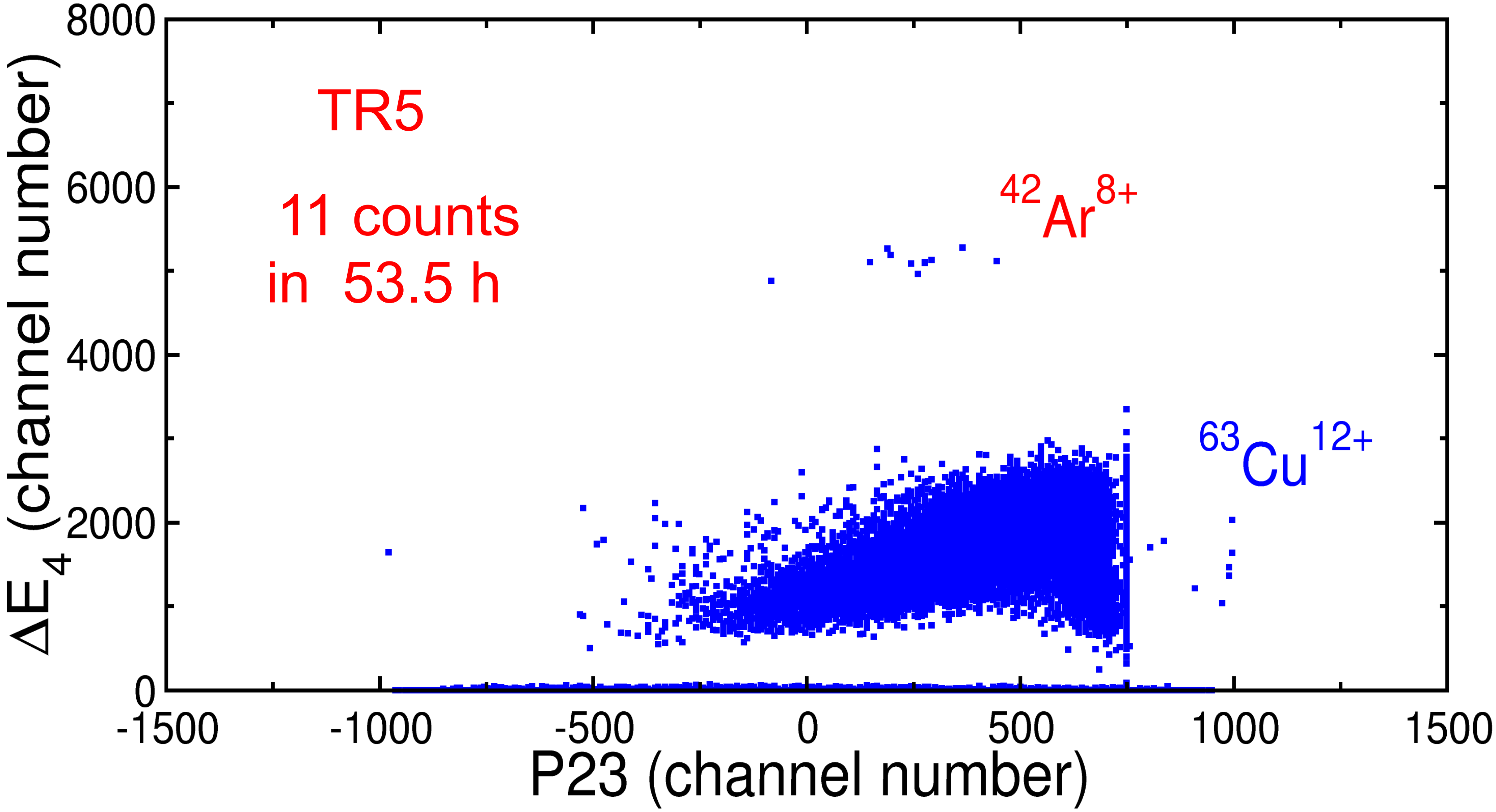


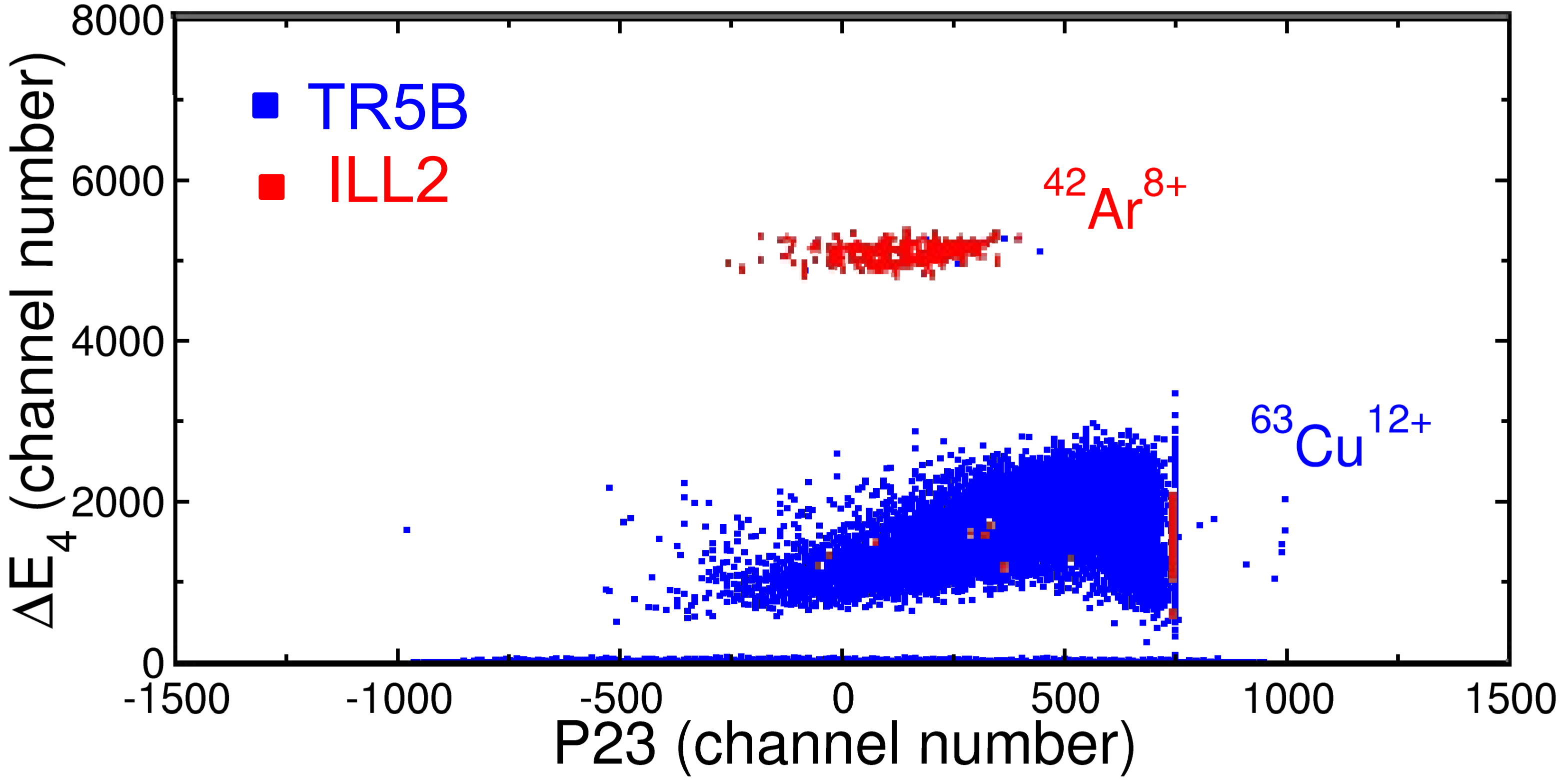
$t_{1/2}(^{42}Ar)$ (AMS)= 30.8 ± 4.9 yr

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

TR5 sample: NIF sample N221002

