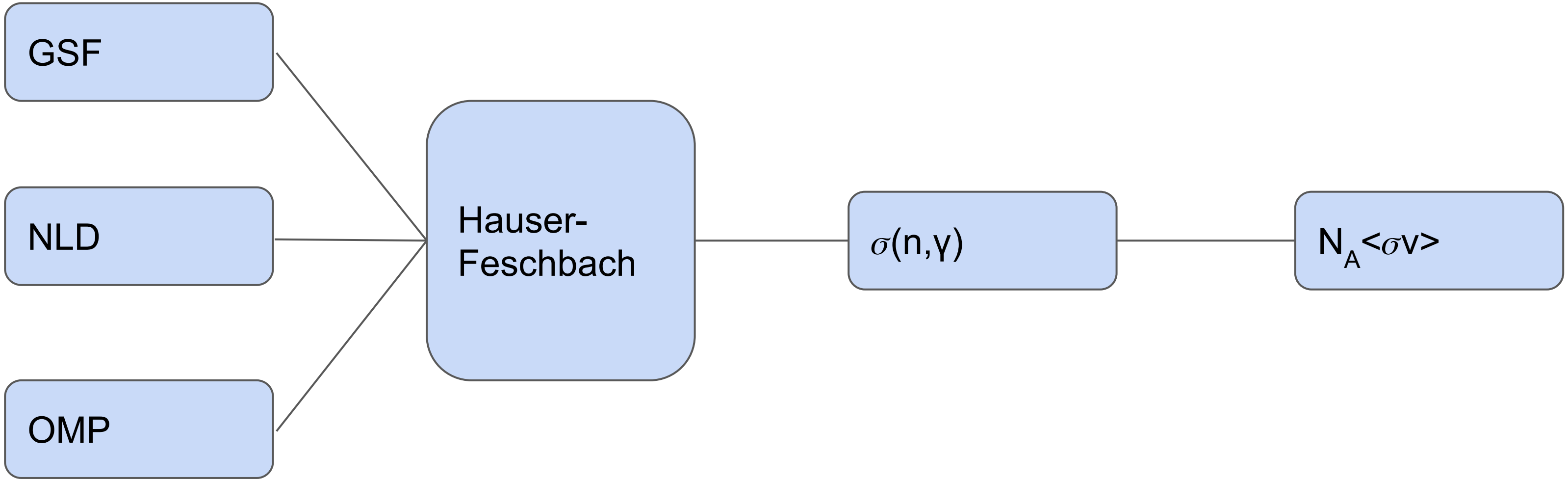
Neutron-capture cross section for *i* process bottleneck ^{75}Ga: $^{75}\mathbf{Ga}(d,p\gamma)^{76}\mathbf{Ga}$

69th Meeting of the INTC
February 9th

Spokeperson: Francesco Pogliano, PhD candidate
University of Oslo, Oslo, Norway

Aims

- Aim: Finding the nuclear level density (NLD) and gamma strength function (GSF) of ^{76}Ga



GSF

NLD

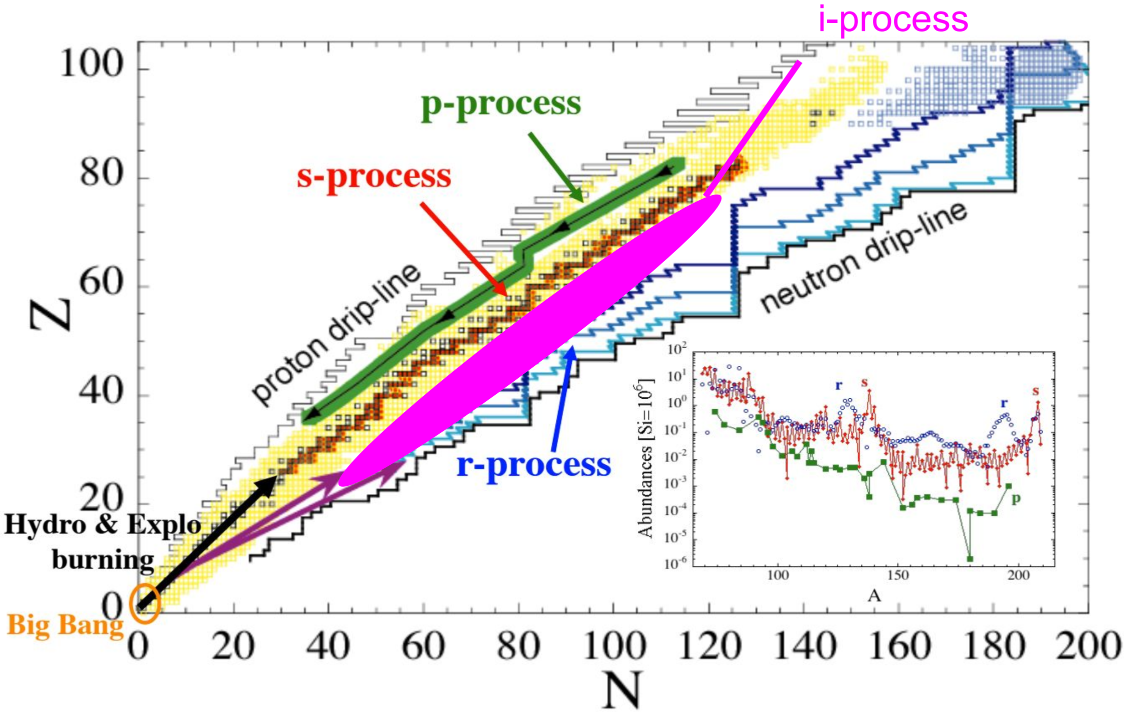
OMP

Hauser-Feschbach

σ(n,γ)

