EMMI Workshop and International Workshop LI on
Nucleosynthesis of Heavy Elements: r-process

Solar r-process abundances and direct neutron-capture measurements on radioactive isotopes

César Domingo Pardo
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MINISTERIO DE CIENCIA E INNOVACIÓN
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Plan de Recuperación, Transformación y Resiliencia
AGENCIA ESTATAL DE INVESTIGACIÓN
European Research Council

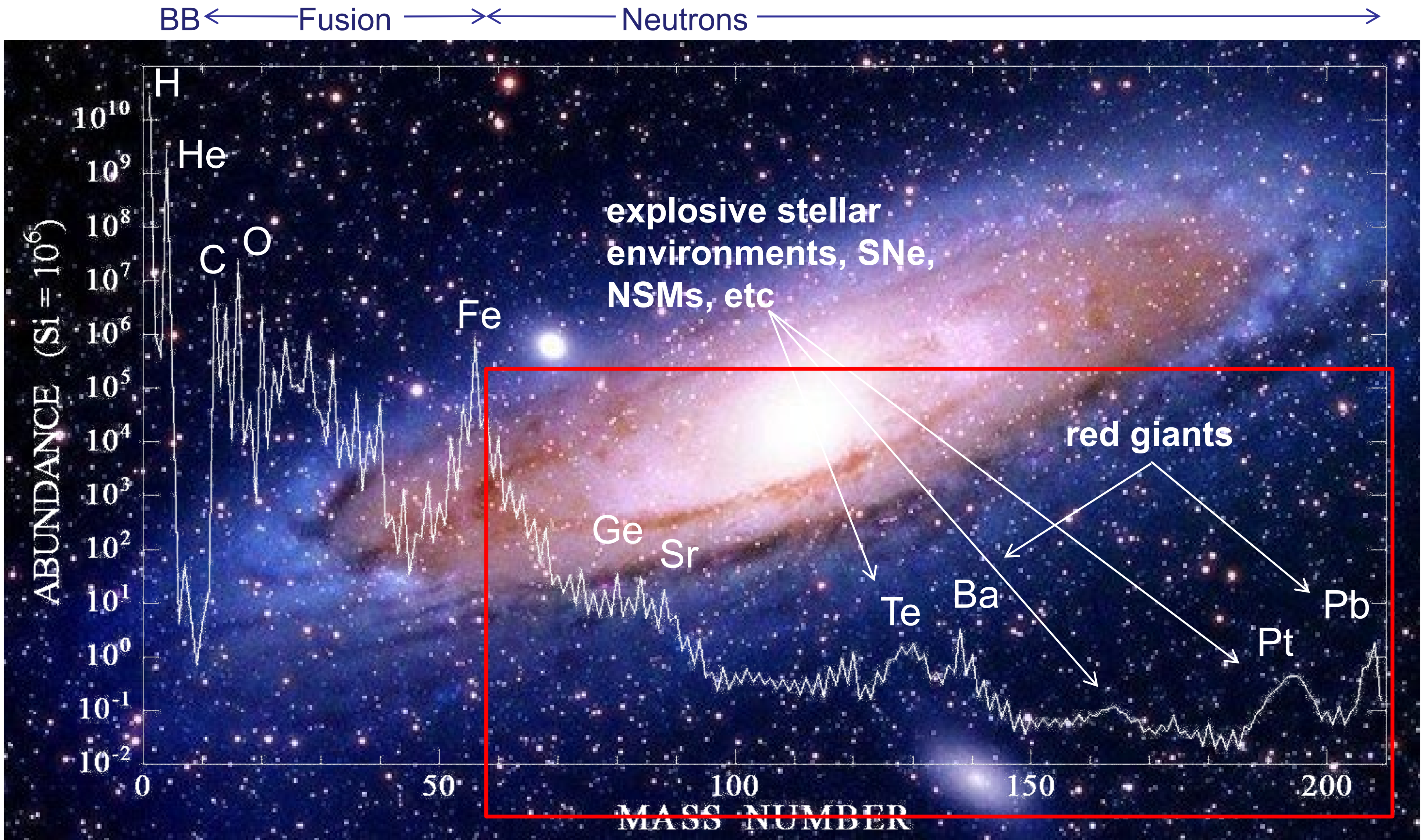
Outline

- R-process (solar) isotopic abundances require accurate neutron-capture measurements along the s-process path on stable <u>and unstable</u> isotopes

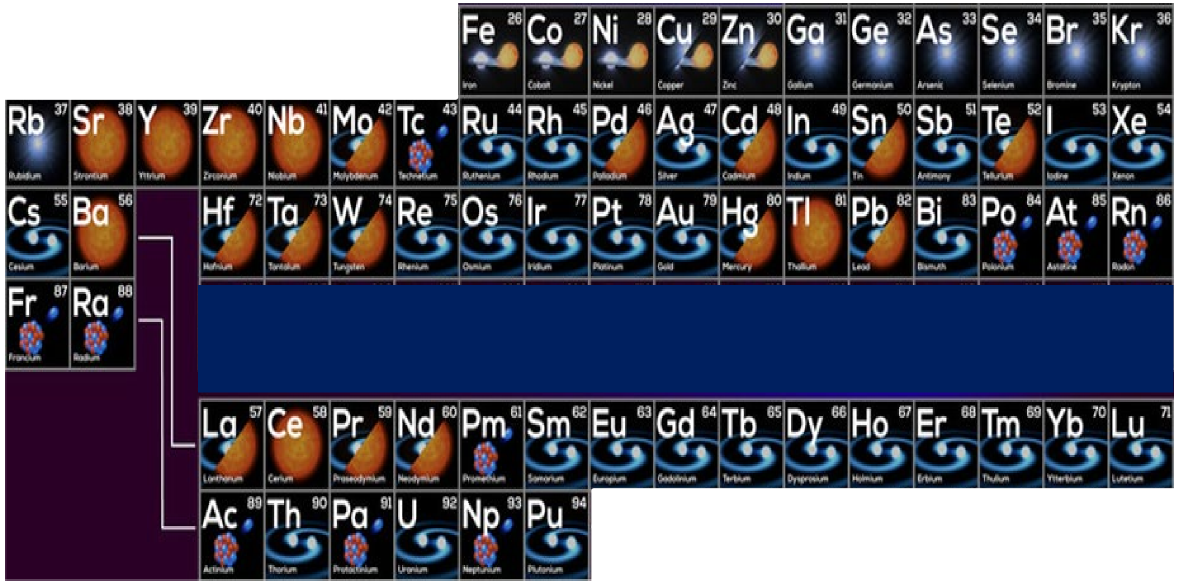
- How far are we from direct neutron capture experiments as input for r-process model calculations?

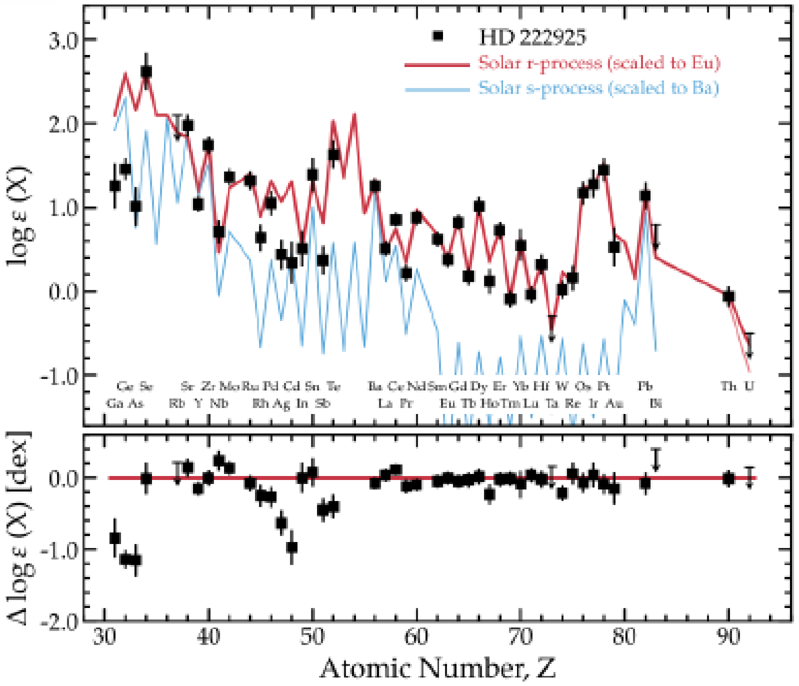
Neutrons in the Universe

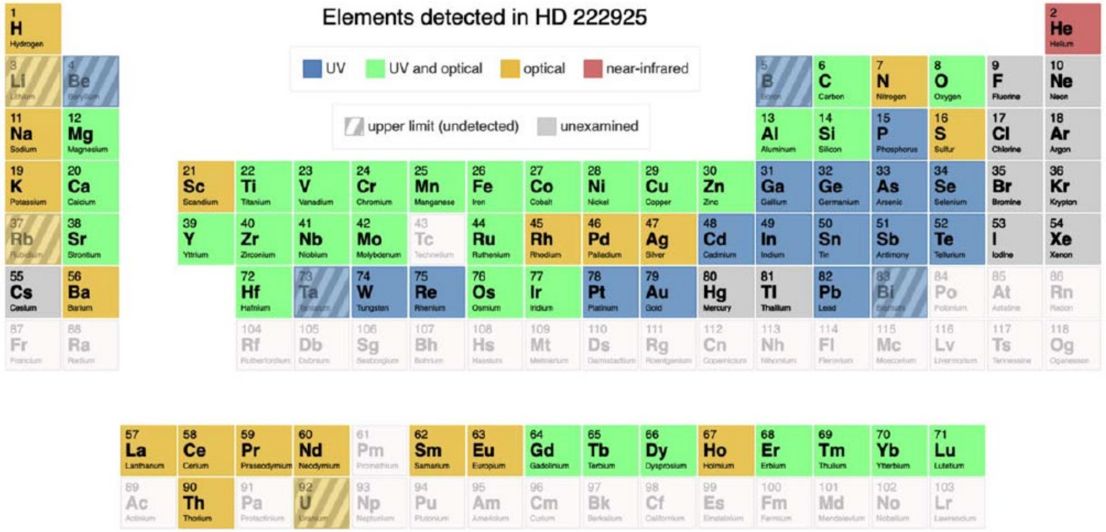
→ **Neutrons produce 75% of all the elements (!)**



Elemental (r-process) abundances





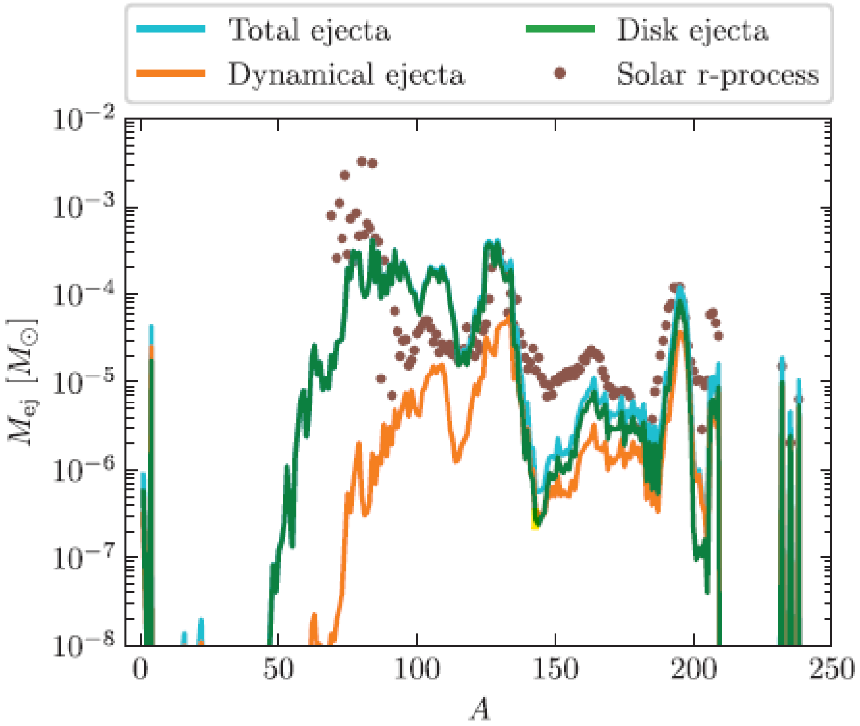


The Astrophysical Journal Supplement Series, 260:27 (29pp), 2022 June https://doi.org/10.3847/1538-4365/ac5cbc

The R-process Alliance: A Nearly Complete R-process Abundance Template Derived from Ultraviolet Spectroscopy of the R-process-enhanced Metal-poor Star HD 222925*

Ian U. Roederer[1,2], James E. Lawler[3], Elizabeth A. Den Hartog[3], Vinicius M. Placco[4], Rebecca Surman[2,5], Timothy C. Beers[2,5], Rana Ezzeddine[2,6], Anna Frebel[2,7], Terese T. Hansen[8], Kohei Hattori[9,10], Erika M. Holmbeck[2,11], and Charli M. Sakari[12]

Isotopic (r-process) abundances



Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 533, 2096–2112 (2024)
https://doi.org/10.1093/mnras/stae1979
Advance Access publication 2024 August 20

Impact of nuclear matter properties on the nucleosynthesis and the kilonova from binary neutron star merger ejecta

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[1]Institut für Kernphysik, Technische Universität Darmstadt, Schlossgartenstr 2, D-64289 Darmstadt, Germany
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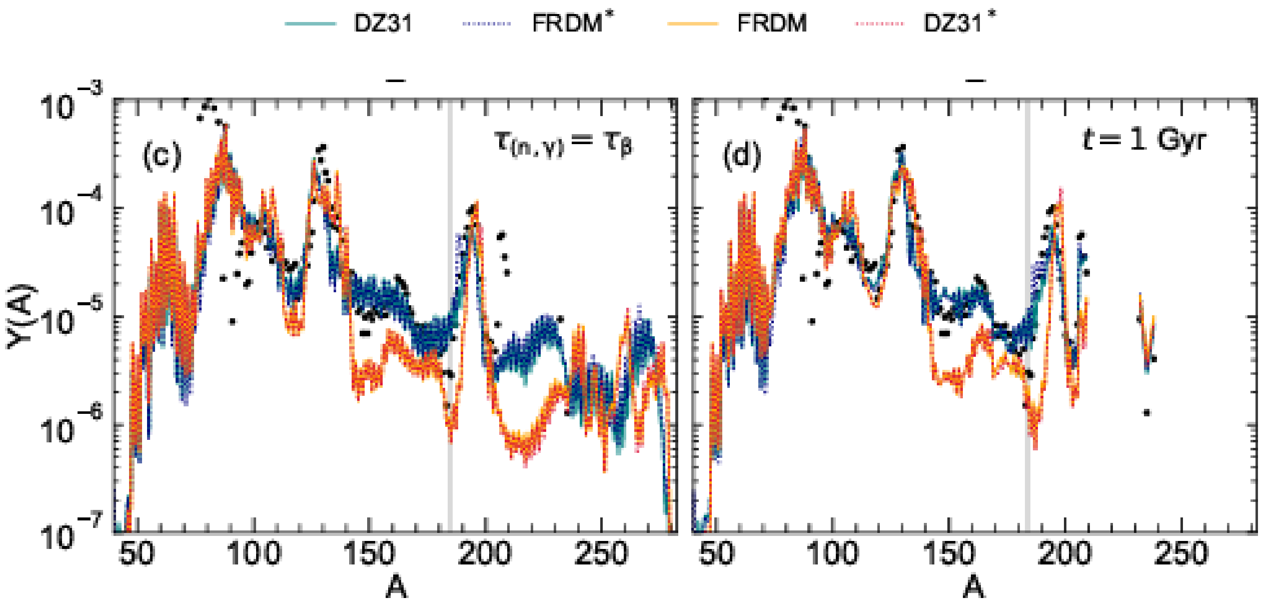

Impact of nuclear masses on r-process nucleosynthesis: bulk properties versus shell effects