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





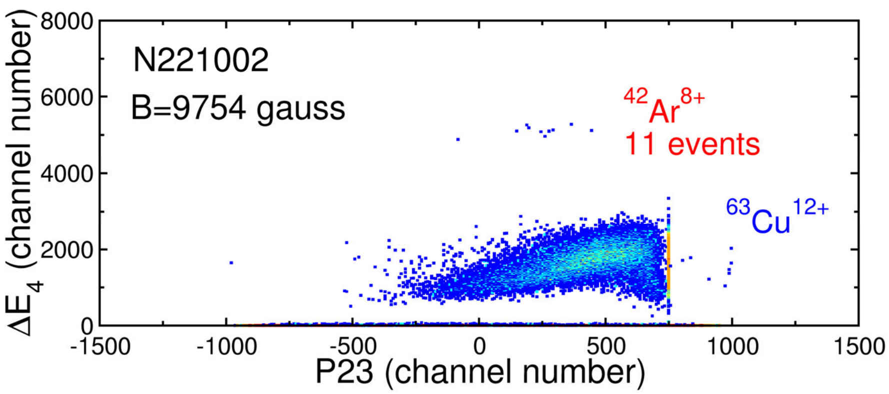
TR5B
ILL2
$^{42}Ar^{8+}$
$^{63}Cu^{12+}$
8000
6000
4000
2000
0
-1500
-1000
-500
0
500
1000
1500
ΔE_4 (channel number)
P23 (channel number)