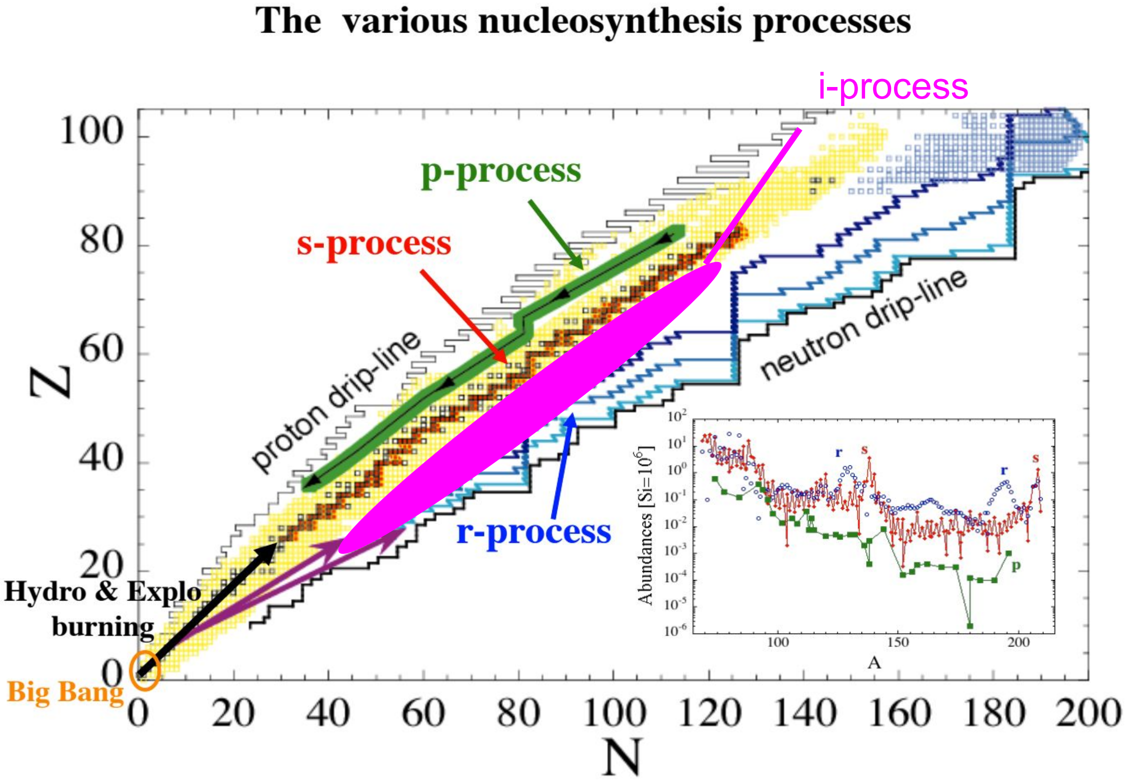
$N_A\langle\sigma v\rangle$

Aims


The various nucleosynthesis processes

Neutron capture rates important for nucleosynthesis

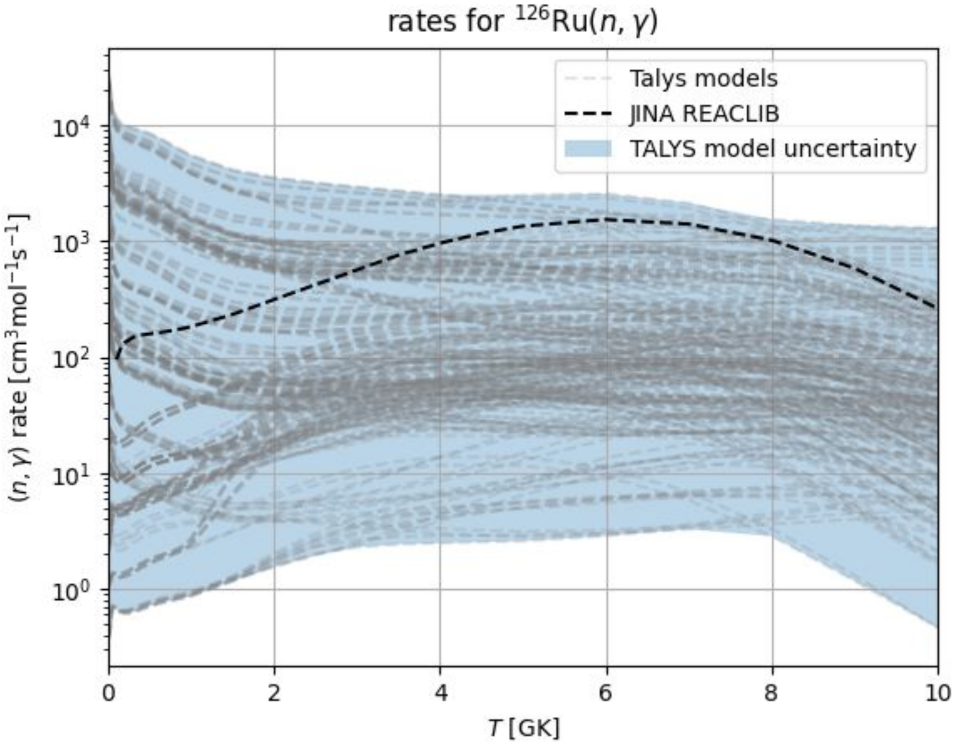
Aims



Neutron capture rates important for nucleosynthesis

i and r process involve neutron-rich nuclei

Aims



Neutron capture rates important for nucleosynthesis

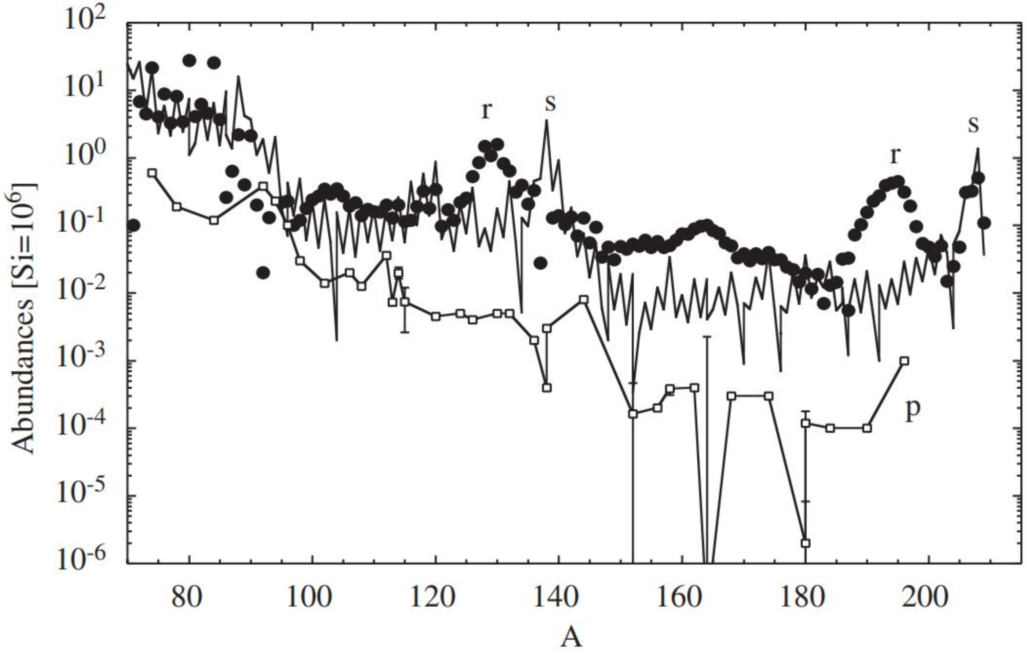
i and r process involve neutron-rich nuclei

We rely on theoretical models

Experiments -> constrain uncertainty

Motivation 1

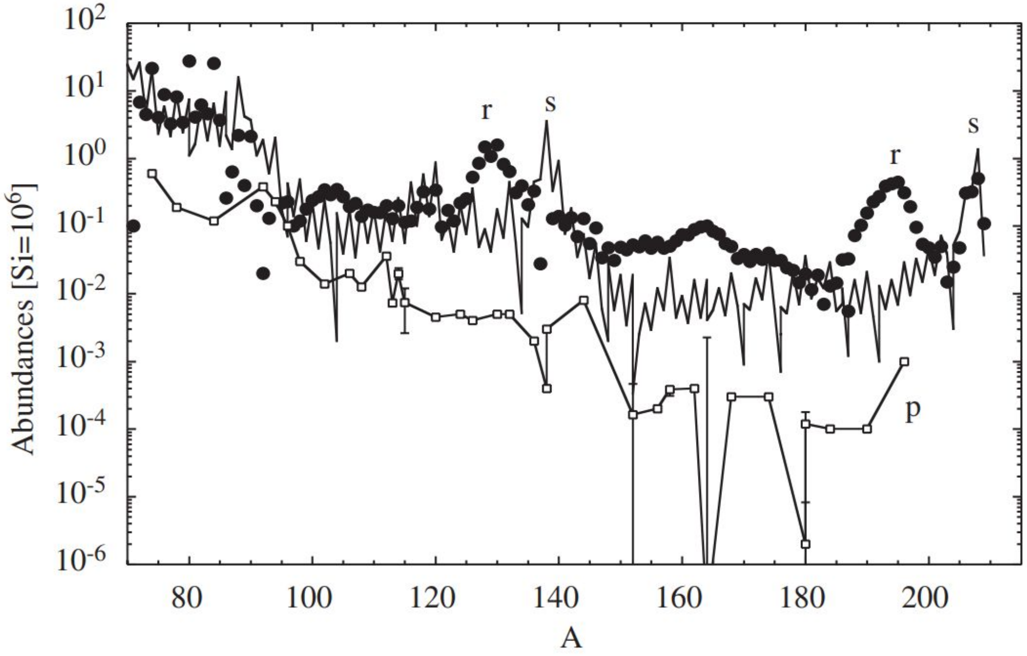
M. Arnould et al. / Physics Reports 450 (2007) 97–213