Samuel A. Giuliani[1,*] Gabriel Martínez-Pinedo[2,3,4,†] Andreas Bauswein[2,4,‡] and Vimal Vijayan[2,§]
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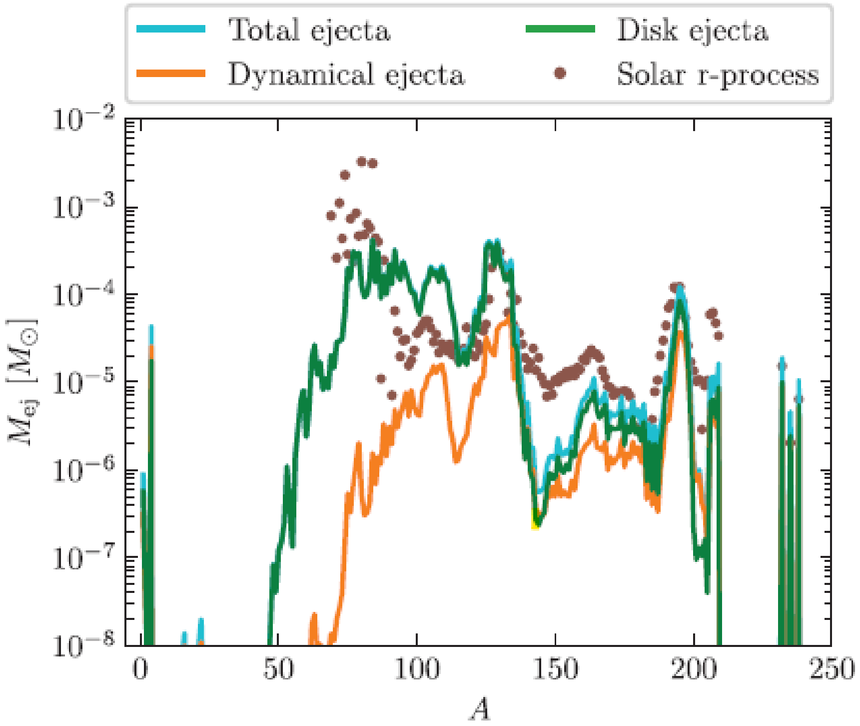
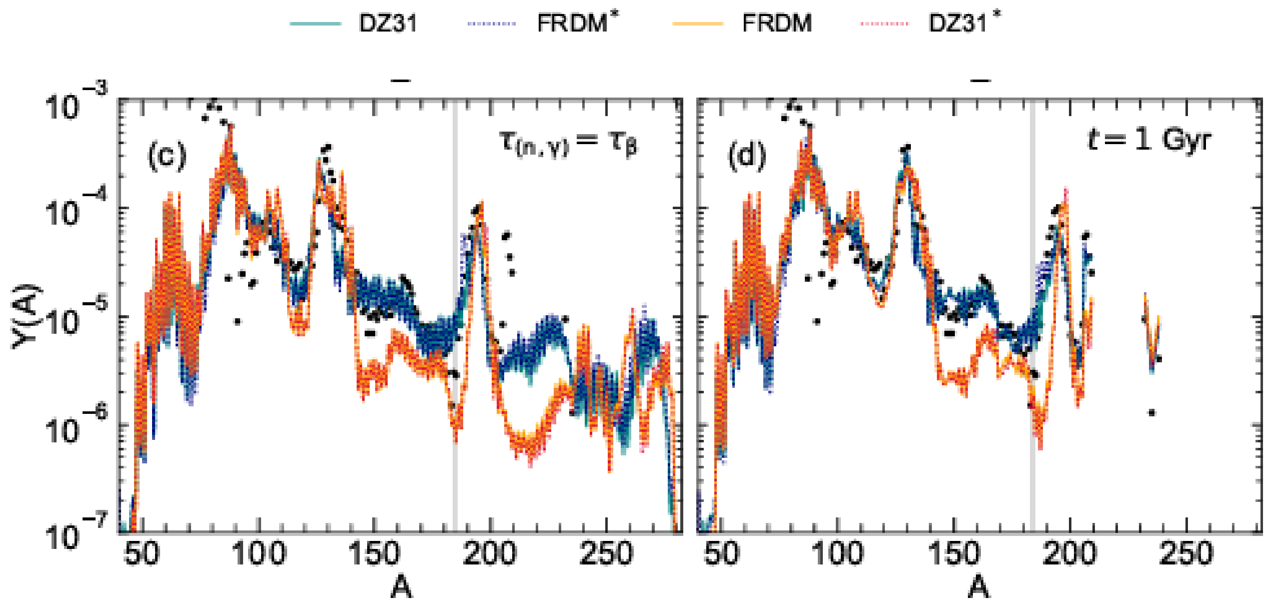
(Dated: December 5, 2024)

Isotopic (r-process) abundances





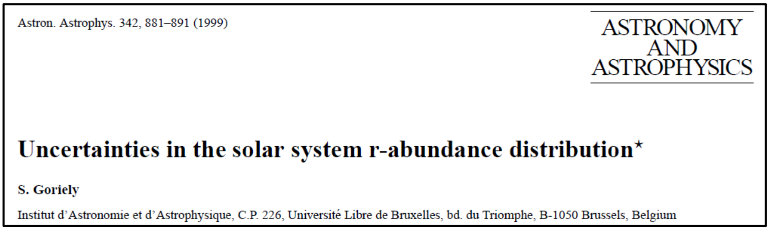
→ Uncertainties on isotopic (r-process) solar abundances.

→ Large in some cases: needed for a detailed/quantitative comparison

→ How to improve them (experimentally)

Isotopic (r-process) abundances

$N_r = N_{\odot} - N_s$



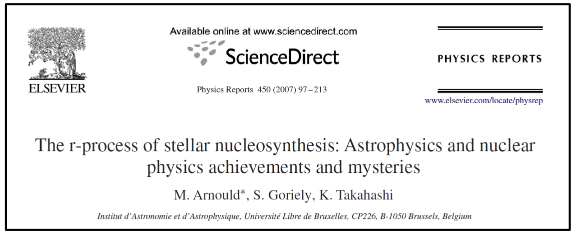
Astron. Astrophys. 342, 881–891 (1999)

ASTRONOMY AND ASTROPHYSICS

Uncertainties in the solar system r-abundance distribution*

S. Goriely

Institut d'Astronomie et d'Astrophysique, C.P. 226, Université Libre de Bruxelles, bd. du Triomphe, B-1050 Brussels, Belgium



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Physics Reports 450 (2007) 97–213

PHYSICS REPORTS

www.elsevier.com/locate/physrep

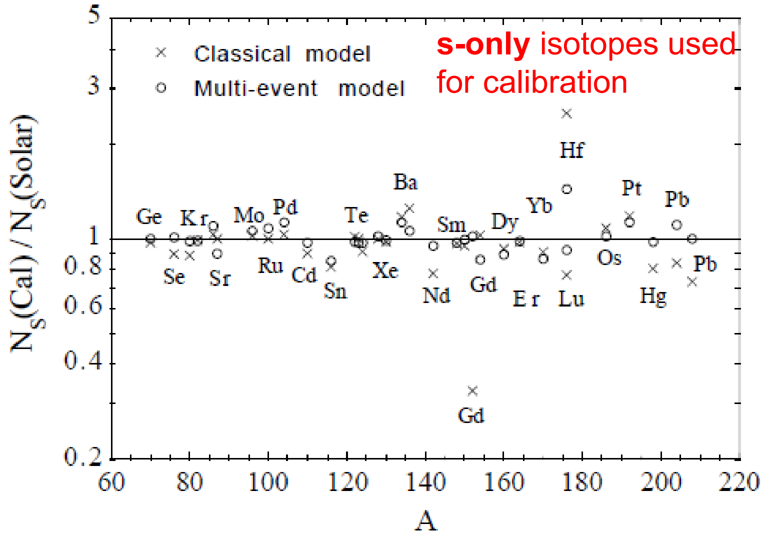
The r-process of stellar nucleosynthesis: Astrophysics and nuclear physics achievements and mysteries

M. Arnould*, S. Goriely, K. Takahashi

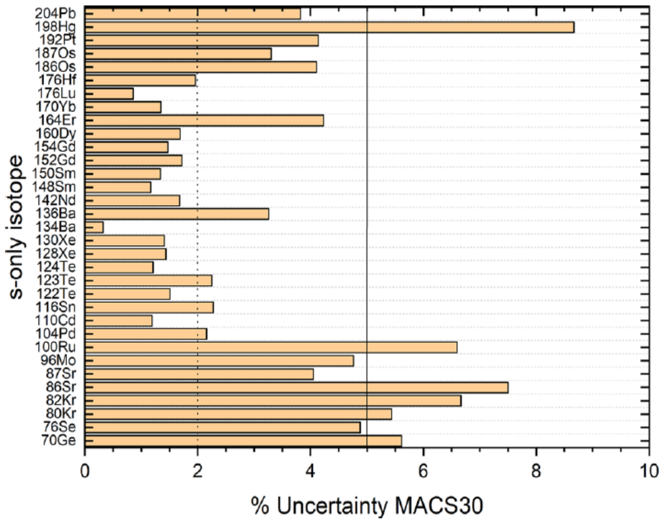
Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, CP226, B-1050 Brussels, Belgium

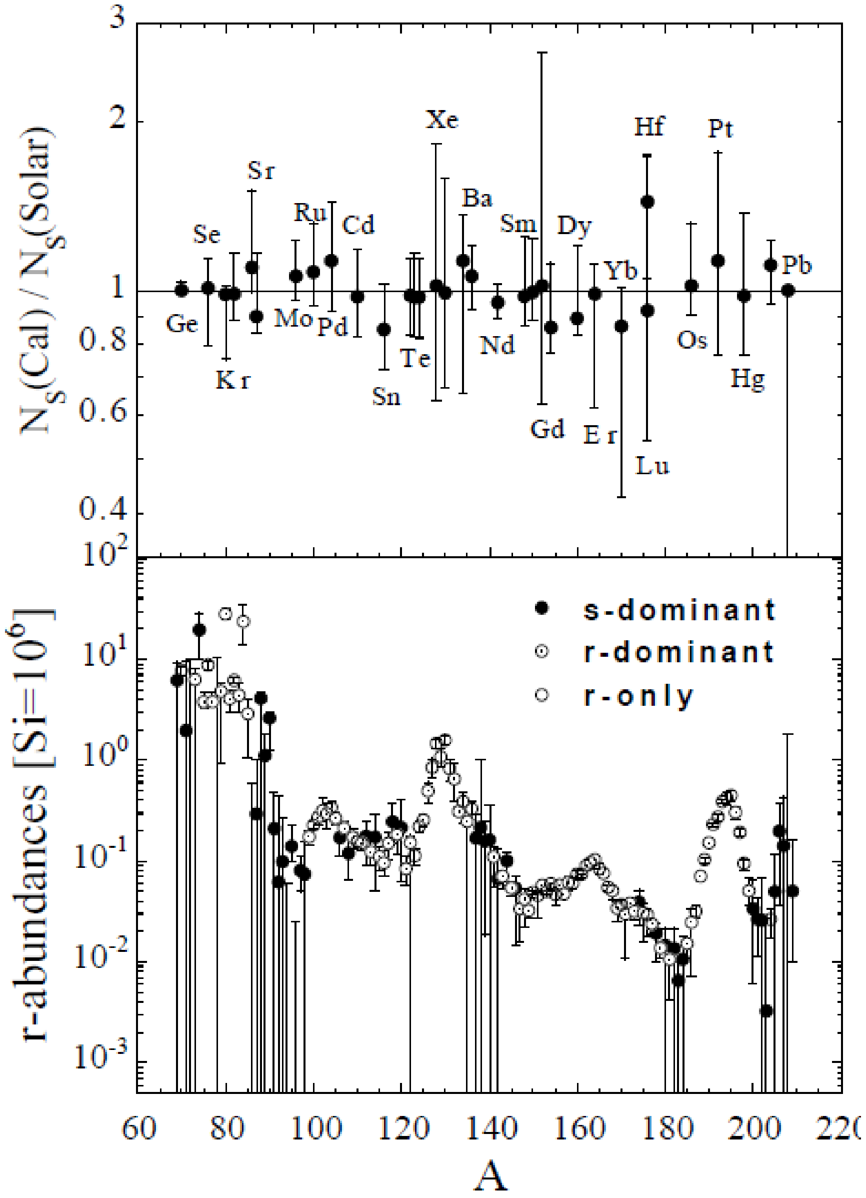
MES-model **calibrated with s-only nuclei; uncertainty budget:**

- SS abundances for the s-only isotopes
- (n,γ) CSs **affecting** s-only isotopes



I.Dillmann+ 2023





R-abundances uncertainties **larger for cases with dominant s-process contr.**

- **Fit to s-only**: SS + Canonical Multi-Event S-process (MES)
- Needs accurate experimental (n,g) XSs for the s-process part

Isotopic (r-process) abundances

$N_r = N_\odot - N_s^{GCE}$

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 491, 1832–1850 (2020) doi:10.1093/mnras/stz3154
Advance Access publication 2019 November 11

Chemical evolution with rotating massive star yields II. A new assessment of the solar s- and r-process components

N. Prantzos,[1★] C. Abia,[2] S. Cristallo,[3,4] M. Limongi[5,6] and A. Chieffi[7,8]

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Advance Access publication 2018 February 6

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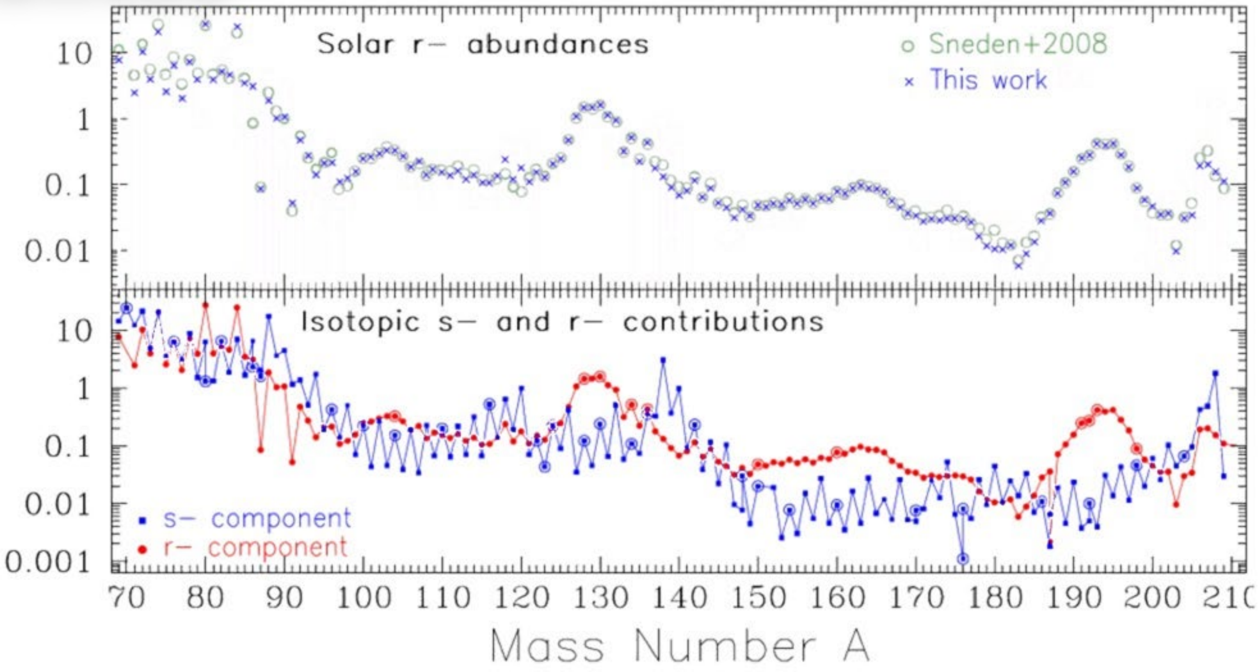

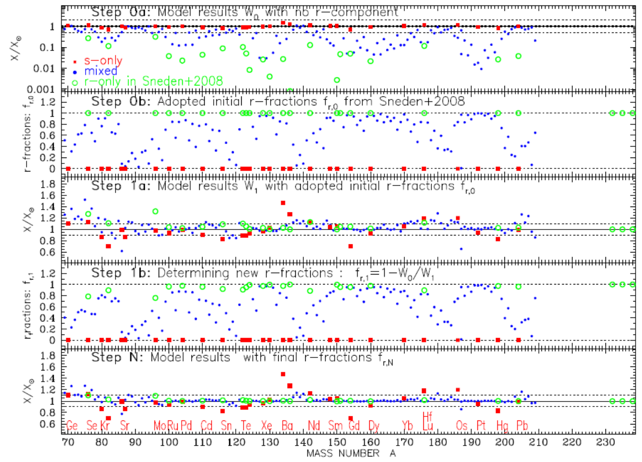

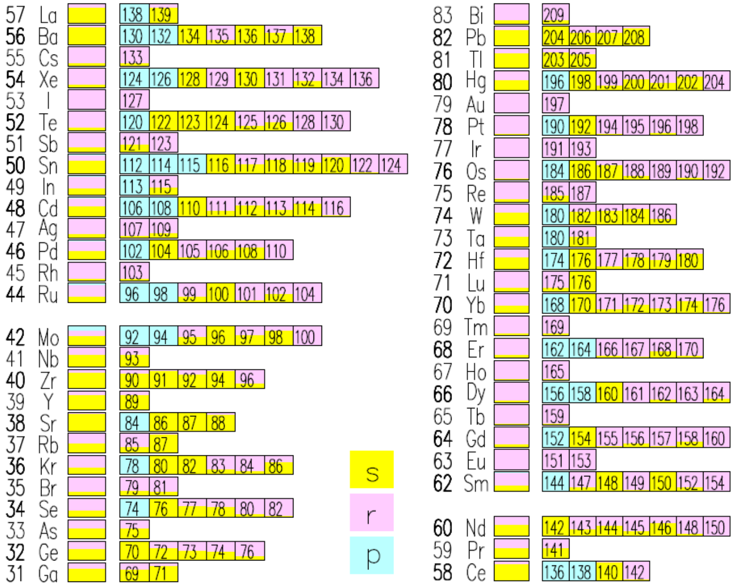

- Starts with s-process fraction and s-only isotopes
- Iterative method for r-"residuals" based on GCE (AGB- and MS-models)
- Needs accurate experimental (n,g) XSs for the s-process part