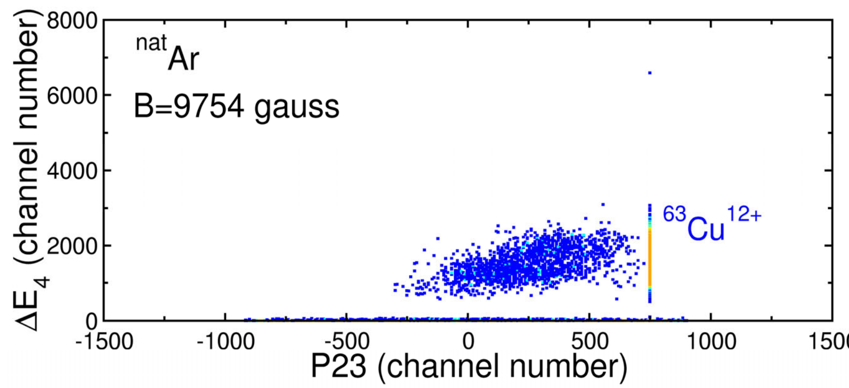
Preliminary results

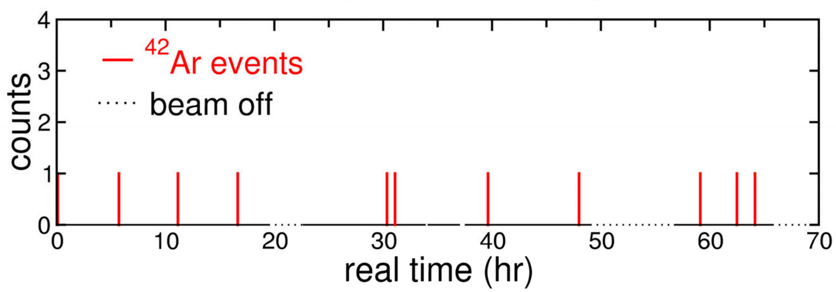
$^{42}Ar/^{38}Ar = (1.0 \pm 0.3) \times 10^{-14}$

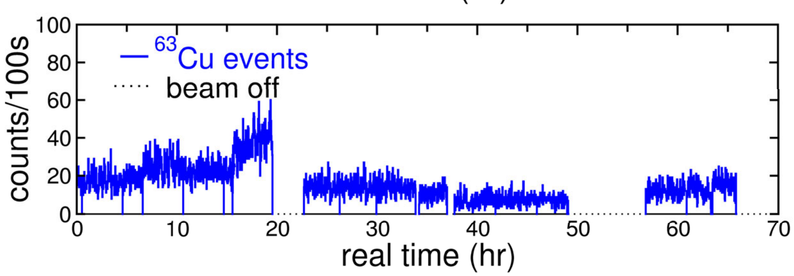
$N(^{42}Ar, TR5) = 1.6 \pm 0.5 \times 10^{6}$ atoms

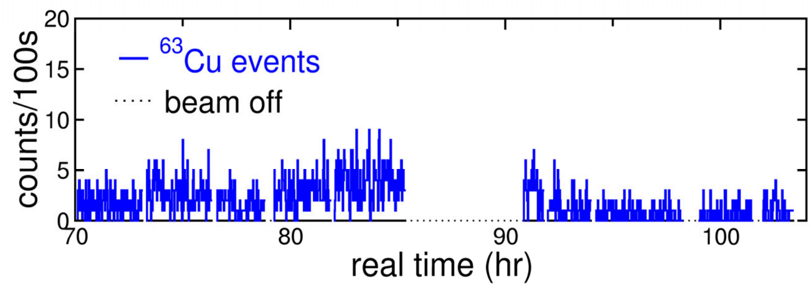
- 11 counts of ^{42}Ar from TR5 sample during a 53.5-hour run: **1.0 ct/5 h**
- 0 ^{42}Ar counts for UHP Ar during a 25.9-hour run: **< 0.2 ct/5h**











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

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

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

Summary

1. Good agreement between HYDRA simulation and NOGAMS data of N221002 for $^{40}Ar(n,2n)^{39}Ar$. Independent measurement of the $^{40}Ar(n,2n)^{39}Ar$ reaction, in good agreement with recent calculations

2. Slight discrepancy between HYDRA simulation and NOGAMS data for ^{41}Ar

3. The origin of the ^{42}Ar events observed in N221002 is under investigation:

- the number of events (1.6×10^6 ^{42}Ar atoms) is incompatible with HYDRA simulations

Note: The $^{41}Ar(n,\gamma)^{42}Ar$ THERMAL cross section was measured as 400 mb via the calibration sample ILL2. Can neutrons capture on $^{41}Ar^*$ isomeric/excited states alive during the dense medium phase?

- the charged particle two-neutron transfer candidate $^{40}Ar(t,p)^{42}Ar$ requires a tertiary reaction by upscattered tritons e.g. $d(t,\alpha)n(t,n')t'(^{40}Ar,p)^{42}Ar$

4. The result requires confirmation by an **independent measurement**