The case of Ga-75

Different abundance patterns for s and r process

Motivation 1



M. Arnould et al. / Physics Reports 450 (2007) 97–213

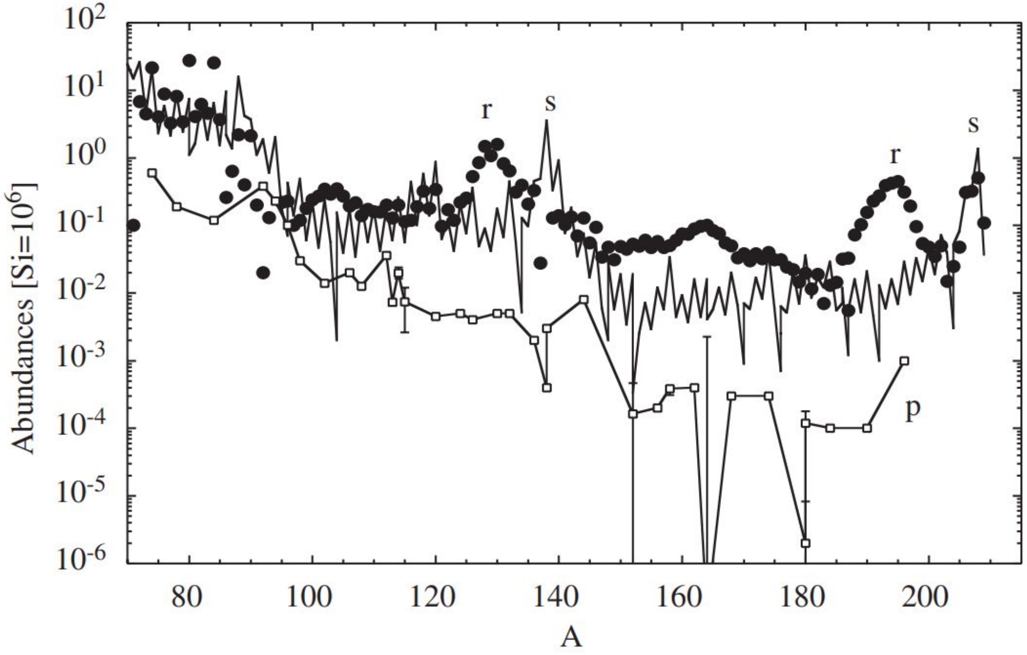
The case of Ga-75

Different abundance patterns for s and r process

Abundance in stars: combination of *r* and *s* process abundance patterns

Motivation 1

M. Arnould et al. / Physics Reports 450 (2007) 97–213



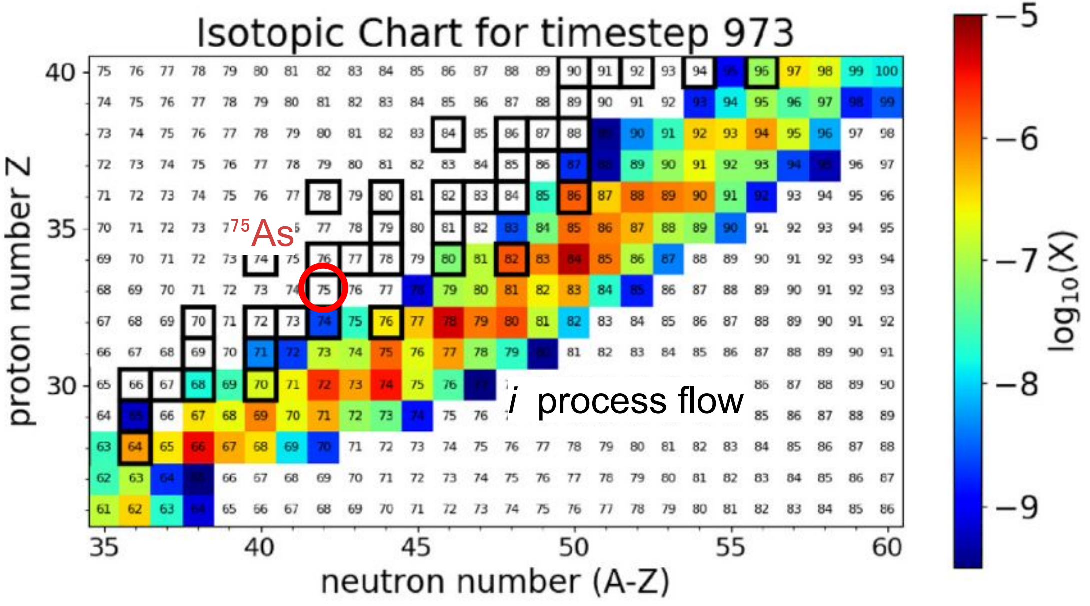
The case of Ga-75

Different abundance patterns for s and r process

Abundance in stars: combination of *r* and *s* process abundance patterns

Sometimes not enough

Motivation 1

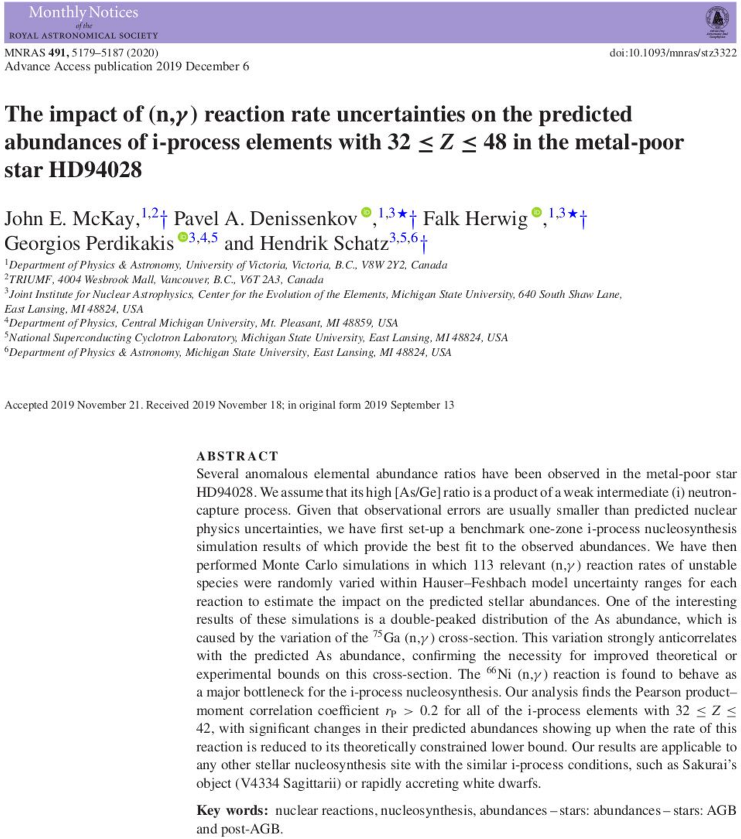


J. E. McKay et al. In: MNRAS 491.4 (2019), p. 5179.

Observation of As in carbon-poor, metal-poor star HD94028

Not able to explain its relative abundance by r and s processes alone

Motivation 1



Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS **491,** 5179–5187 (2020) doi:10.1093/mnras/stz3322
Advance Access publication 2019 December 6

The impact of (n,γ) reaction rate uncertainties on the predicted abundances of i-process elements with $32 \le Z \le 48$ in the metal-poor star HD94028