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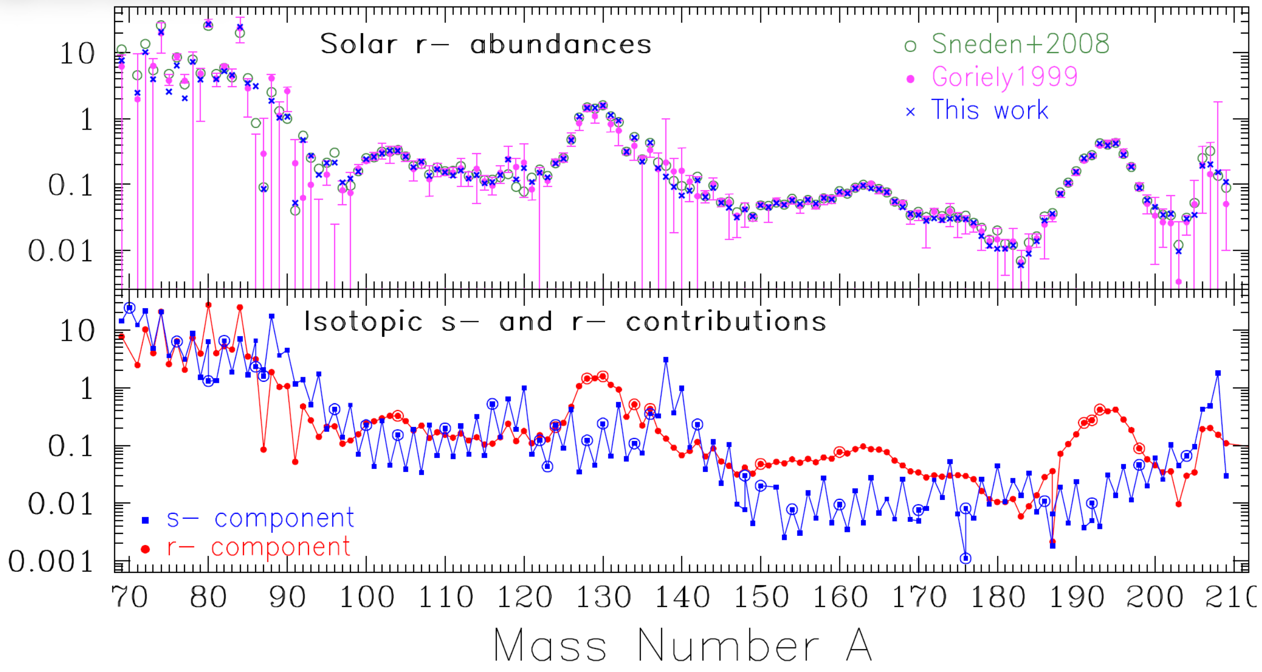
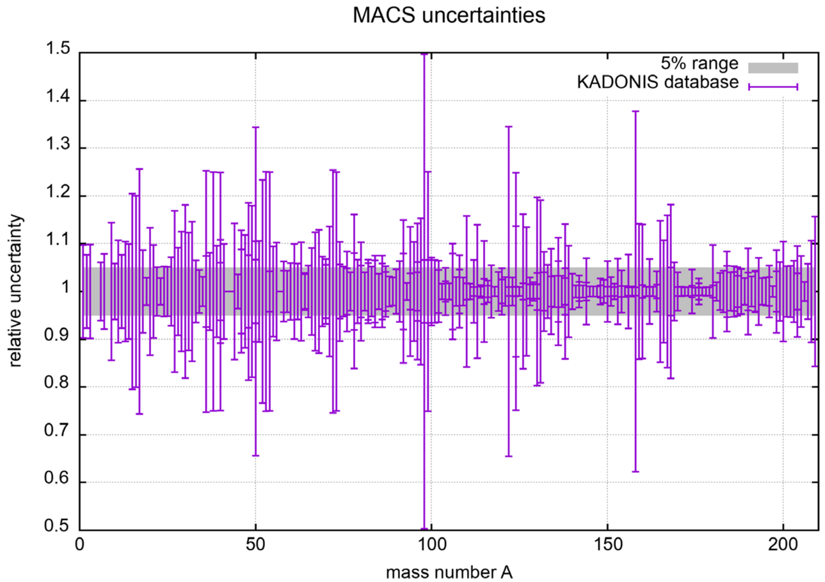
(2008). The former study includes the model uncertainties, resulting from the corresponding uncertainties in the observed Solar system composition, the neutron radiative capture rates (n,γ) and the β-decay rates. The uncertainties in those quantities date back to more than 20 yr ago and some of them have been reduced in the meantime. However, the work of Goriely (1999) is the only one up to now to include a systematic evaluation of those uncertainties and we chose to display them here in order to provide some idea of their importance.



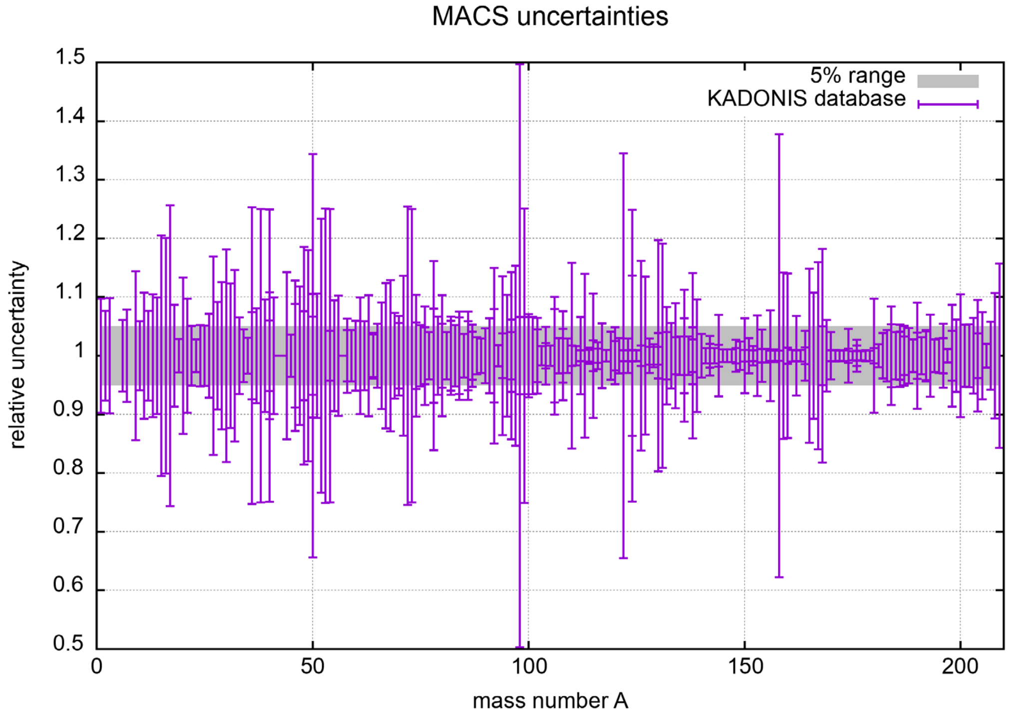


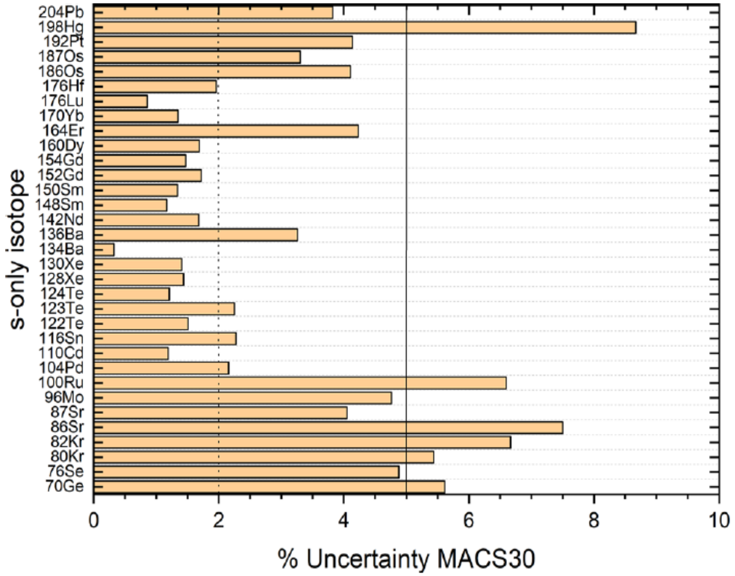
- Starts with s-process fraction and s-only isotopes
- Iterative method for r-”residuals” based on GCE (AGB- and MS-models)
- Needs accurate experimental (n,g) XSs for the s-process part

Isotopic r-process abundances: uncertainties from (n,γ) Cross Sections

$$N_r = N_\odot - N_s$$

- In general, the uncertainties on many XSs (>10%) still dominating the final r-process isotopic uncertainties → New (more accurate) measurements on specific stable isotopes are needed!
- Calibration methodology relies on s-only isotopes, but (most of) the s-only abundances are not due to s-only capture cross sections!!





Eur. Phys. J. A (2023) 59:105
https://doi.org/10.1140/epja/s10050-023-01012-9

THE EUROPEAN PHYSICAL JOURNAL A

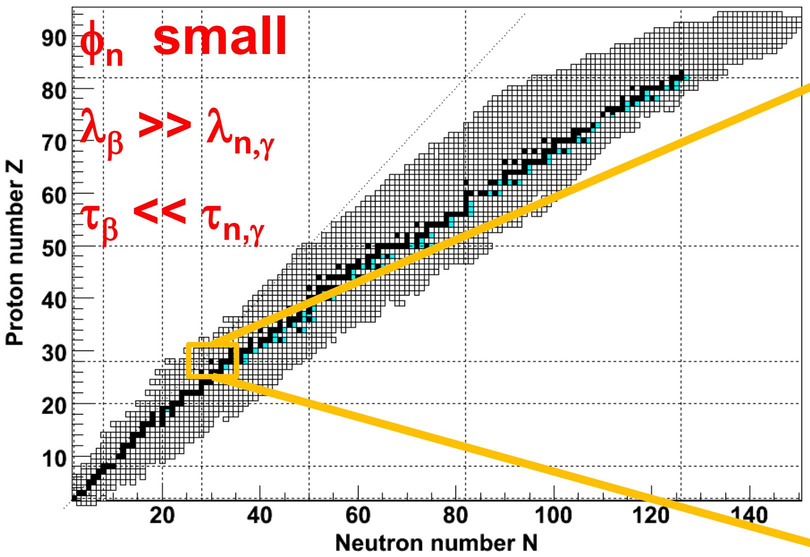
Regular Article - Experimental Physics

Measuring neutron capture cross sections of radioactive nuclei

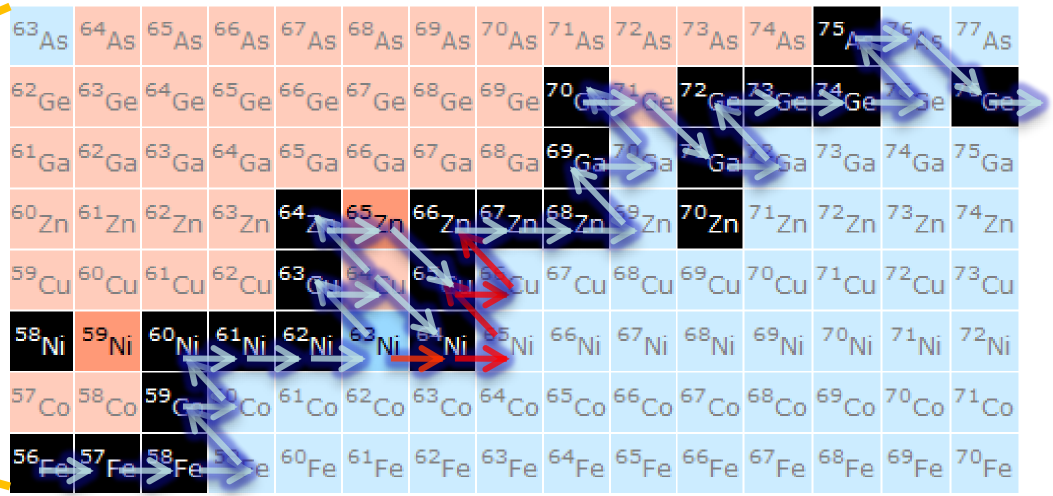
From activations at the FZK Van de Graaff to direct neutron captures in inverse kinematics with a storage ring at TRIUMF

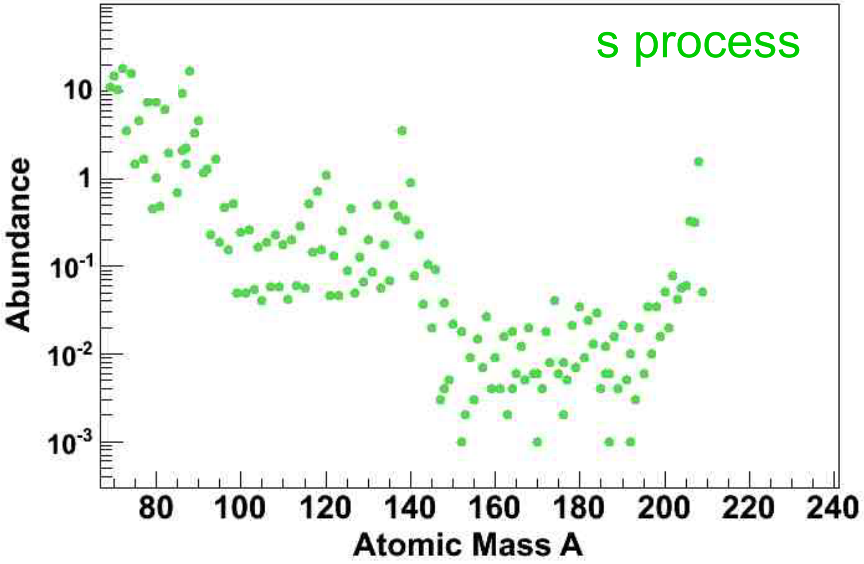
Iris Dillmann[1,2,a], Oliver Kester[1,2], Richard Baartman[1,2], Alan Chen[3], Tobias Junginger[1,2], Falk Herwig[2], Dobrin Kaltchev[1], Annika Lennarz[1,3], Thomas Planche[1,2], Chris Ruiz[1,2], Nicole Vassh[1]

The slow neutron-capture process (s-process) mechanism



s process in Massive Stars (Red Giants)





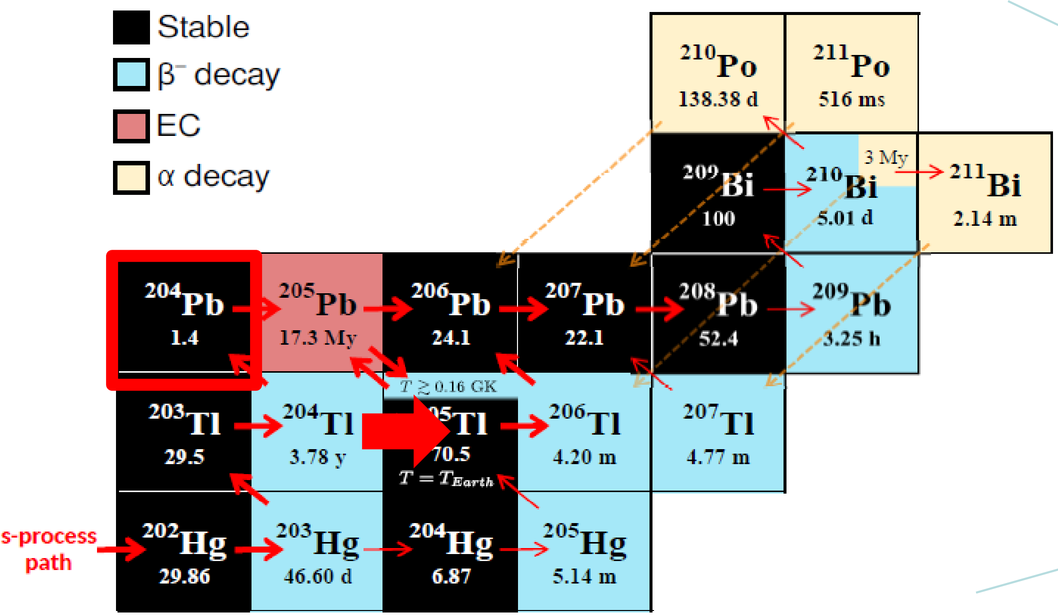
core He-burning	shell C-burning
$3\text{-}3.5 \cdot 10^8$ K	$\sim 1 \cdot 10^9$ K
kT=25 keV	kT=90 keV
10^6 cm^{-3}	**10^{11}-10^{12} cm^{-3}**

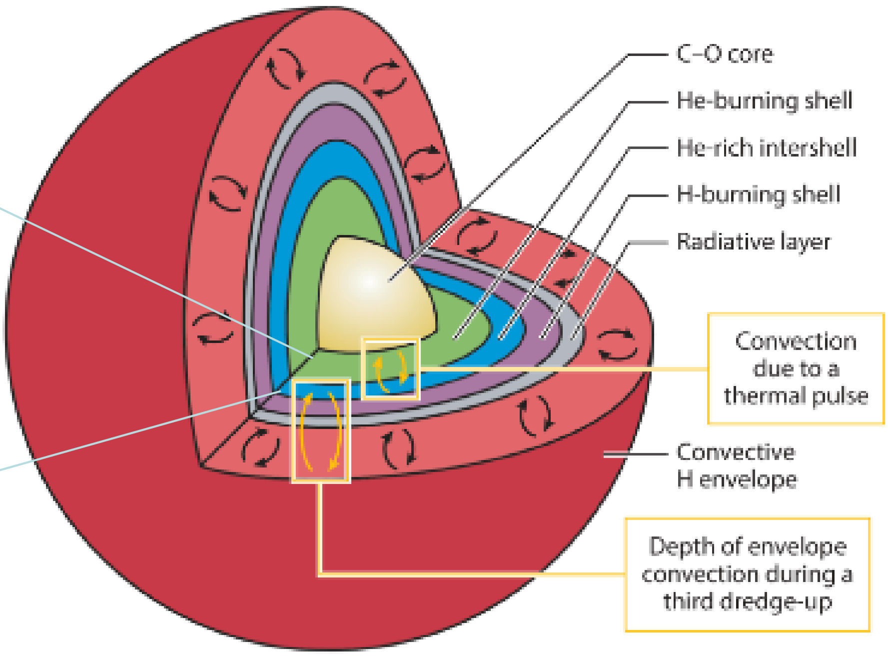
^{22}Ne(^{4}He,n)^{25}Mg

 = $^{A}Z(n,\gamma)\,^{A+1}Z$

- → Site well identified MSs and low-mass TP AGB Stars
- → Reliable stellar models (5-10% uncertainty)
- → Need:
  - → Accurate (n,g) cross sections (5-10%) for the stable isotopes
  - → 10-20% for unstable isotopes