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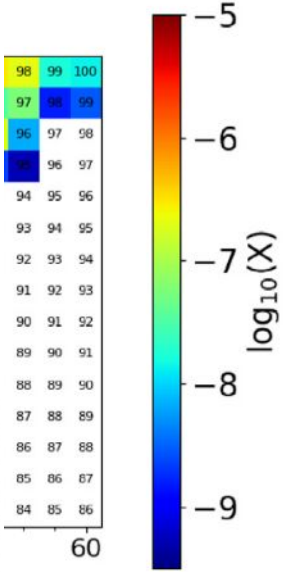
Accepted 2019 November 21. Received 2019 November 18; in original form 2019 September 13

ABSTRACT

Several anomalous elemental abundance ratios have been observed in the metal-poor star HD94028. We assume that its high [As/Ge] ratio is a product of a weak intermediate (i) neutron-capture process. Given that observational errors are usually smaller than predicted nuclear physics uncertainties, we have first set-up a benchmark one-zone i-process nucleosynthesis simulation results of which provide the best fit to the observed abundances. We have then performed Monte Carlo simulations in which 113 relevant (n,γ) reaction rates of unstable species were randomly varied within Hauser–Feshbach model uncertainty ranges for each reaction to estimate the impact on the predicted stellar abundances. One of the interesting results of these simulations is a double-peaked distribution of the As abundance, which is caused by the variation of the ^{75}Ga (n,γ) cross-section. This variation strongly anticorrelates with the predicted As abundance, confirming the necessity for improved theoretical or experimental bounds on this cross-section. The ^{66}Ni (n,γ) reaction is found to behave as a major bottleneck for the i-process nucleosynthesis. Our analysis finds the Pearson product–moment correlation coefficient $r_P > 0.2$ for all of the i-process elements with $32 \le Z \le 42$, with significant changes in their predicted abundances showing up when the rate of this reaction is reduced to its theoretically constrained lower bound. Our results are applicable to any other stellar nucleosynthesis site with the similar i-process conditions, such as Sakurai's object (V4334 Sagittarii) or rapidly accreting white dwarfs.

Key words: nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: AGB and post-AGB.

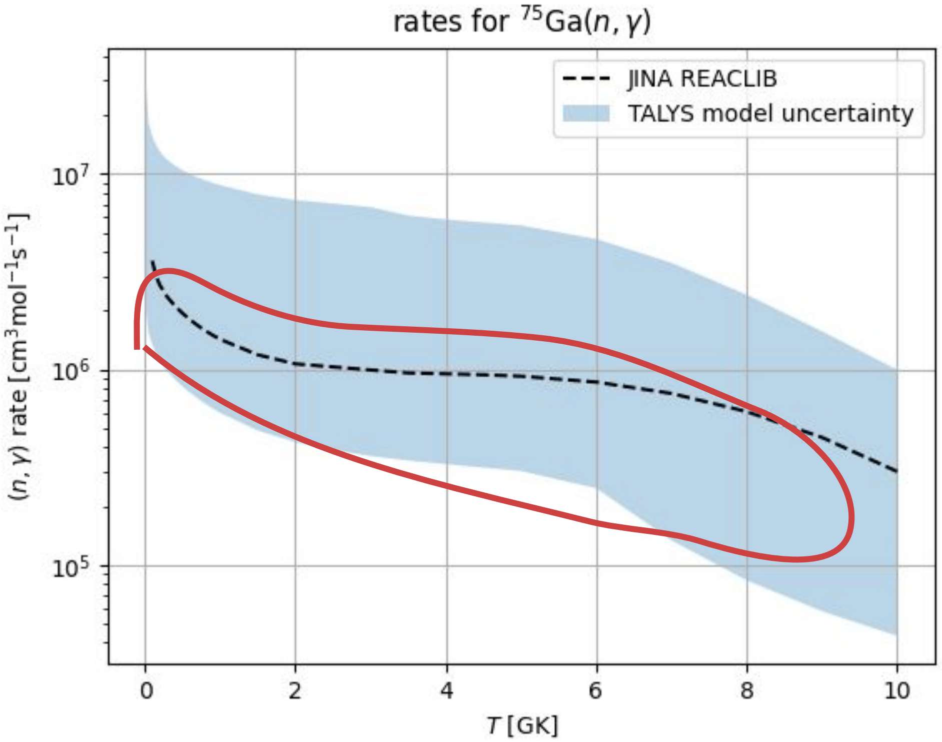


Observation of As in carbon-poor, metal-poor star HD94028

Not able to explain its relative abundance by r and s processes alone

i process might explain this

Motivation 1



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i process might explain this

but only if ^{75}Ga(n,γ) rate is low

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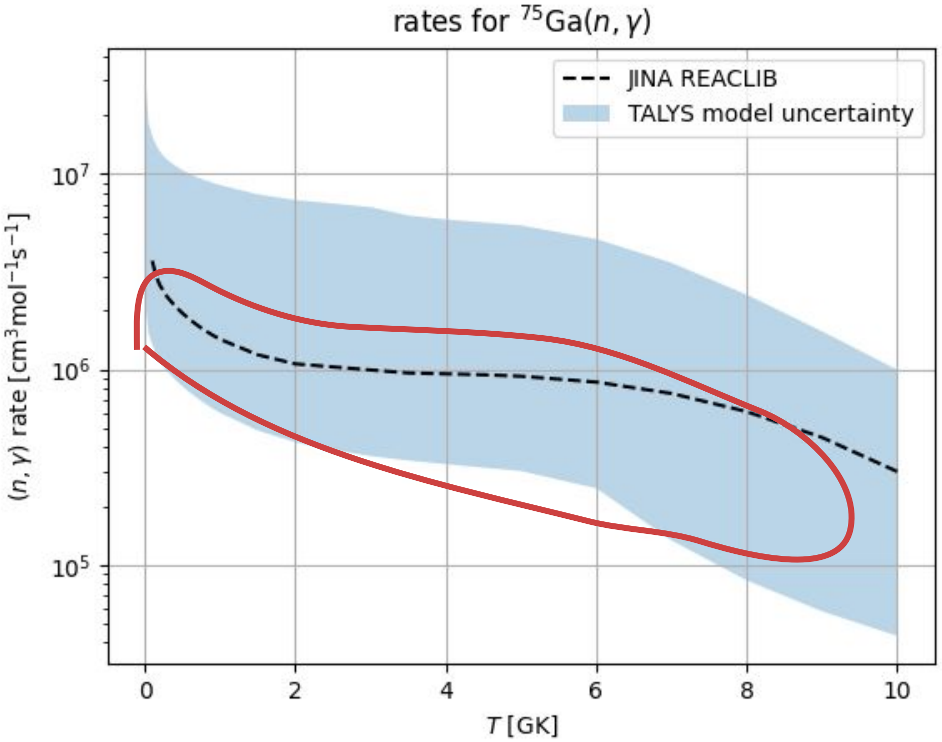

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Uncertainties too large conclude

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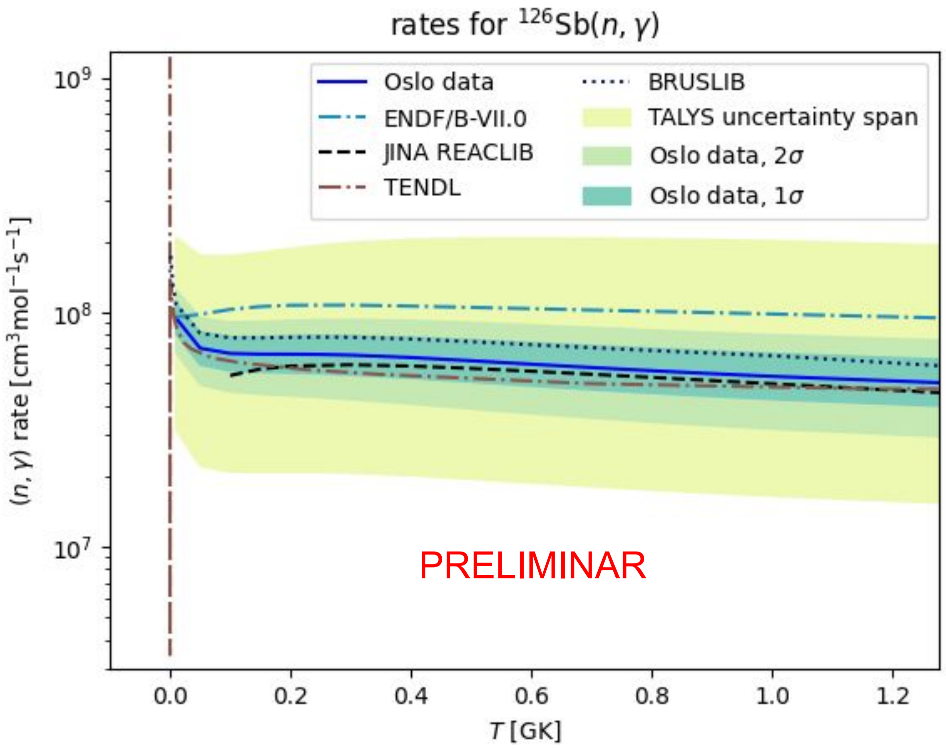
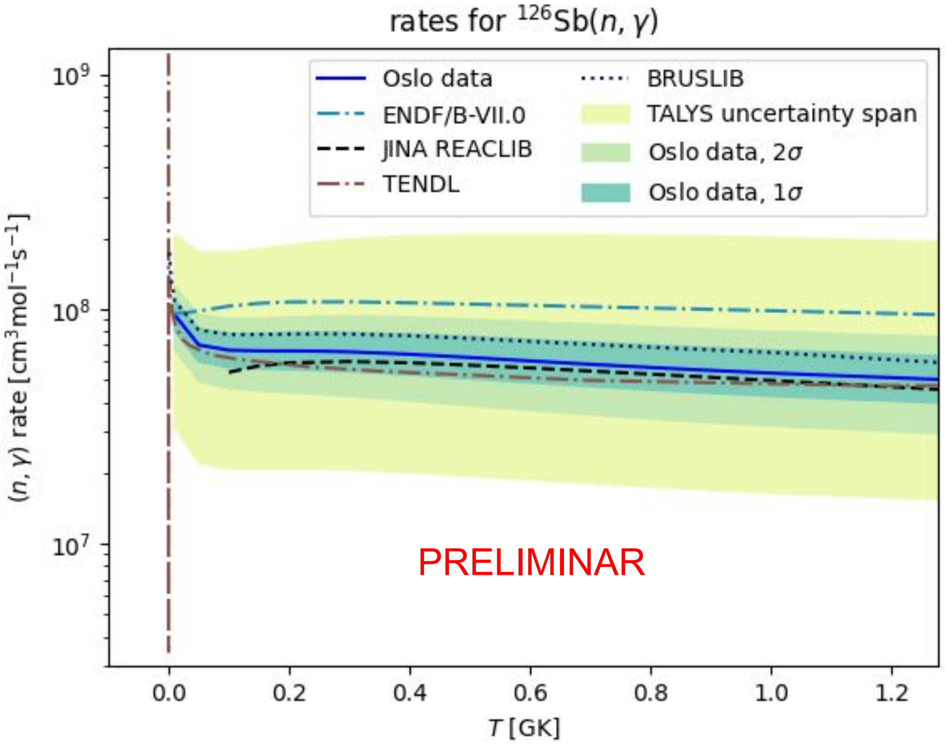


Measuring indirectly the neutron-capture rate
-> constrain the uncertainty

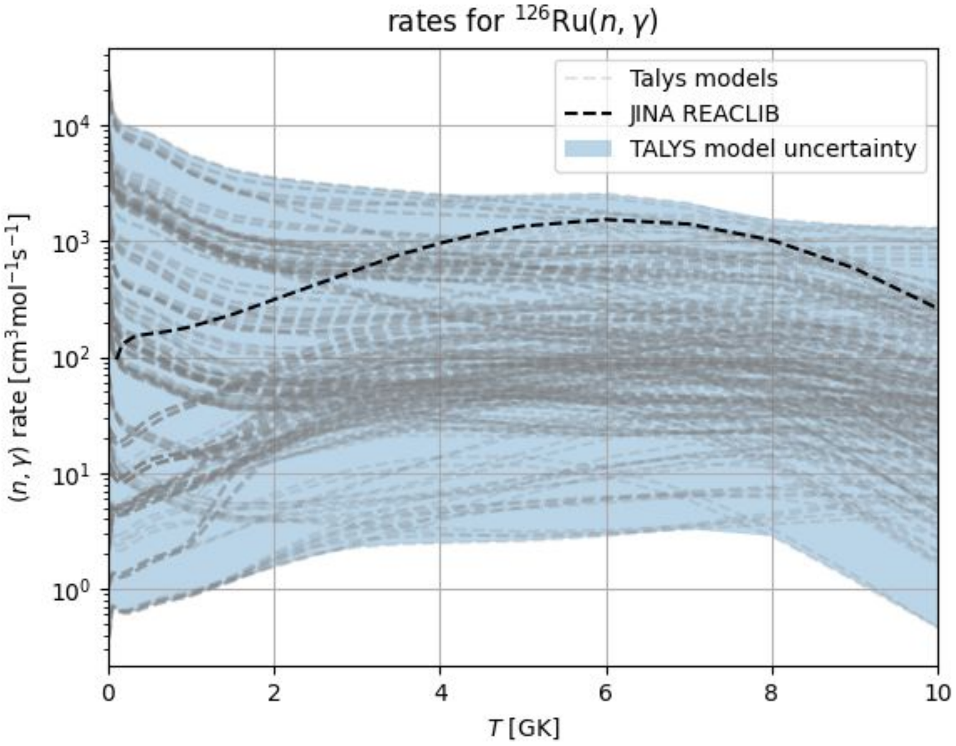
Motivation 1



Measuring indirectly the neutron-capture rate
-> constrain the uncertainty

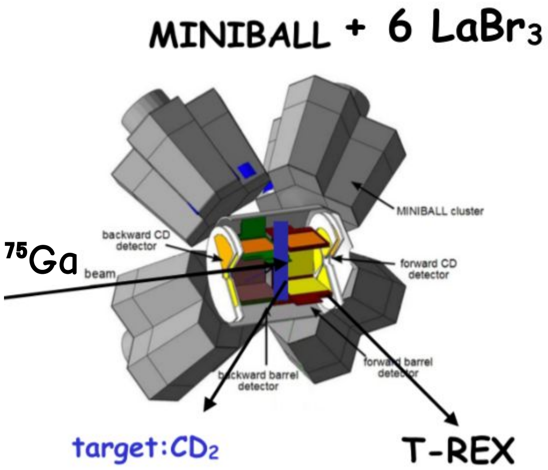
Either clearer picture of the i process, or uncovering the need of a new, yet unknown theory

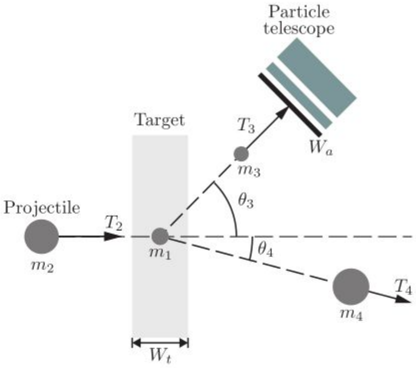
Motivation 2



Providing useful experimental data, useful for the *i* process and for the *r* process.