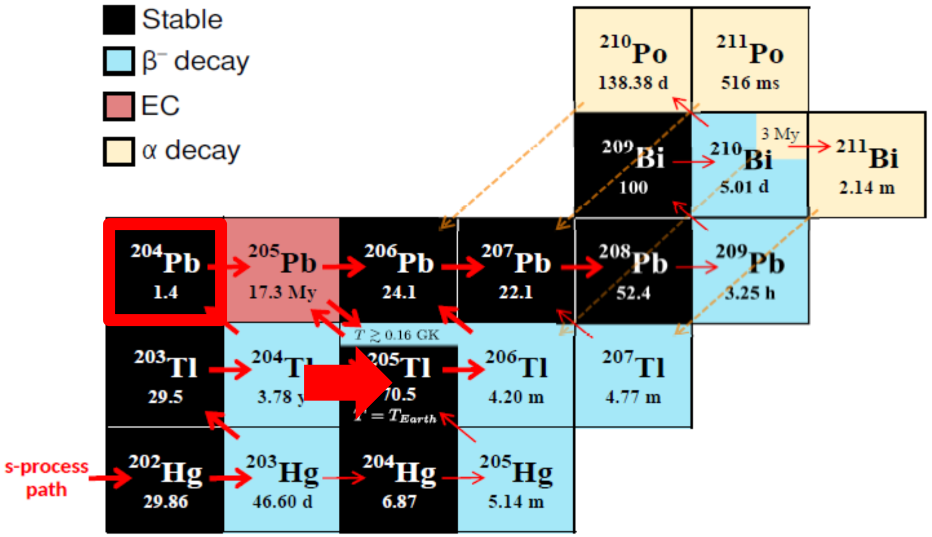
^{204}Pb: an s-only determined by an s-branching





Lugaro M, et al. 2023
Annu. Rev. Nucl. Part. Sci. 73:315–40

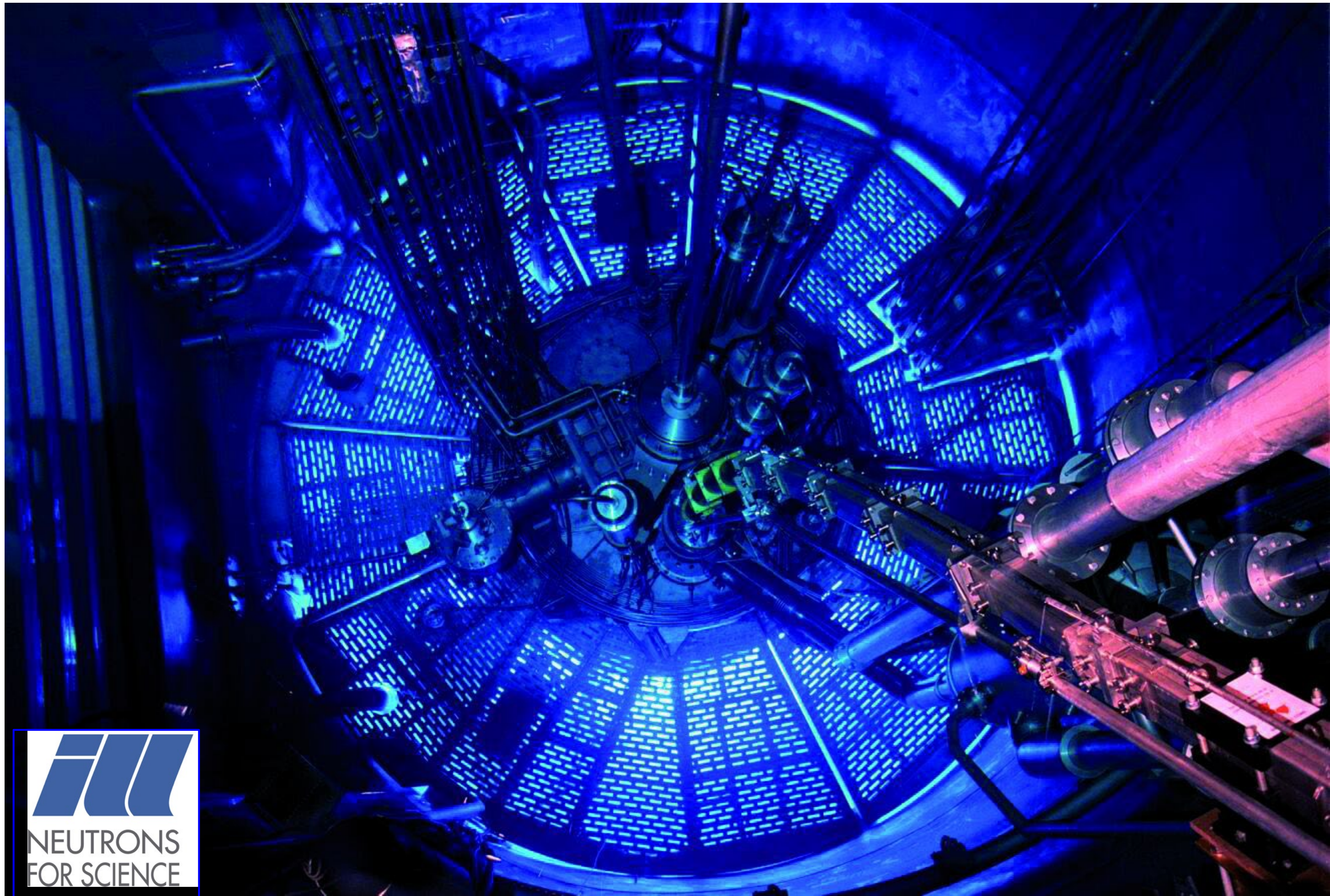
^{204}Pb determined by the s-branching at ^{204}Tl (3.78y)



^{203}Tl (225 mg)

^{203}Tl
+
^{204}Tl (9 mg)

There is no ^{204}Tl in nature!



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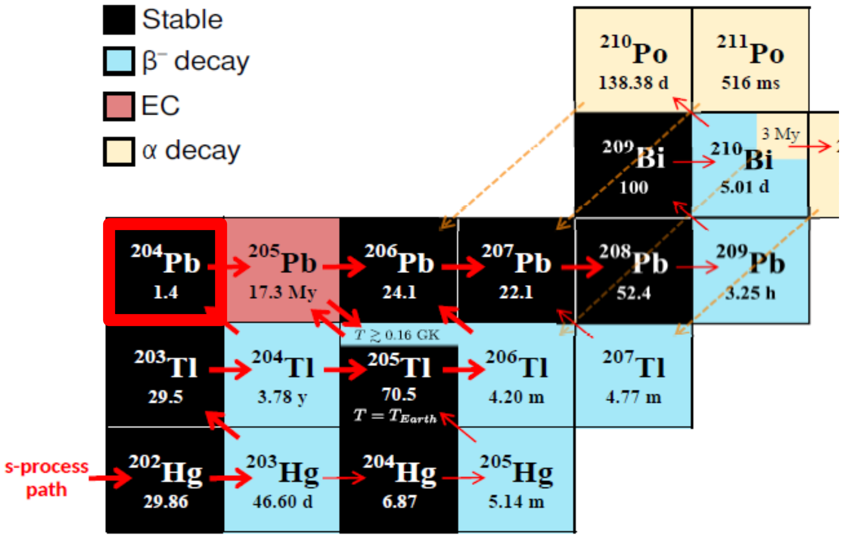
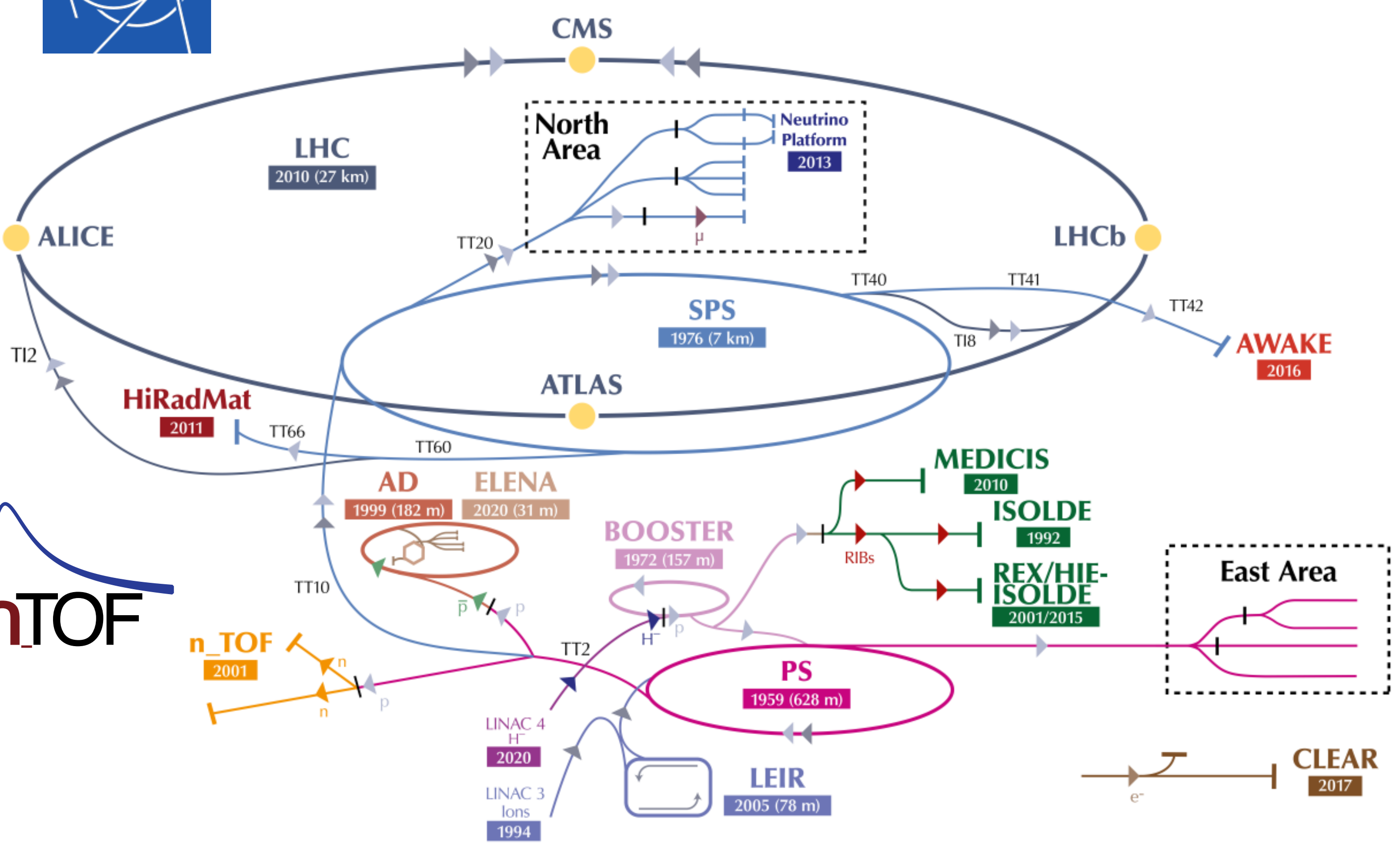


^{203}Tl (225 mg)

^{203}Tl
+
^{204}Tl (9 mg)

The CERN accelerator complex
Complexe des accélérateurs du CERN



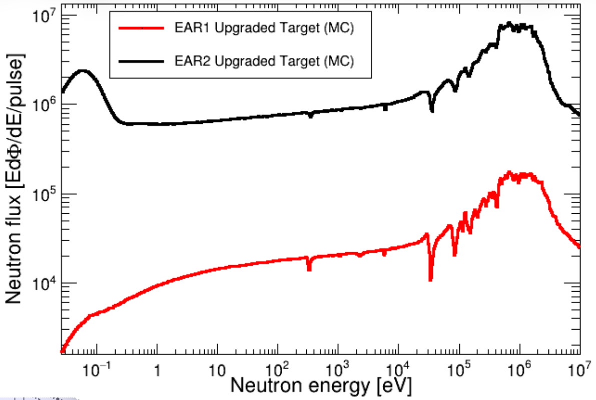
nTOF

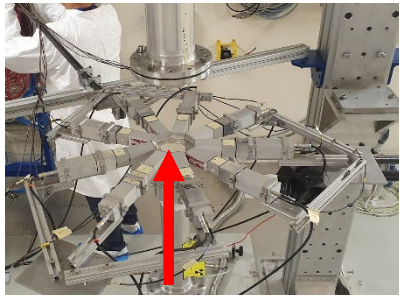
PHYSICAL REVIEW LETTERS 133, 052702 (2024)

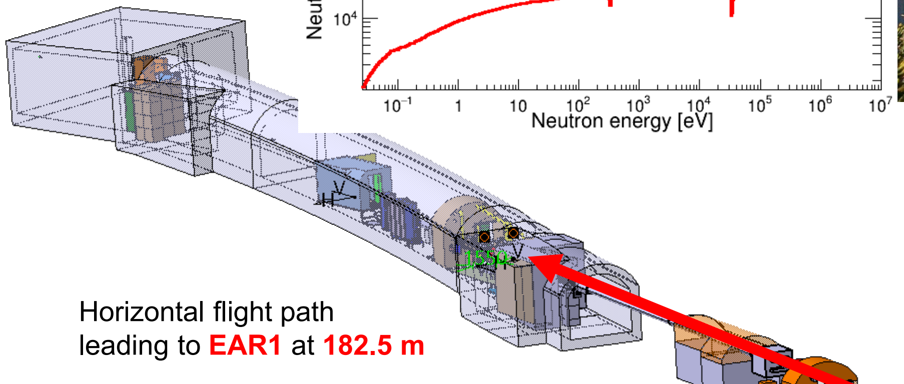
Shedding Light on the Origin of ^{204}Pb, the Heaviest *s*-Process–Only Isotope in the Solar System

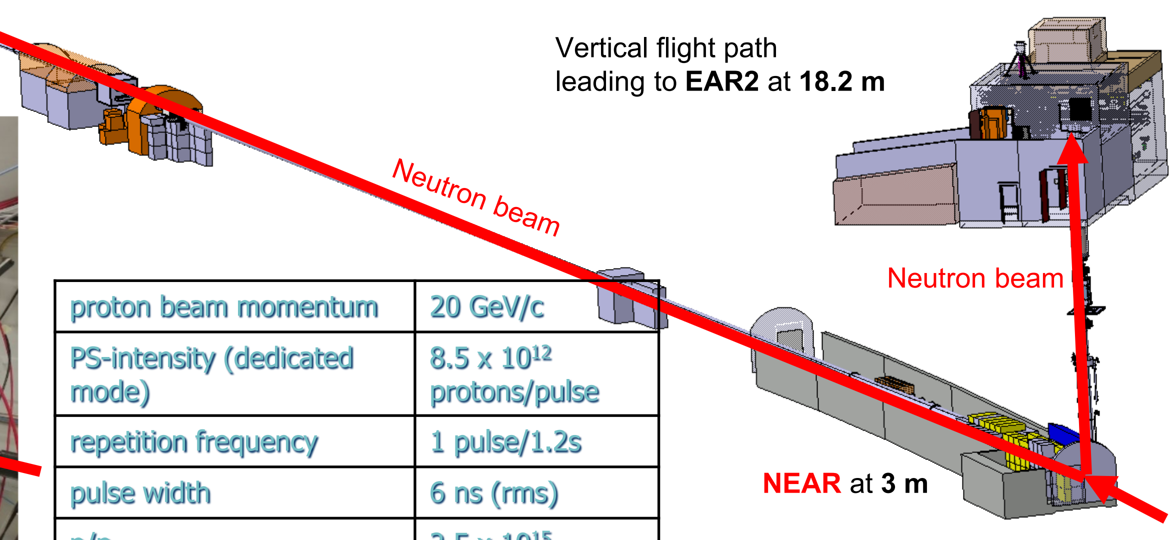
A. Casanovas-Hoste,[1,2,3,*] C. Domingo-Pardo,[2] J. Lerendegui-Marco,[4] C. Guerrero,[4] A. Tarifeño-Saldivia,[2] M. Krtička,[5] M. Pignatari,[6,7,8,9] F. Calviño,[1] D. Schumann,[10] S. Heinitz,[10] R. Dressler,[10] U. Köster,[11] O. Aberle,[3] J. Andrzejewski,[12] L. Audouin,[13] V. Bécares,[14] M. Bacak,[15] J. Balibrea-Correa,[14] M. Barbagallo,[16] S. Barros,[17] F. Bečvář,[5] C. Beinrucker,[18]