Experiment

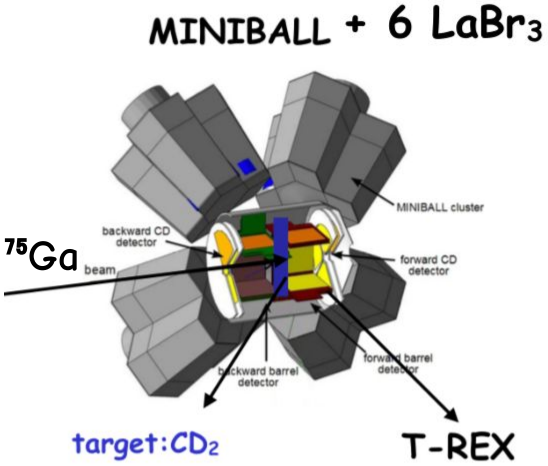


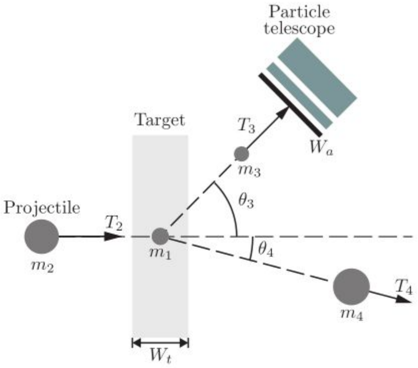


Steps:

A beam of ^{75}Ga is impinged onto a CD_2 target

Experiment



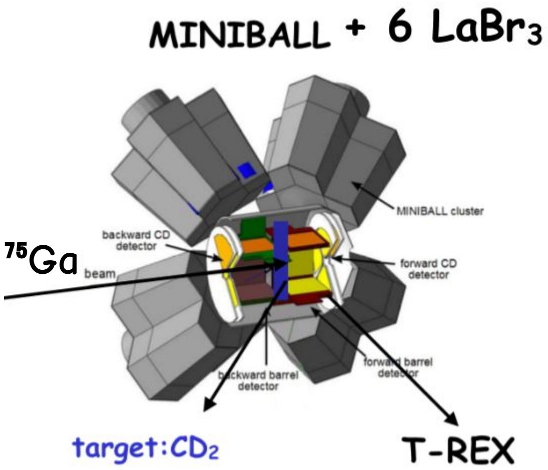


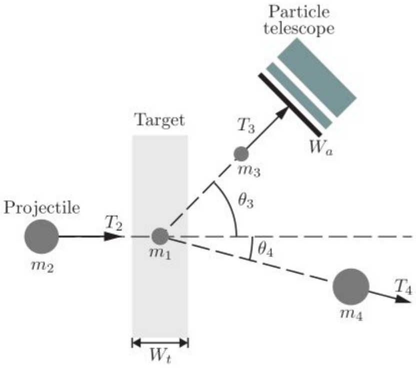
Steps:

A beam of ^{75}Ga is impinged onto a CD_2 target

Detect p-γ coincidences with MINIBALL, Oslo's LaBr3 and T-REX

Experiment





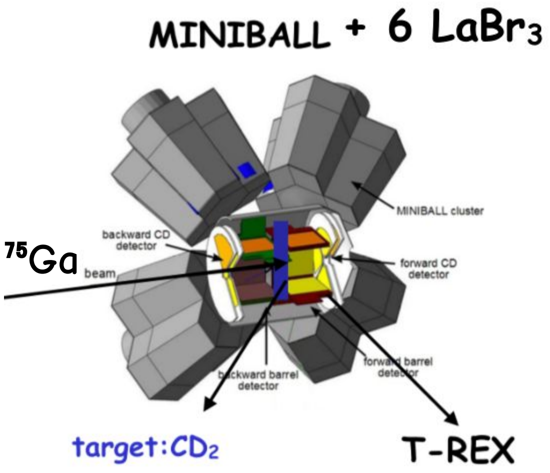
Steps:

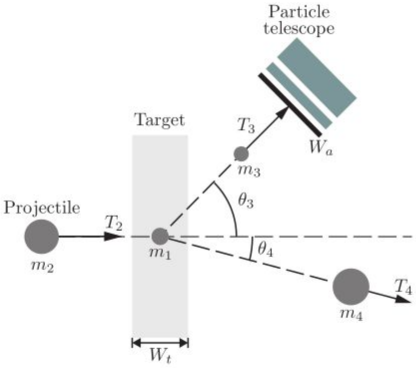
A beam of ^{75}Ga is impinged onto a CD_2 target

Detect p-γ coincidences with MINIBALL, Oslo's LaBr3 and T-REX

Calculate excitation energy of ^{76}Ga via kinematics

Experiment





Steps:

A beam of ^{75}Ga is impinged onto a CD_2 target

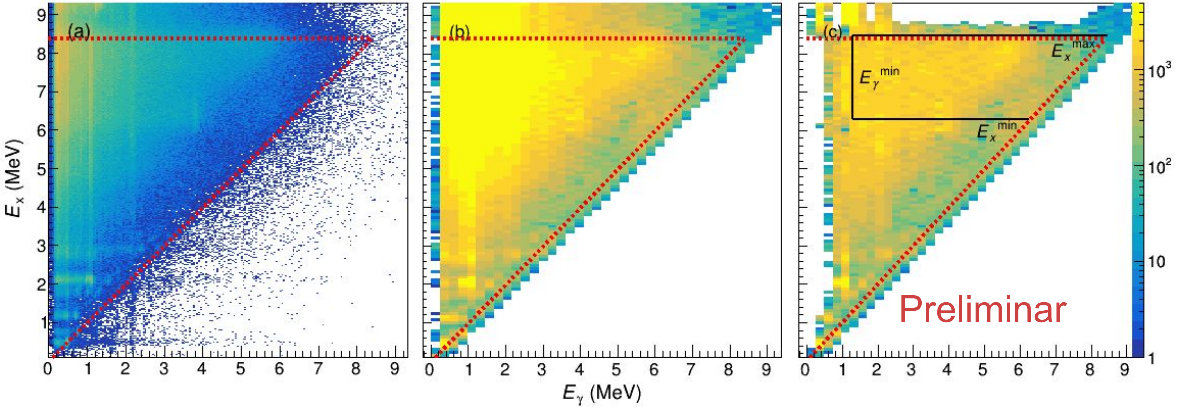
Detect p-γ coincidences with MINIBALL, Oslo's LaBr3 and T-REX

Calculate excitation energy of ^{76}Ga via kinematics

Make "raw" matrix

Experiment

Data for ^{127}Sb at OCL



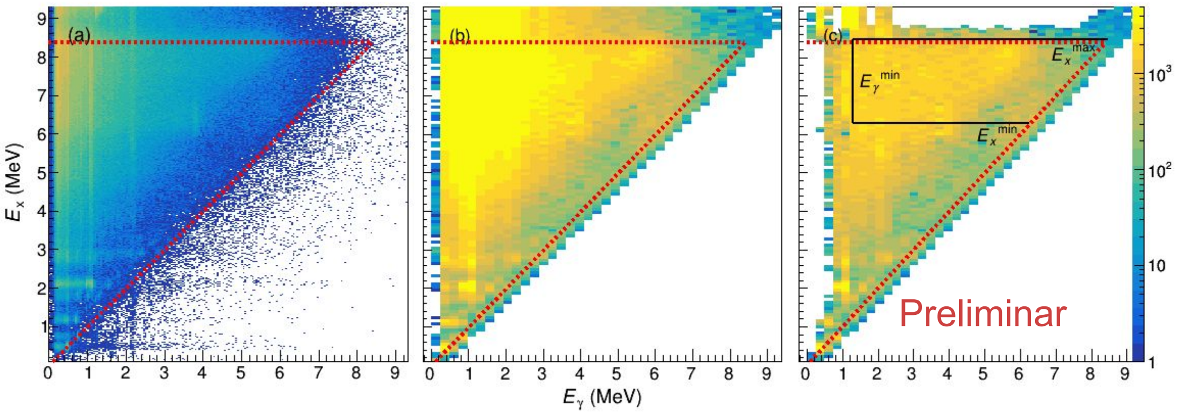
Oslo method (in inverse kinematics)