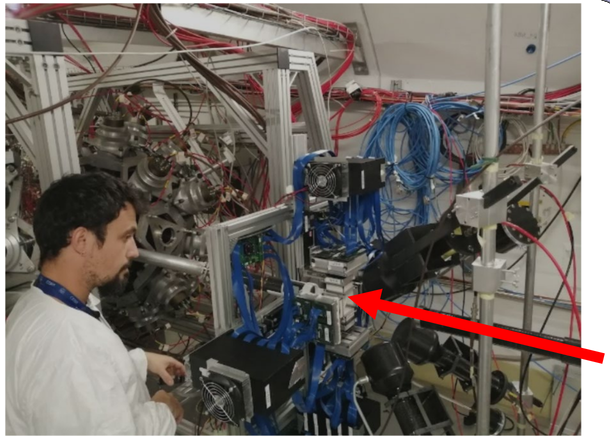
Time-of-flight technique for high resolution & high acuracy (n,g) cross section measurements



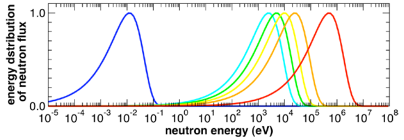








proton beam momentum	20 GeV/c
PS-intensity (dedicated mode)	8.5 x 10^{12} protons/pulse
repetition frequency	1 pulse/1.2s
pulse width	6 ns (rms)
n/p	2.5 x 10^{15} n/pulse
lead target dimensions	70x76x63 cm^3
cooling & moderation material	N_2 & H_2O (borated)



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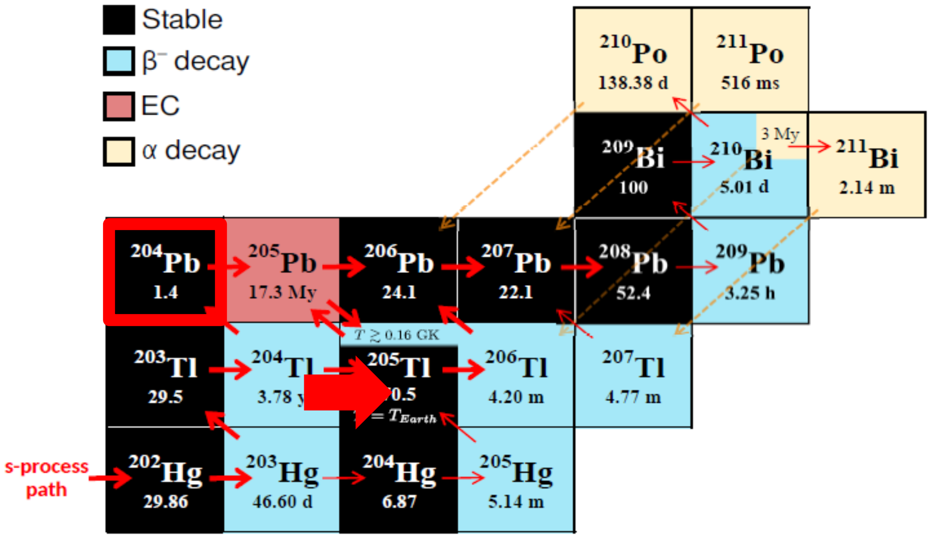

^{203}Tl (225 mg)

^{203}Tl
+
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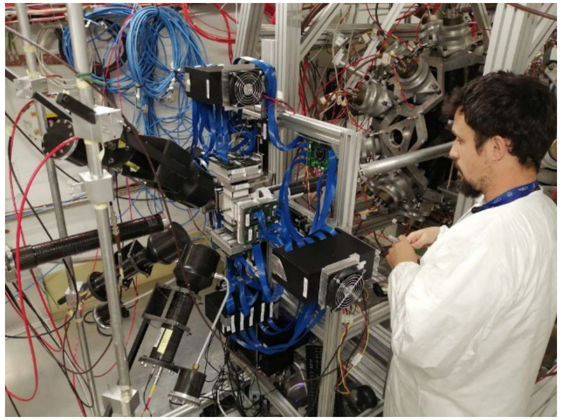

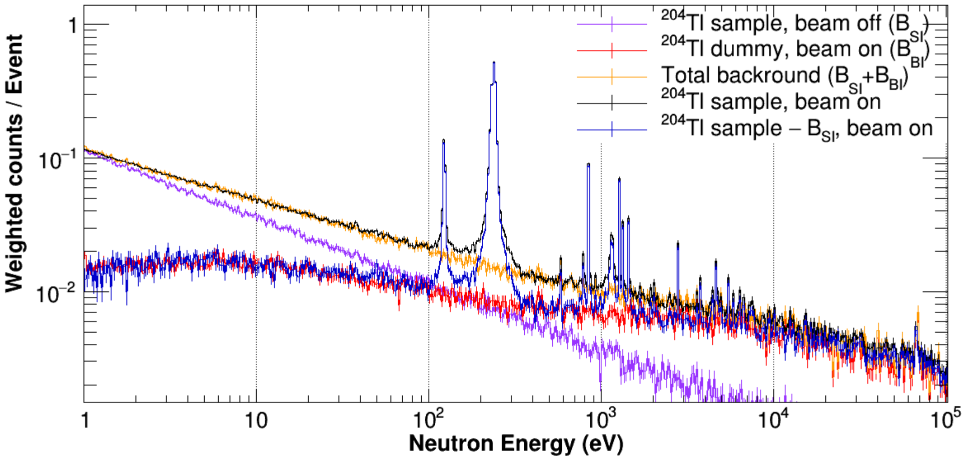

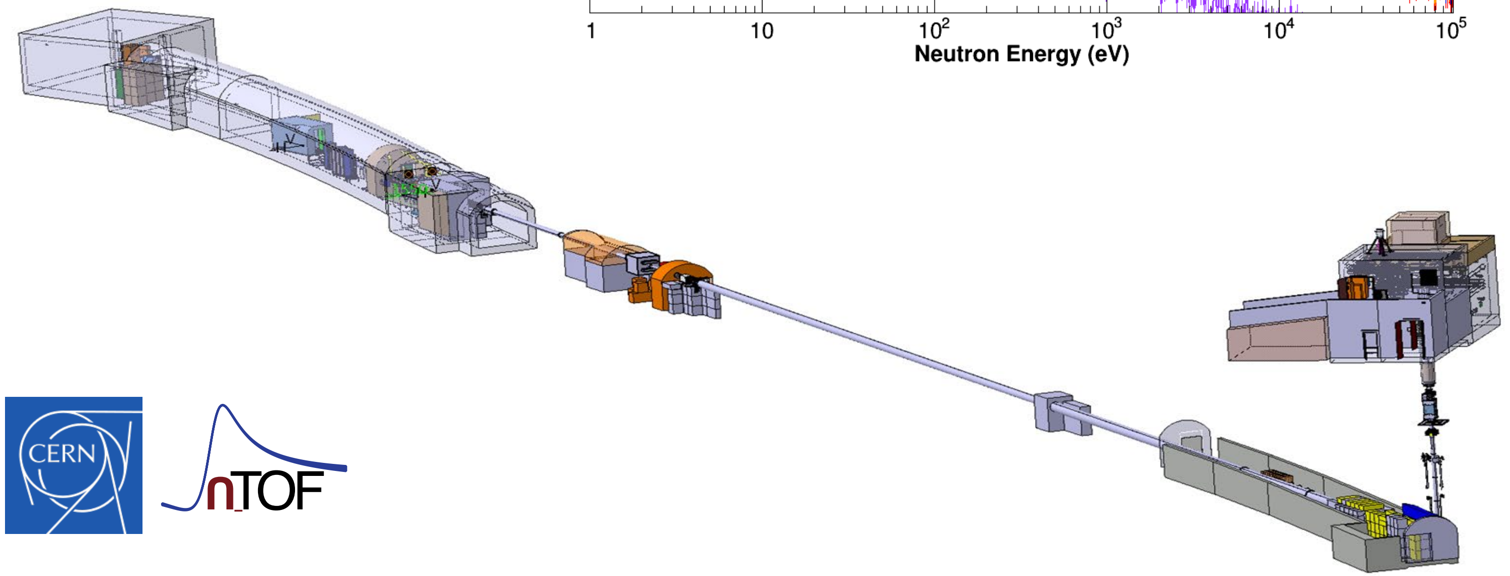

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CERN

nTOF

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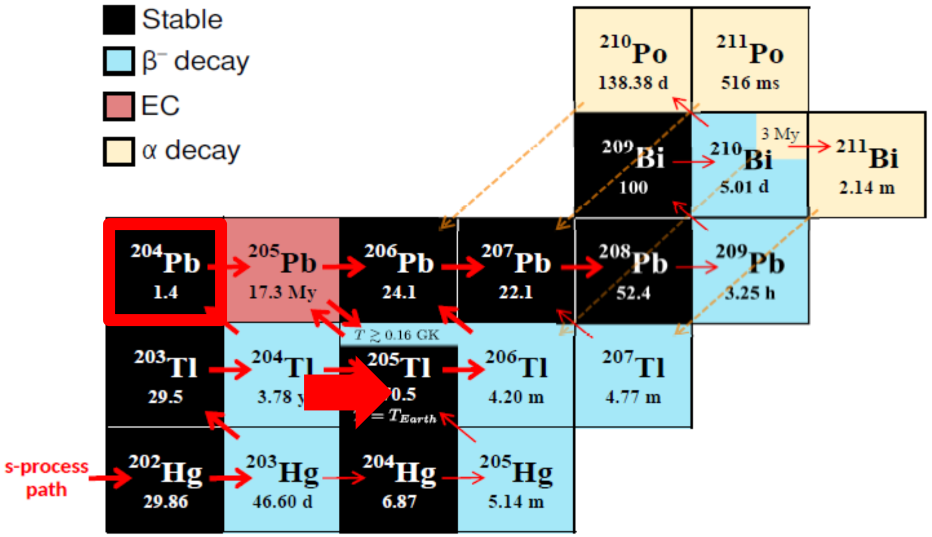

^{203}Tl (225 mg)

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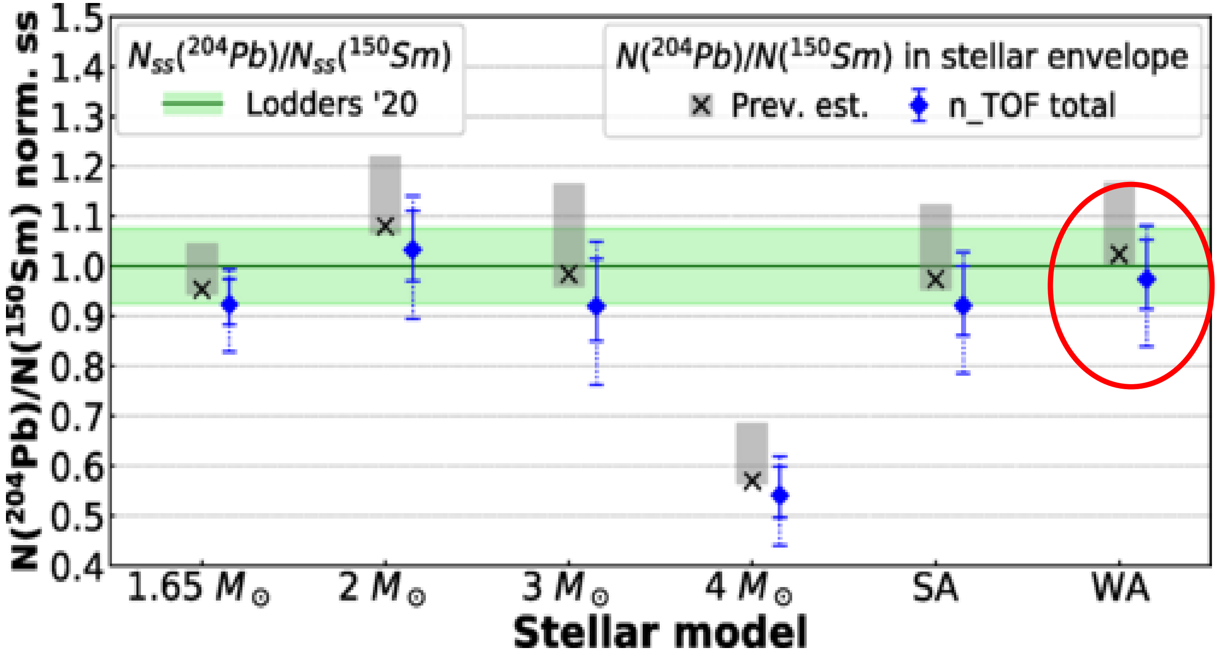
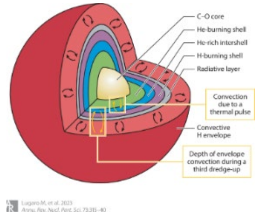




NUGRID

MESA

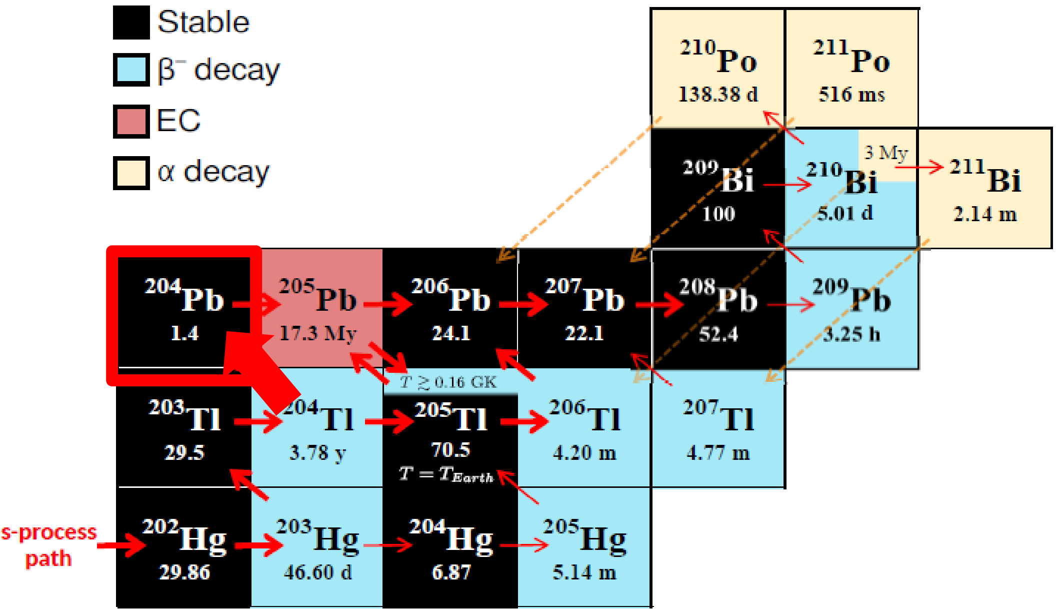
PHYSICAL REVIEW LETTERS 133, 052702 (2024)

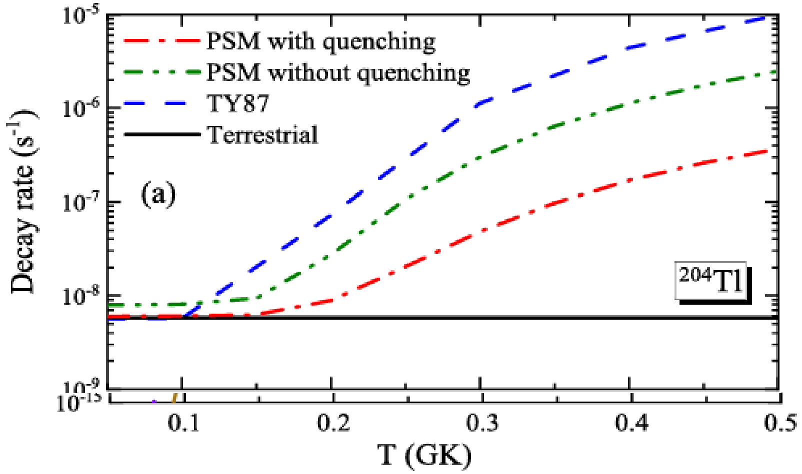
Shedding Light on the Origin of ^{204}Pb, the Heaviest *s*-Process–Only Isotope in the Solar System

A. Casanovas-Hoste,[1,2,3,*] C. Domingo-Pardo,[2] J. Lerendegui-Marco,[4] C. Guerrero,[4] A. Tarifeño-Saldivia,[2] M. Krtička,[5] M. Pignatari,[6,7,8,9] F. Calviño,[1] D. Schumann,[10] S. Heinitz,[10] R. Dressler,[10] U. Köster,[11] O. Aberle,[3] J. Andrzejewski,[12] L. Audouin,[13] V. Bécares,[14] M. Bacak,[15] J. Balibrea-Correa,[14] M. Barbagallo,[16] S. Barros,[17] F. Bečvář,[5] C. Beinrucker,[18]

The uncertainty arising from the ^{204}Tl(n,γ) cross section on the *s*-process abundance of ^{204}Pb has been reduced from ~30% down to **+8%/−6%**, and the *s*-process calculations are in agreement with K. Lodders in 2021.

^{204}Pb: an s-only determined by an s-branching





Stellar β-decay rate of *s*-process branching-point ^{204}Tl: forbidden transitions

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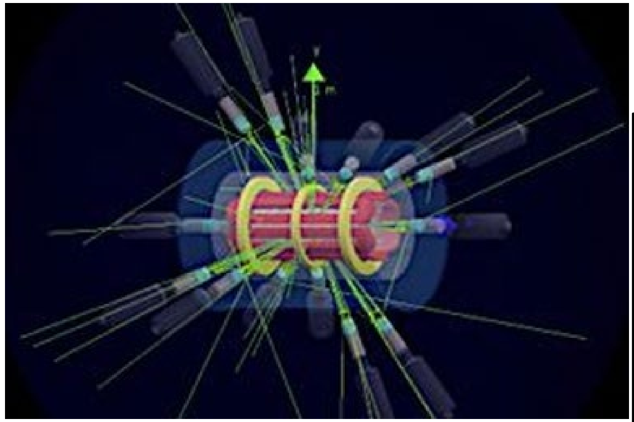
School of Physical Science and Technology, Southwest University, Chongqing 400715, China
(Dated: July 30, 2024)

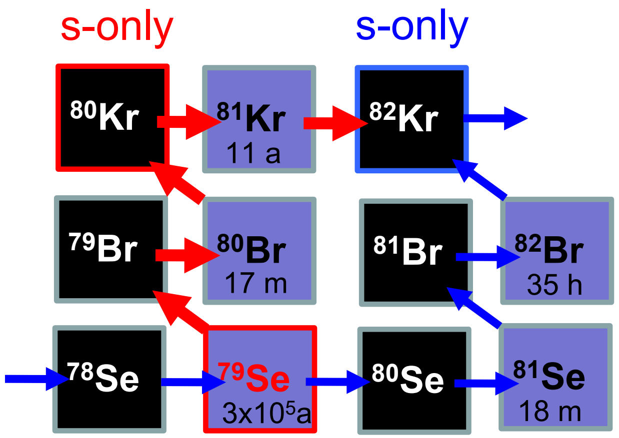


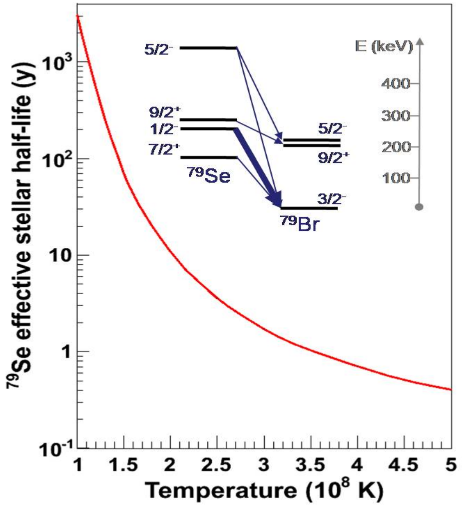
EPJ Web of Conferences **279**, 06007 (2023) https://doi.org/10.1051/epjconf/202327906007
NPA-X 2022

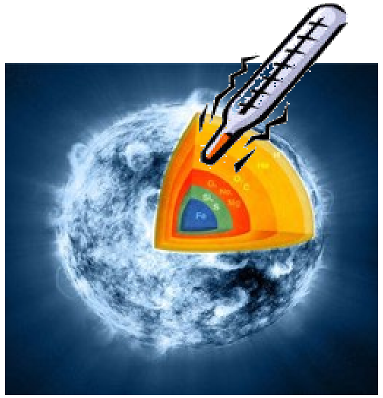
A new approach to β-decays studies impacting nuclear physics and astrophysics: the PANDORA setup

D. Mascali[1*], D. Santonocito[1], M. Busso[2,3], L. Celona[1], A. Galatà[4], M. La Cognata[1], G. S. Mauro[1], A. Mengoni[5,6], E. Naselli[1], F. Odorici[5], S. Palmerini[2,3], A. Pidatella[1], R. Ràcz[7], S. Taioli[8,9,10], G. Torrisi[1]

^{79}Se branching determines s-only ^{80,82}Kr







ILL: ~3 mg of ^{79}Se (<0.1%) via ^{78}Se n-activation

6MBq γ-ray emmiters
3 mg of ^{79}Se
1.6 MBq of ^{60}Co
5 MBq of ^{75}Se

PSI: ^{208}Pb^{78}Se alloy

2.8 g of ^{208}Pb
1.0 g of ^{78}Se

PAUL SCHERRER INSTITUT

Nuclear Inst. and Methods in Physics Research, A 1029 (2022) 166443

Contents lists available at ScienceDirect

Nuclear Inst. and Methods in Physics Research, A

journal homepage: www.elsevier.com/locate/nima

ELSEVIER

Preparation of PbSe targets for ^{79}Se neutron capture cross section studies

Nadine M. Chiera[a,*], Emilio Andrea Maugeri[a], Ivan Danilov[a], Javier Balibrea-Correa[b], Cesar Domingo-Pardo[b], Ulli Köster[c], Jorge Lerendegui-Marco[b], Mario Veicht[a,d], Ivan Zivadinovic[a,e], Dorothea Schumann[a], the n_TOF collaboration

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[b] Instituto de Física Corpuscular - Consejo Superior de Investigaciones Científicas/Universitat de València, Spain
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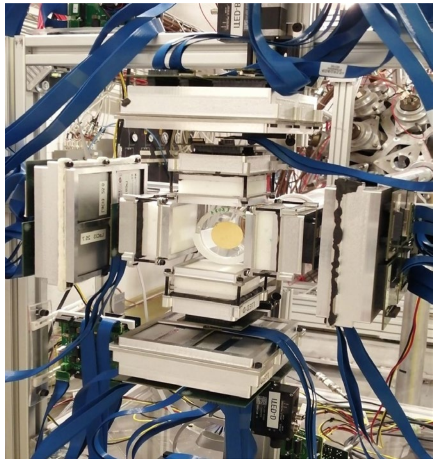
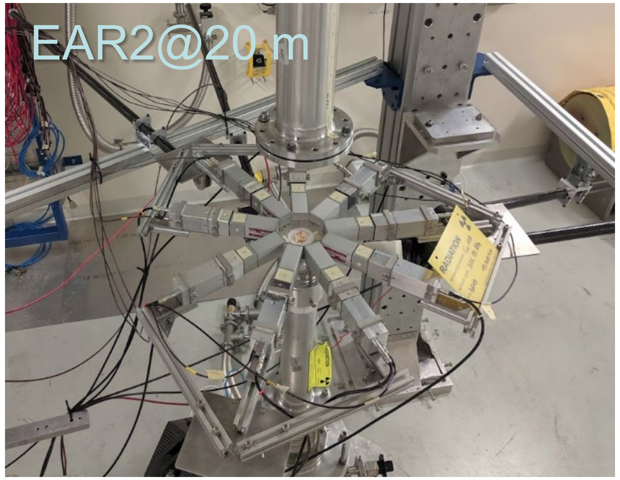
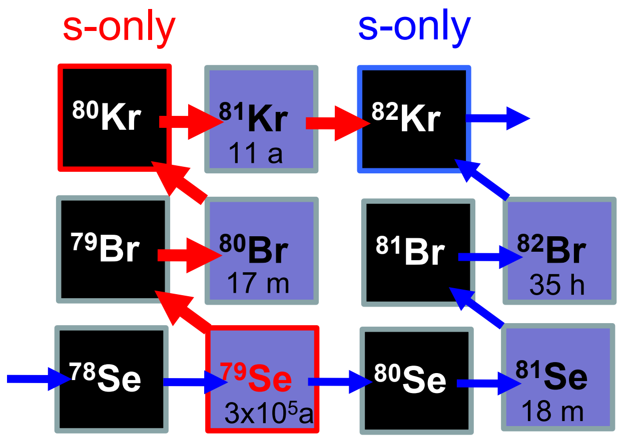
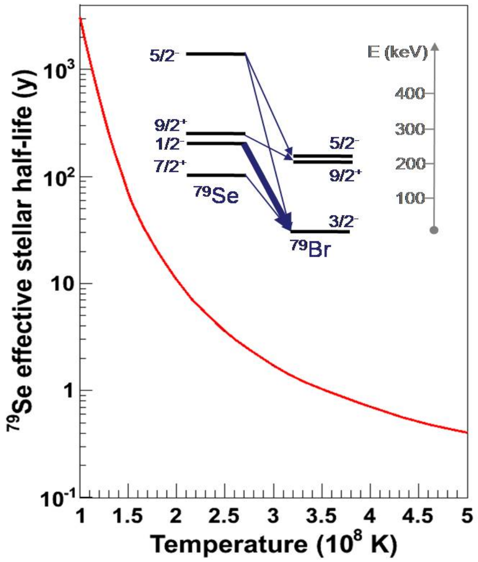
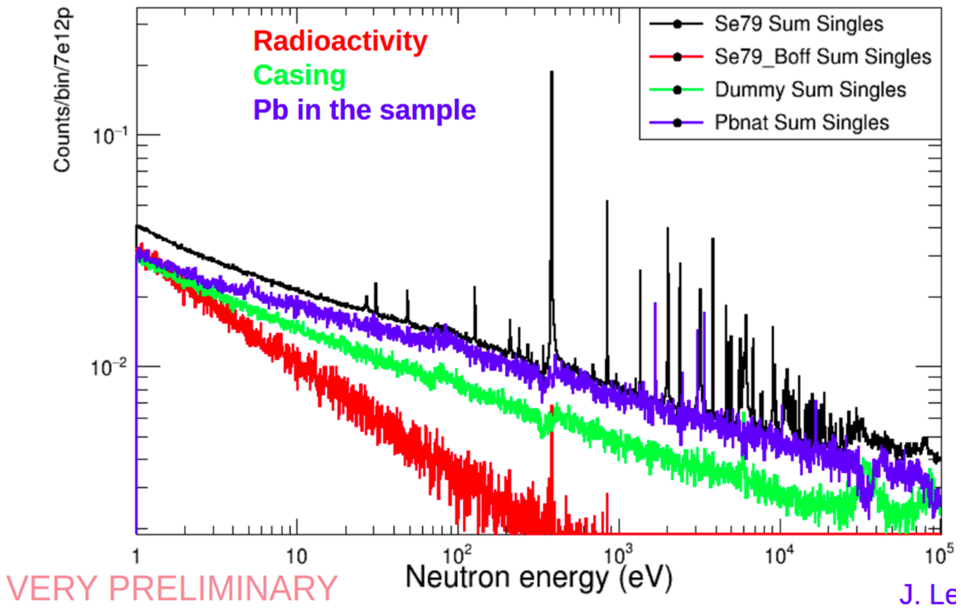


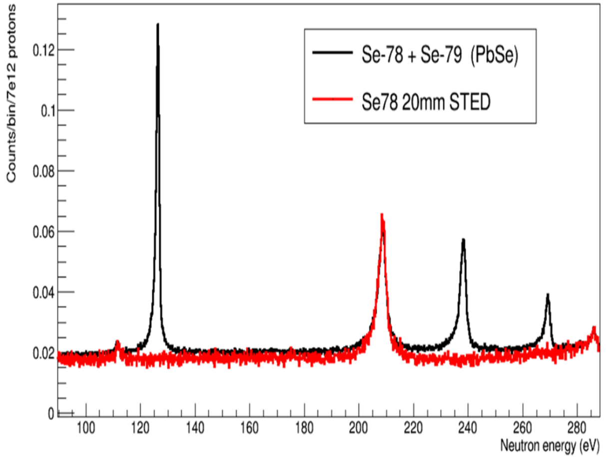


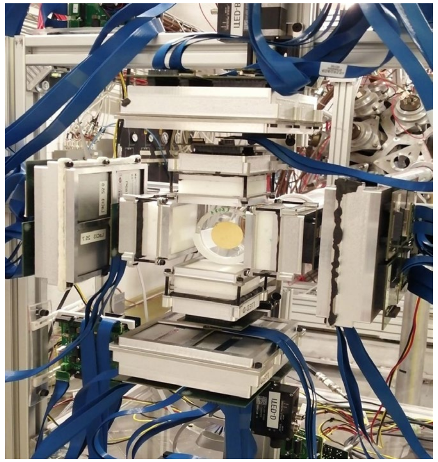
^{79}Se branching determines s-only ^{80,82}Kr