Unfolding

First generation

Experiment

Data for ^{127}Sb at OCL



Oslo method (in inverse kinematics)

Unfolding

First generation

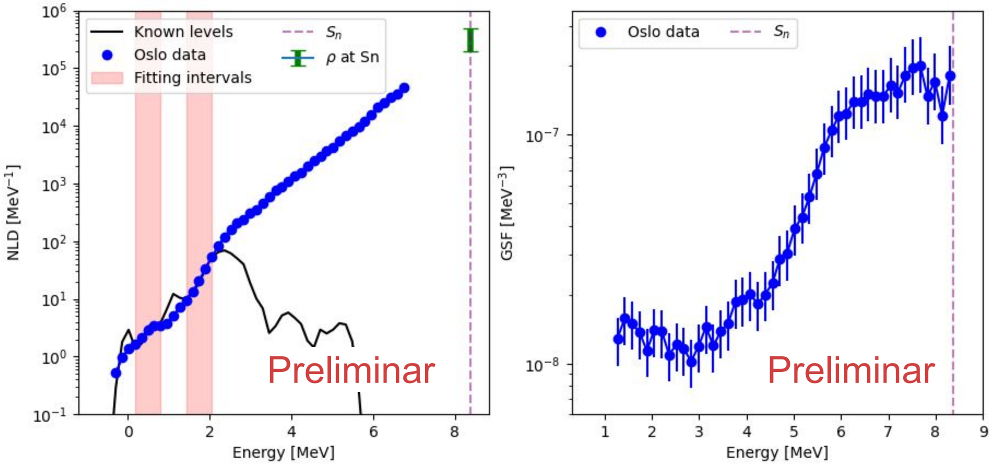
Fermi’s golden rule:

$$P(E_\gamma, E_x) \propto \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

GSF:

$$\mathcal{T}(E_\gamma) = \frac{f(E_\gamma)}{2\pi E_\gamma^3}$$

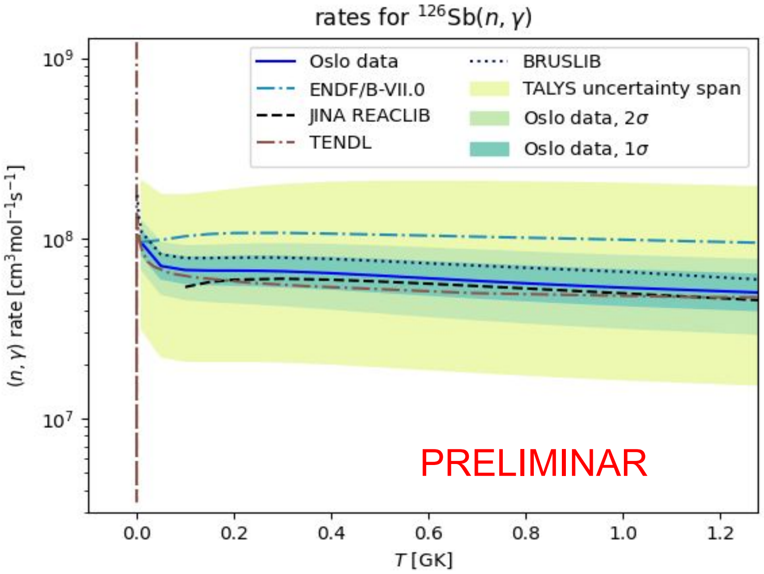
Experiment



Data for ^{127}Sb at OCL

From the NLD and the GSF it is possible to retrieve the (n,γ) cross section using the HF formalism

Experiment



$$N_A \langle \sigma v \rangle_{n\gamma}(T) = \left(\frac{8}{\pi \tilde{m}}\right)^{1/2} \frac{N_A}{(k_B T)^{3/2} G_t(T)} \int_0^\infty \sum_\mu \frac{2J_t^\mu + 1}{2J_t^0 + 1} \sigma_{n\gamma}^\mu(E) E \exp\left[-\frac{E + E_x^\mu}{k_B T}\right] \mathrm{d}E$$

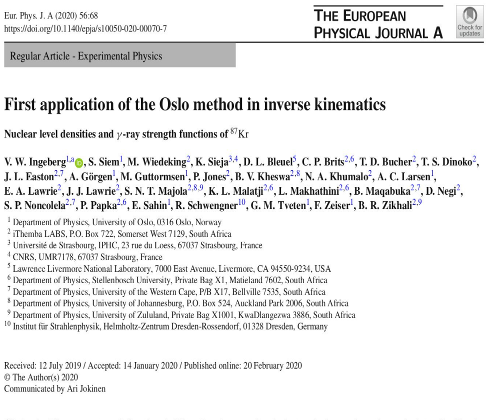
$$N_A\langle\sigma v\rangle = \frac{N_A\langle\sigma\rangle}{v_T}$$

From the NLD and the GSF it is possible to retrieve the (n,γ) cross section using the HF formalism

MACS and capture rate for A-1 nucleus

(Calculations with reaction code TALYS)

Experiment



Eur. Phys. J. A (2020) 56:68
https://doi.org/10.1140/epja/s10050-020-00070-7

THE EUROPEAN
PHYSICAL JOURNAL A

Regular Article - Experimental Physics

First application of the Oslo method in inverse kinematics

Nuclear level densities and γ-ray strength functions of ^{87}Kr

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Received: 12 July 2019 / Accepted: 14 January 2020 / Published online: 20 February 2020

Communicated by Ari Jokinen

Abstract The γ-ray strength function (γSF) and nuclear
level density (NLD) have been extracted for the first t
from inverse kinematic reactions with the Oslo met
This novel technique allows measurements of these p
erties across a wide range of previously inaccessible nu
Proton–γ coincidence events from the d(^{86}Kr, pγ)^{87}Kr r
tion were measured at iThemba LABS and the γSF
NLD in ^{87}Kr was obtained. The low-energy region of
γSF is compared to shell-model calculations, which sug
this region to be dominated by M1 strength. The γSF

absorb photons in the quasi-continuum is determined by the

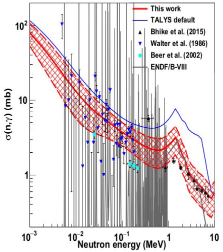


Fig. 3 ^{86}Kr(n, γ) cross sections. The red-hashed area represents the total uncertainty based on both systematical and statistic errors. The gray and blue lines are from the evaluation of ENDF/B-VII.1 [8] and the TALYS default input, respectively, and is provided for comparison. The black triangles shows the direct measurements of Bhike et al. [58], the blue upside-down triangles are results from time-of-flight measurements of Walter et al. [59] and the turquoise circles are the results from the activation measurements of Beer et al. [60]

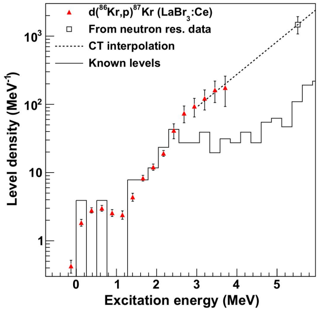


Fig. 1 Normalized ^{87}Kr nuclear level densities for LaBr$_3$:Ce (red circles) detectors. The black line shows the known levels while the open square is the level density at the neutron separation energy. The dashed line is the constant temperature interpolation. The error bars represent the upper and lower uncertainty limit due to all known statistical and systematic effects