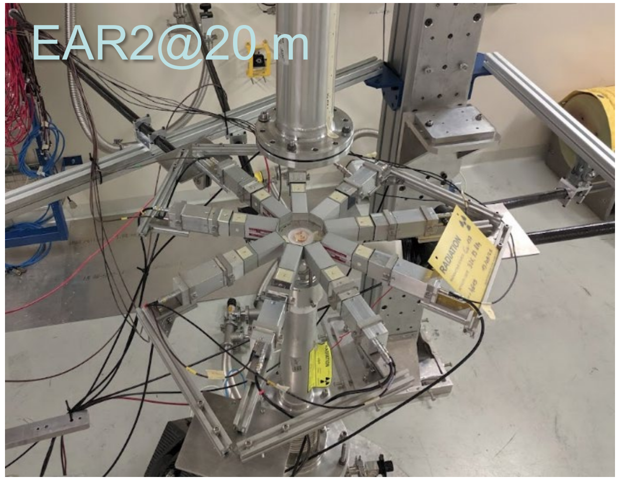








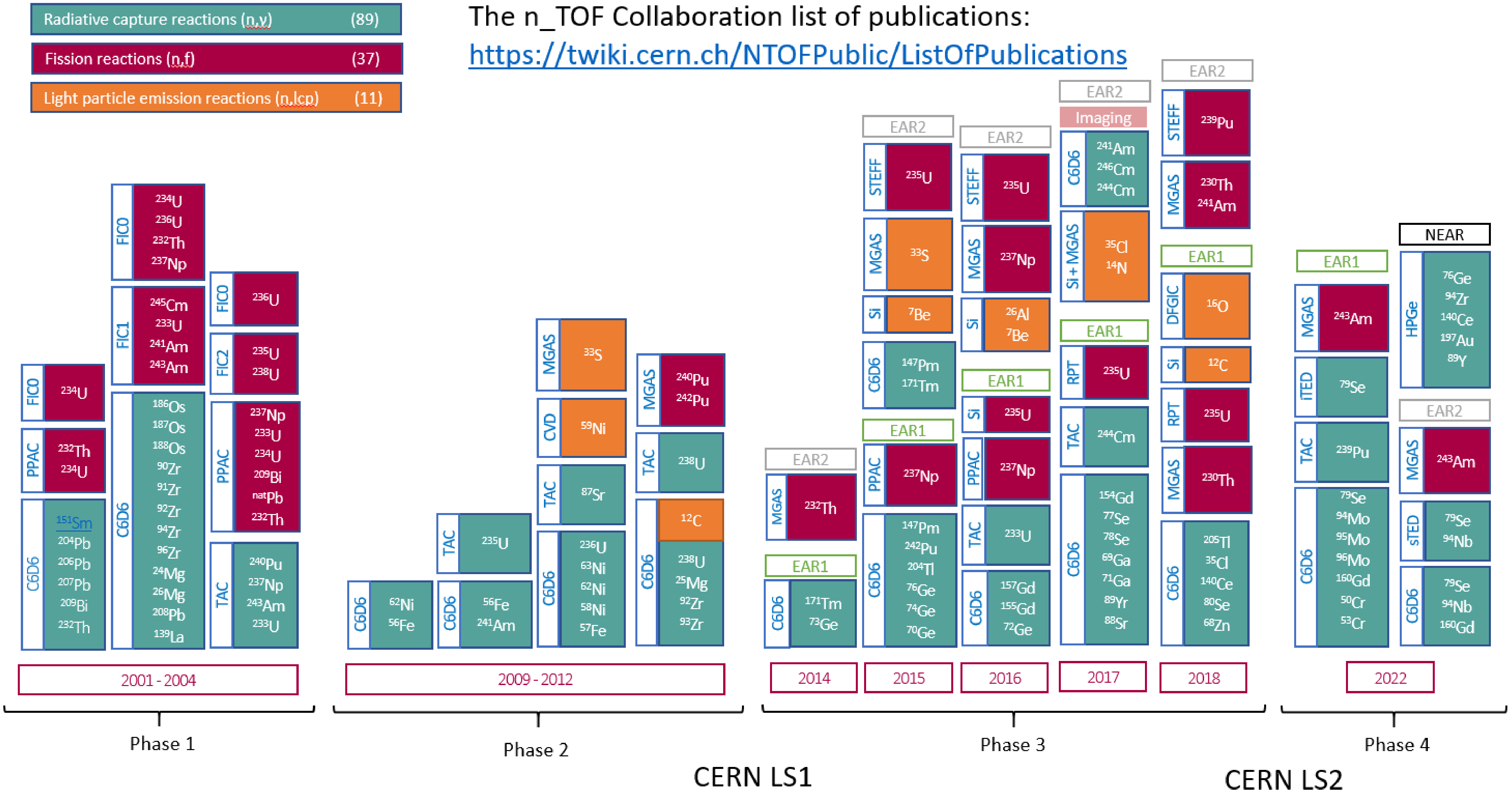




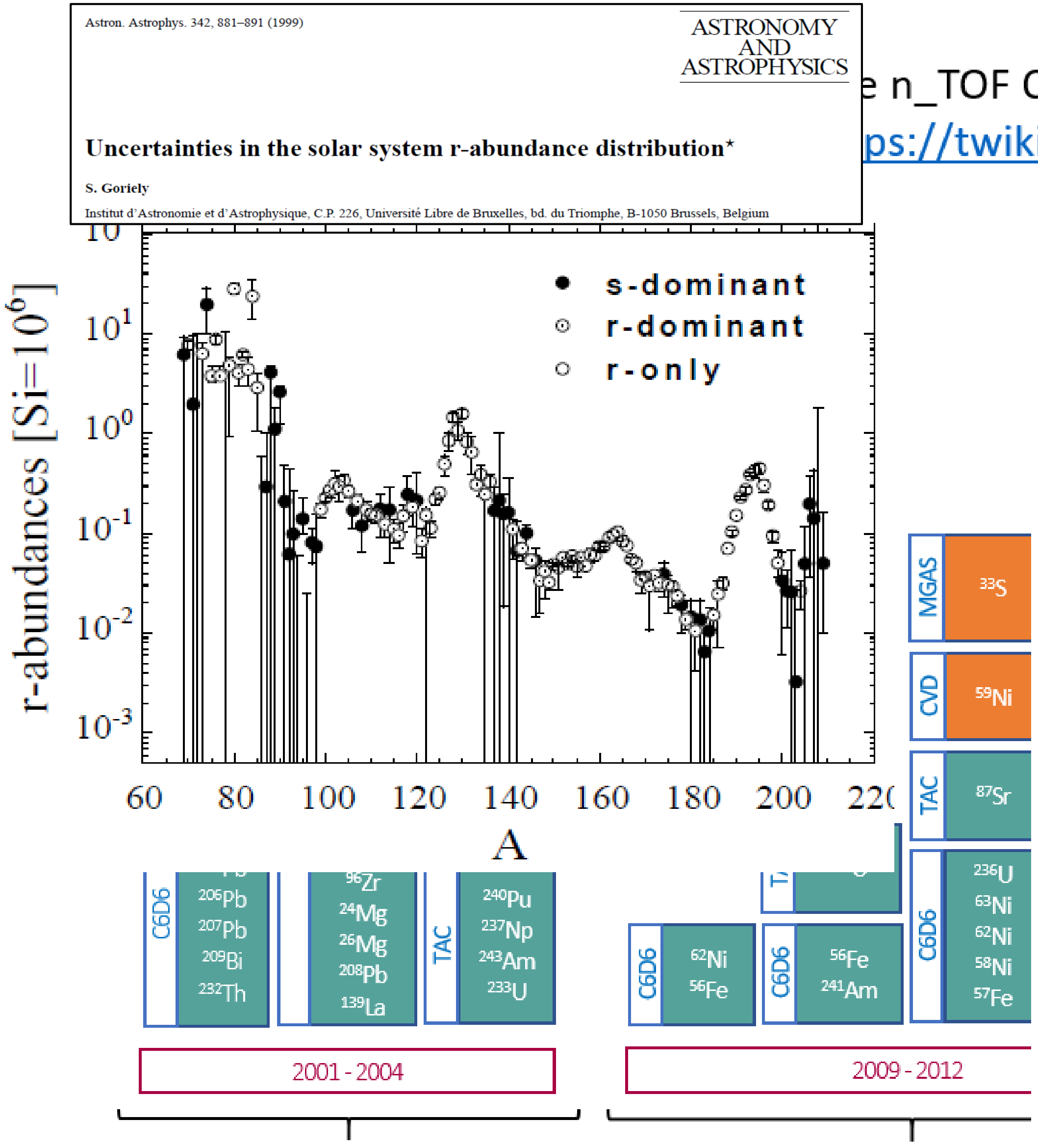
J. Lerendegui-Marco et al. (analysis in progress)

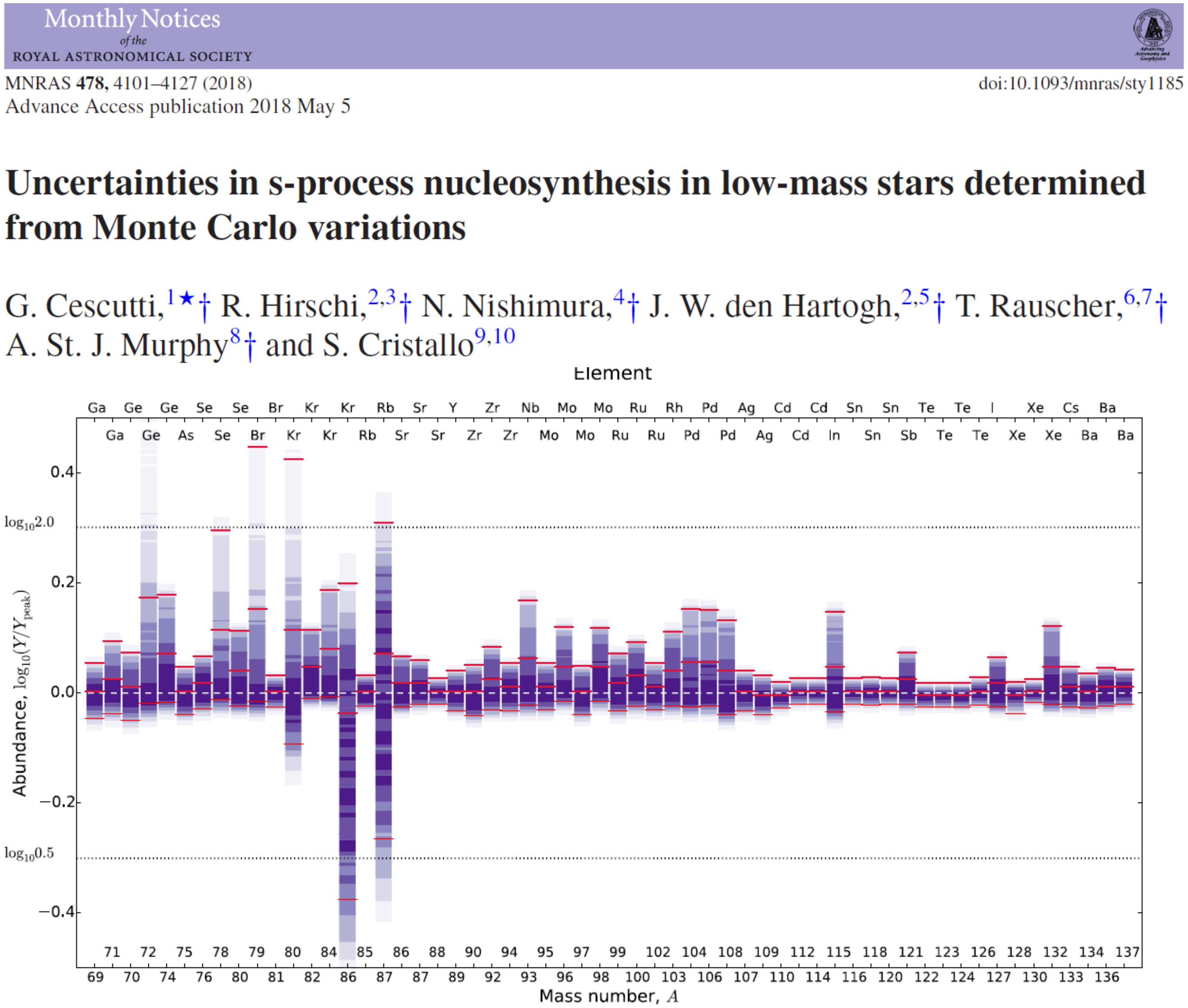
About 50% of (n,γ) measurements at CERN n_TOF are related to astrophysics

The n_TOF Collaboration list of publications:
https://twiki.cern.ch/NTOFPublic/ListOfPublications



About 50% of (n,γ) measurements at CERN n_TOF are related to astrophysics





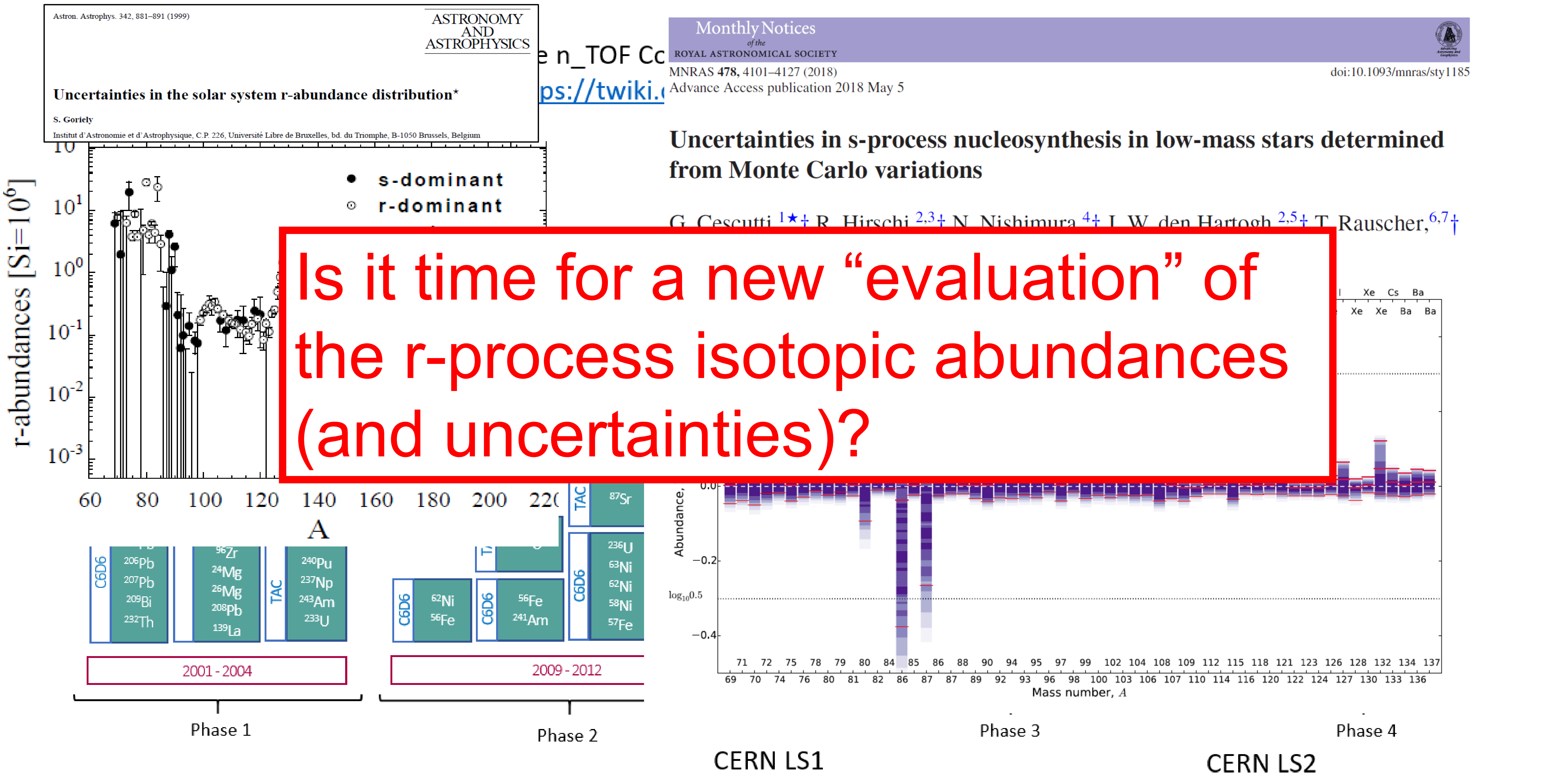
Phase 3

Phase 4

CERN LS1

CERN LS2

About 50% of (n,γ) measurements at CERN n_TOF are related to astrophysics



Is it time for a new "evaluation" of the r-process isotopic abundances (and uncertainties)?

Outline

- R-process (solar) isotopic abundances require accurate neutron-capture measurements along the s-process path on stable <u>and unstable</u> isotopes

- **How far are we from direct neutron capture experiments as input for r-process model calculations?**

Sensitivity studies for (n,γ) in r-process nucleosynthesis

PHYSICAL REVIEW C **83**, 045809 (2011)

Dynamical *r*-process studies within the neutrino-driven wind scenario and its sensitivity to the nuclear physics input

A. Arcones[1,2,*] and G. Martínez-Pinedo[2]
[1]*Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany*
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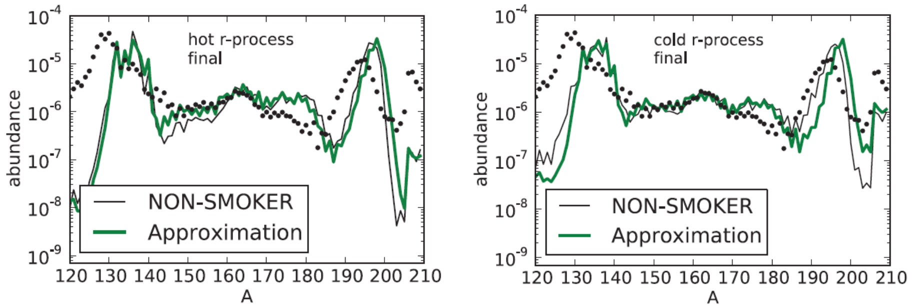
(Received 23 August 2010; revised manuscript received 22 December 2010; published 27 April 2011)



Progress in Particle and Nuclear Physics 86 (2016) 86–126

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

journal homepage: www.elsevier.com/locate/ppnp

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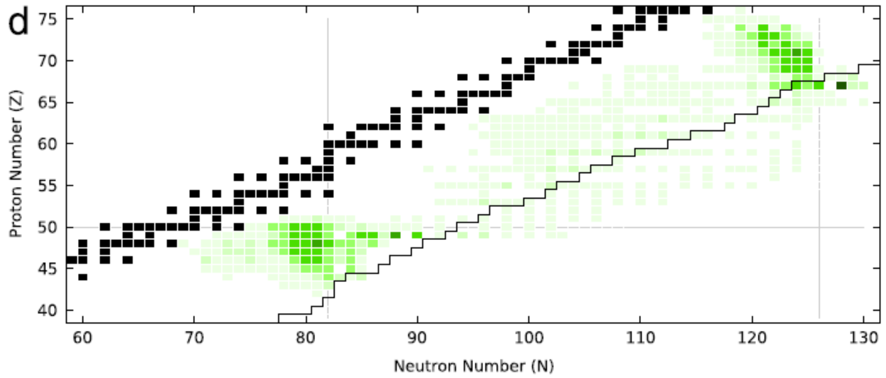
Review

The impact of individual nuclear properties on *r*-process nucleosynthesis

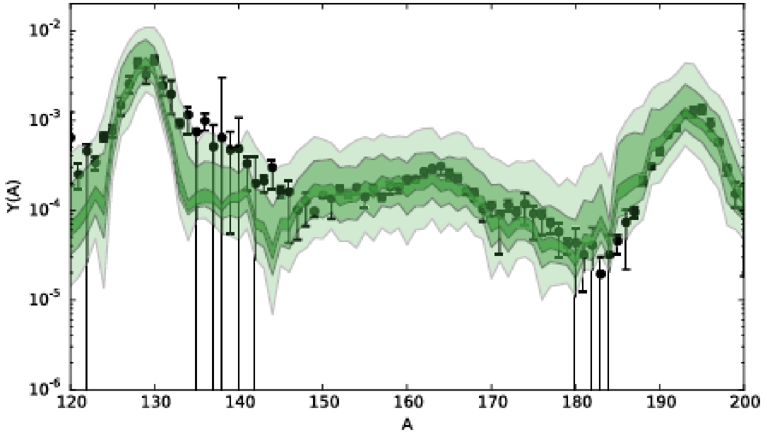
M.R. Mumpower[a], R. Surman[a,*], G.C. McLaughlin[b], A. Aprahamian[a]



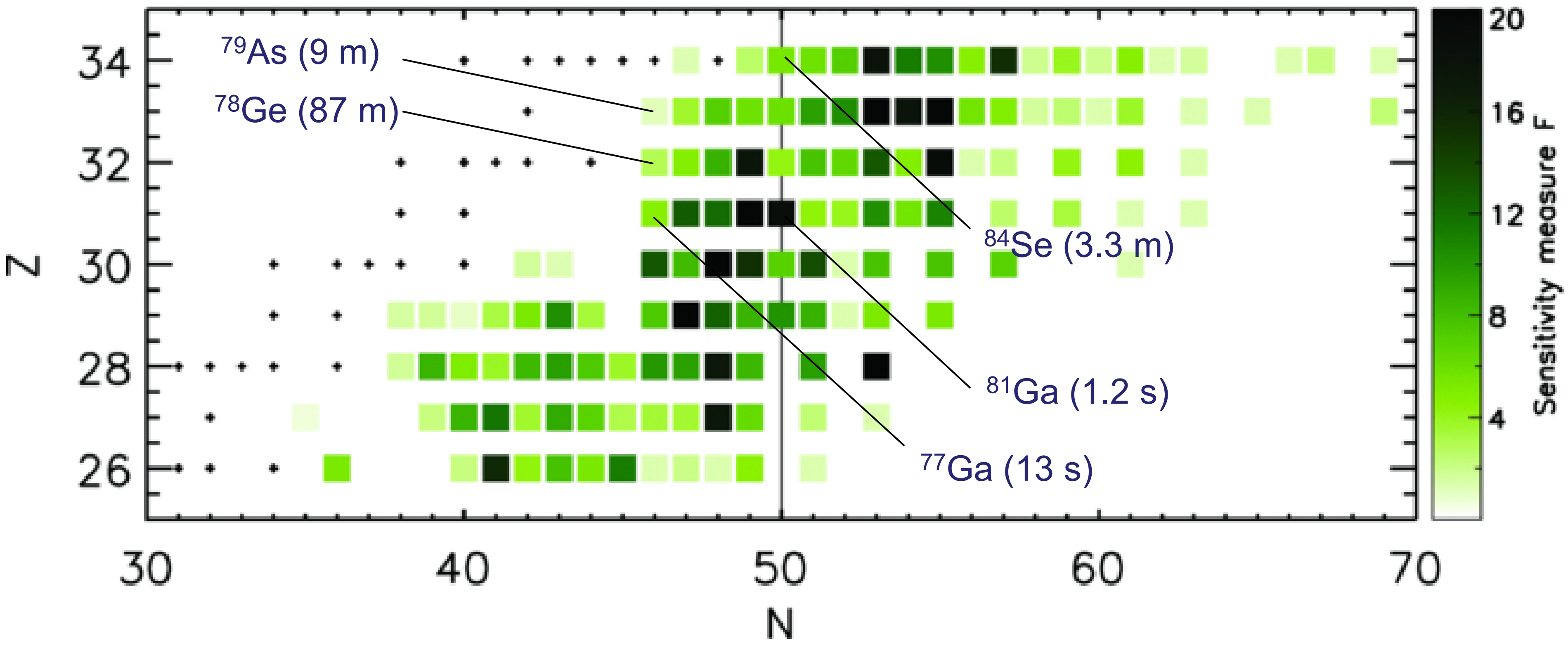
PRL **116,** 242502 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

Experimental Neutron Capture Rate Constraint Far from Stability

S. N. Liddick,[1,2] A. Spyrou,[1,3,4] B. P. Crider,[1] F. Naqvi,[1] A. C. Larsen,[5] M. Guttormsen,[5] M. Mumpower,[6,7] R. Surman,[6] G. Perdikakis,[8,1,4] D. L. Bleuel,[9] A. Couture,[10] L. Crespo Campo,[5] A. C. Dombos,[1,3,4] R. Lewis,[1,2] S. Mosby,[10] S. Nikas,[8,4] C. J. Prokop,[1,2] T. Renstrom,[5] B. Rubio,[11] S. Siem,[5] and S. J. Quinn[1,3,4]



How far are direct (n,γ) measurements from r-nuclei?

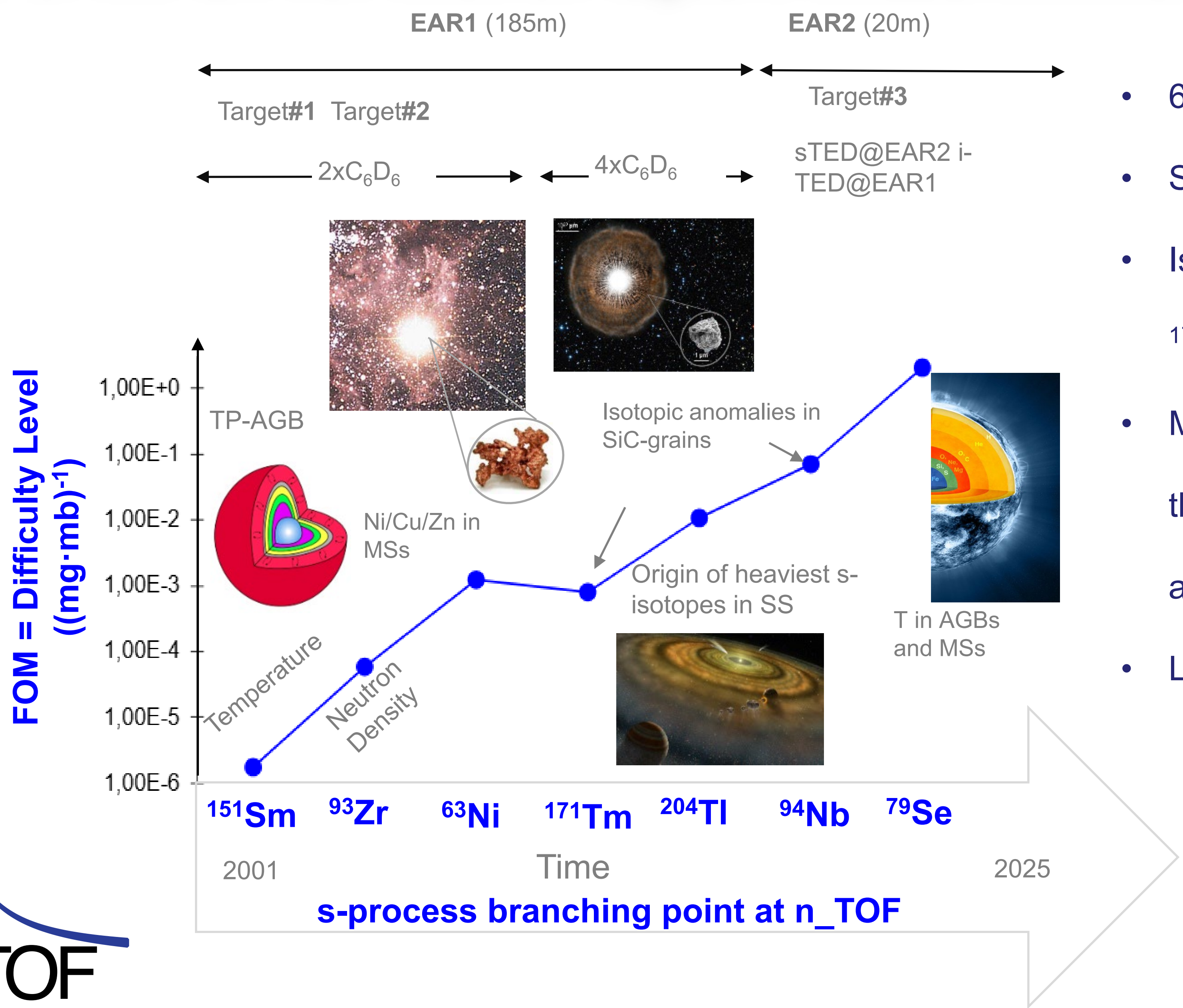


AIP ADVANCES **4**, 041008 (2014)

Sensitivity studies for the weak *r* process: neutron capture rates

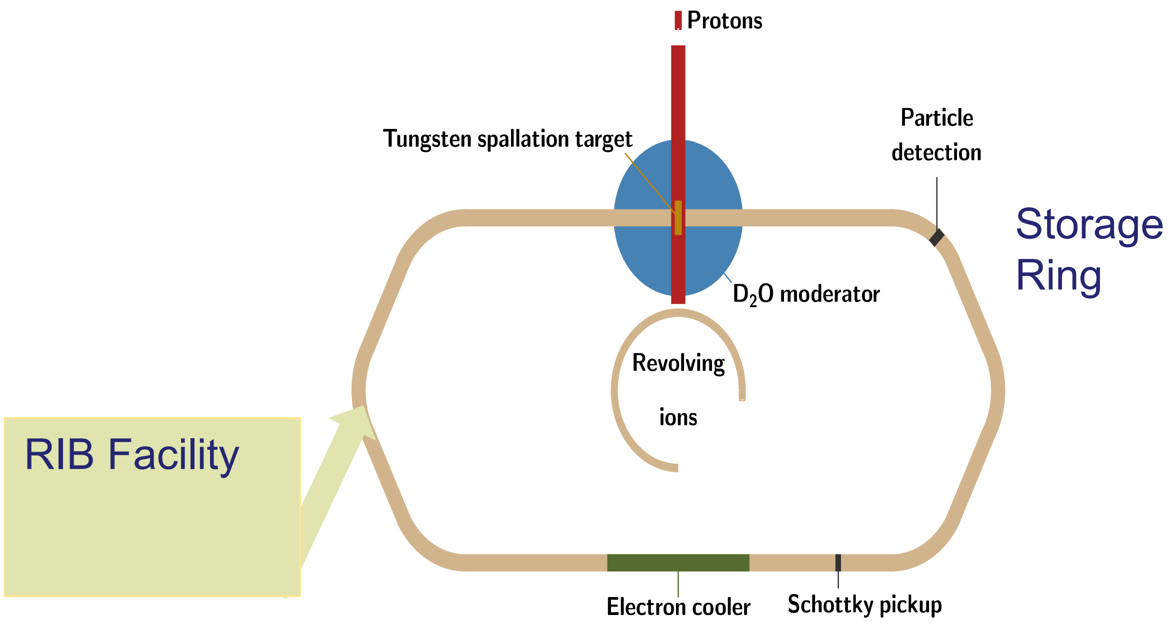
R. Surman,[1,a] M. Mumpower,[2] R. Sinclair,[3] K. L. Jones,[3] W. R. Hix,[3,4] and G. C. McLaughlin[5]

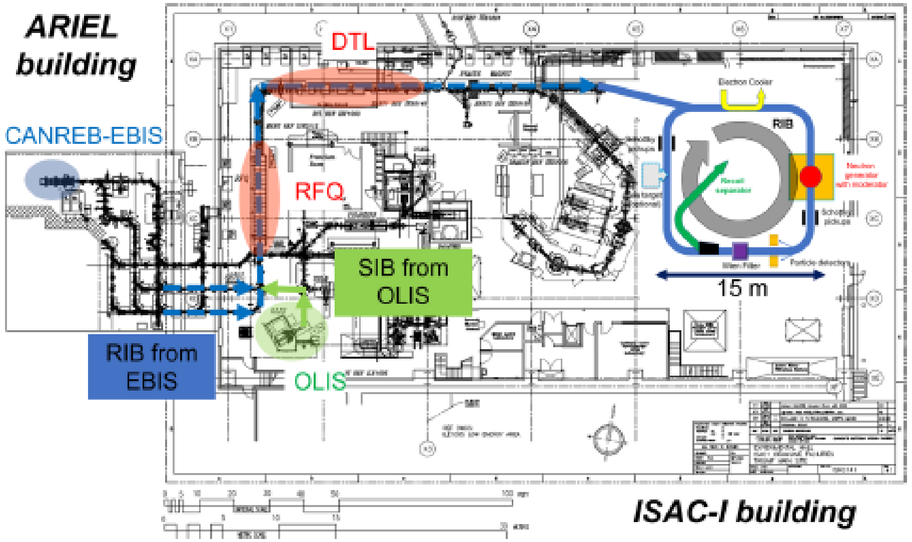
State-of-the-art TOF neutron-capture measurements:



- 6 oom improvement over the last 25 y
- Still shortest lived isotope few yr
- Isotope with shortest t1/2 measured is ^{171}Tm(n,γ) ($t_{1/2}$=701 d)
- More recently ^{88}Zr(n,γ) ($t_{1/2}$=83 d), but only in the thermal neutron-energy range and it has a huge cross section
- Limitations (luminosity):
    - sample atoms (>10^{18}),
    - sample half-life / production rates
    - Attainable neutron fluxes

How far are r-nuclei from direct (n, γ) measurements?





Eur. Phys. J. A (2023) 59:105
https://doi.org/10.1140/epja/s10050-023-01012-9
THE EUROPEAN PHYSICAL JOURNAL A
Regular Article - Experimental Physics

Measuring neutron capture cross sections of radioactive nuclei

From activations at the FZK Van de Graaff to direct neutron captures in inverse kinematics with a storage ring at TRIUMF

Iris Dillmann[1,2,a], Oliver Kester[1,2], Richard Baartman[1,2], Alan Chen[3], Tobias Junginger[1,2], Falk Herwig[2], Dobrin Kaltchev[1], Annika Lennarz[1,3], Thomas Planche[1,2], Chris Ruiz[1,2], Nicole Vassh[1]

PHYSICAL REVIEW ACCELERATORS AND BEAMS **20,** 044701 (2017)

Spallation-based neutron target for direct studies of neutron-induced reactions in inverse kinematics

René Reifarth,* Kathrin Göbel, Tanja Heftrich, and Mario Weigand
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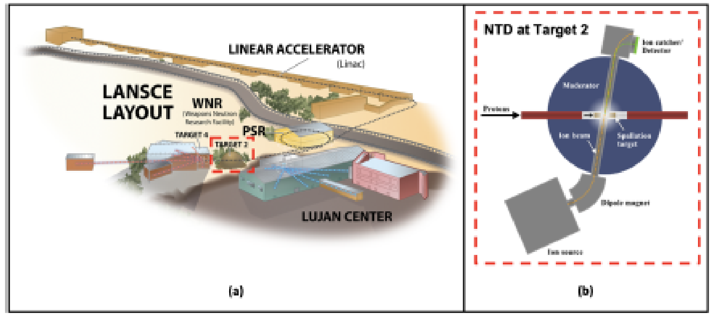
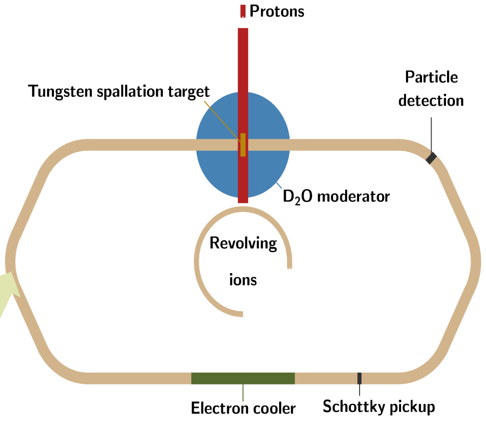


20th International Conference on Ion Sources
Journal of Physics: Conference Series
IOP Publishing
2743 (2024) 012091 doi:10.1088/1742-6596/2743/1/012091

A high-intensity, low-energy heavy ion source for a neutron target proof-of-principle experiment at LANSCE

Andrew L Cooper[1], S Mosby[1], R Reifarth[2], A Couture[1], E Bennett[1], N Gibson[1], D Gorelov[1], C Keith[1], A Lovell[1], G Misch[1], and M Mumpower[1]

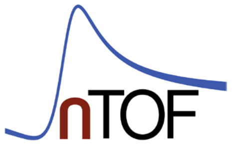
How far are r-nuclei from direct (n, γ) measurements?



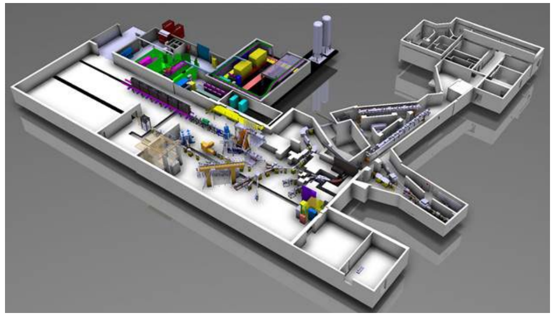
Storage Ring

RIB Facility

+



+ RING?



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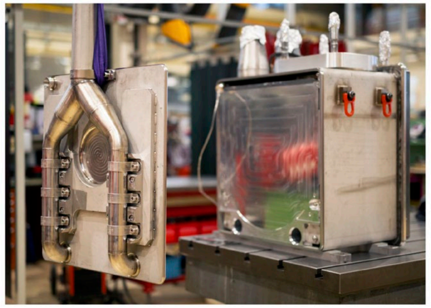
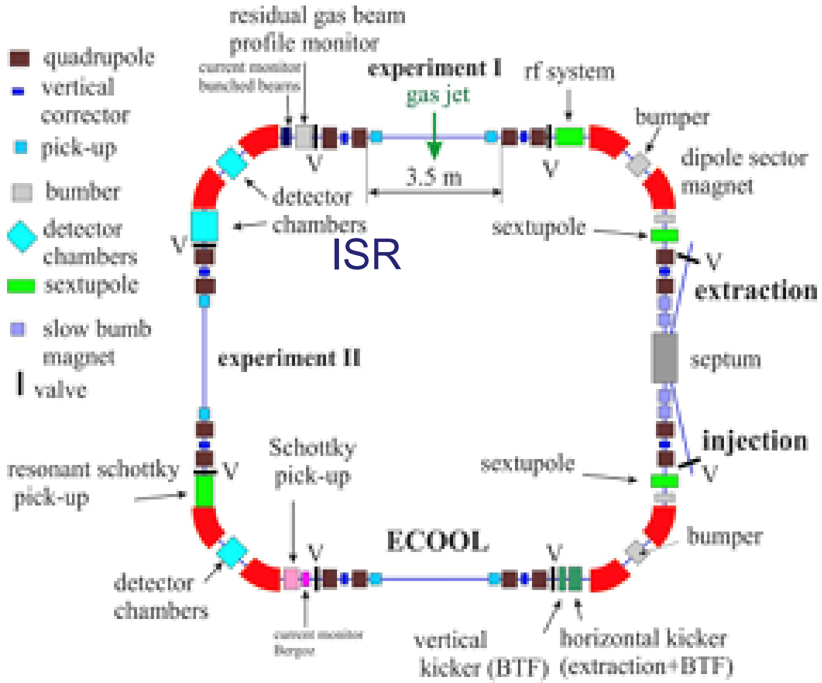


+

+ Other variations/alternatives of this novel method being investigated!



→ISR Project (2030+?)

M. Grieser et al., Eur. Phys. J Spec. Top. 207, 1 (2012)

Summary & Outlook

- R-process (isotopic) abundances are affected by uncertainties which, at least for s-process dominated contributions are dominated by **uncertainties on the (n, γ) capture cross sections** of the corresponding nuclei

- Calculated **s-only** isotopic abundances are used for “calibrating” the free parameters of the models for the r-process “residuals”. (n,γ) cross sections of neighbouring **branching points** can severly affect those s-only abundances used for calibration

- State-of-the-art (TOF) techniques have reached their limit for the measurement of nuclei with half-lives shorter than 1 y

- In the future, alternative novel approaches based on inverse kinematics, utilizing RIB (ISOL) facilities, low-energy ion-storage rings and static neutron targets, could provide access to direct (n,γ) cross section measurements in the neighborhood of the r-process path.

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T. Wright[11]
P. Žugec[12]

The n_TOF Collaboration