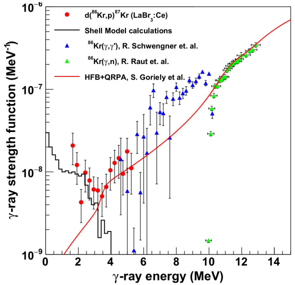
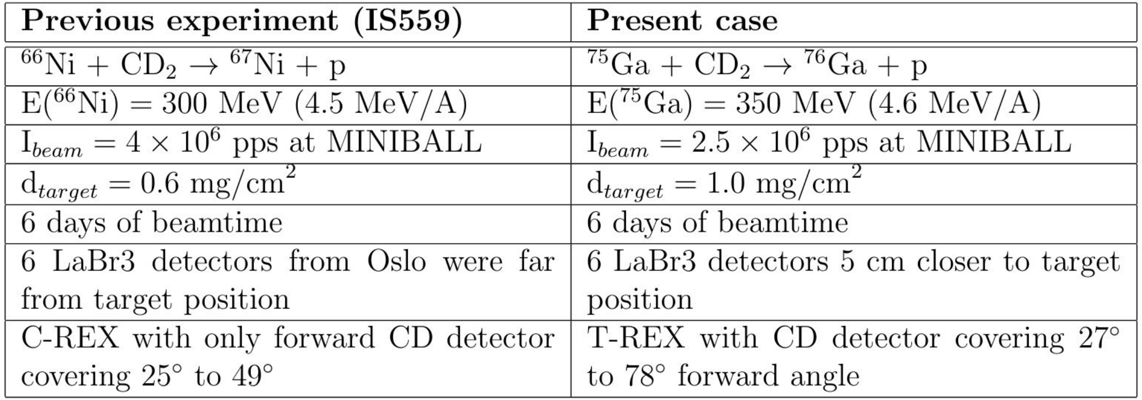


Fig. 2 γ-ray strength function of ^{87}Kr (red circles) compared with the γ-ray strength function of ^{86}Kr extracted from ^{86}Kr(γ, γ') (blue triangles) [35] and ^{86}Kr(γ, n) (green squares) [36]. The solid black line are results from Shell Model calculations with a ^{78}Ni core (see Sect. 5 for details), while the red line is the microscopic HFB+QRPA prediction [37] for the E1 strength. The error bars include all known statistical and systematic errors

This has been done many times before, also in inverse kinematics

Setup

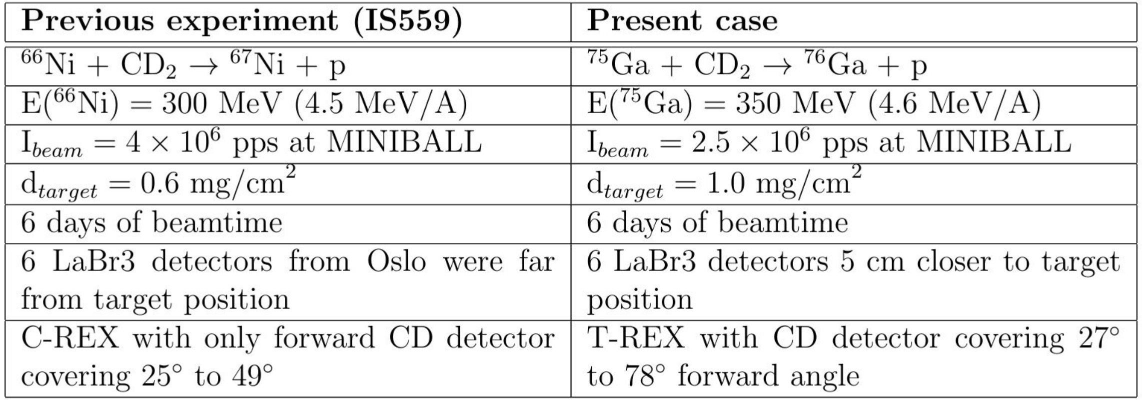
Closely modelled to experiment IS559 on ^{67}Ni



Previous experiment (IS559)	**Present case**
$^{66}\mathrm{Ni} + \mathrm{CD_2} \rightarrow {}^{67}\mathrm{Ni} + \mathrm{p}$	$^{75}\mathrm{Ga} + \mathrm{CD_2} \rightarrow {}^{76}\mathrm{Ga} + \mathrm{p}$
$\mathrm{E}(^{66}\mathrm{Ni}) = 300$ MeV (4.5 MeV/A)	$\mathrm{E}(^{75}\mathrm{Ga}) = 350$ MeV (4.6 MeV/A)
$\mathrm{I}_{beam} = 4 \times 10^6$ pps at MINIBALL	$\mathrm{I}_{beam} = 2.5 \times 10^6$ pps at MINIBALL
$\mathrm{d}_{target} = 0.6\ \mathrm{mg/cm^2}$	$\mathrm{d}_{target} = 1.0\ \mathrm{mg/cm^2}$
6 days of beamtime	6 days of beamtime
6 LaBr3 detectors from Oslo were far from target position	6 LaBr3 detectors 5 cm closer to target position
C-REX with only forward CD detector covering 25° to 49°	T-REX with CD detector covering 27° to 78° forward angle

1.5M good coincidences

Setup



Previous experiment (IS559)	**Present case**
^{66}Ni + CD$_2$ $\rightarrow$ ^{67}Ni + p	^{75}Ga + CD$_2$ $\rightarrow$ ^{76}Ga + p
E(^{66}Ni) = 300 MeV (4.5 MeV/A)	E(^{75}Ga) = 350 MeV (4.6 MeV/A)
$I_{beam} = 4 \times 10^6$ pps at MINIBALL	$I_{beam} = 2.5 \times 10^6$ pps at MINIBALL
$d_{target} = 0.6$ mg/cm^2	$d_{target} = 1.0$ mg/cm^2
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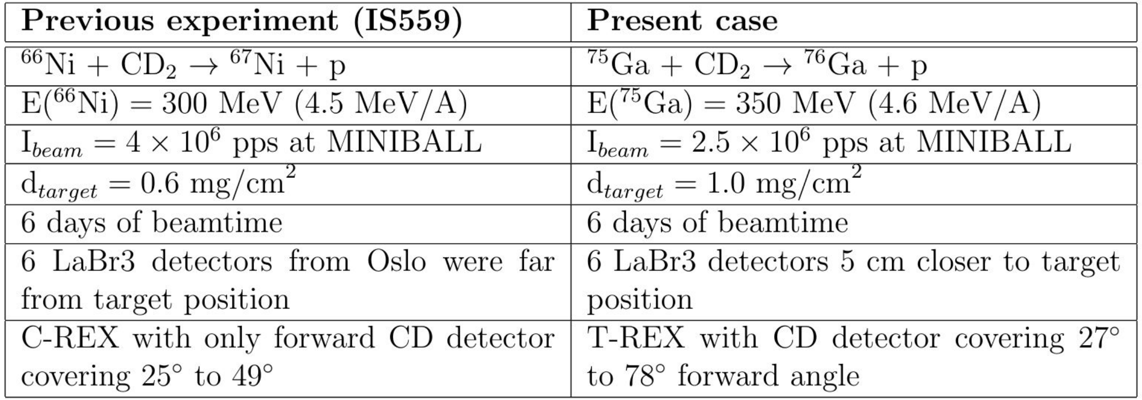
Closely modelled to experiment IS559 on ^{67}Ni

2.5e6 beam of 2005 might not be replicated

Setup



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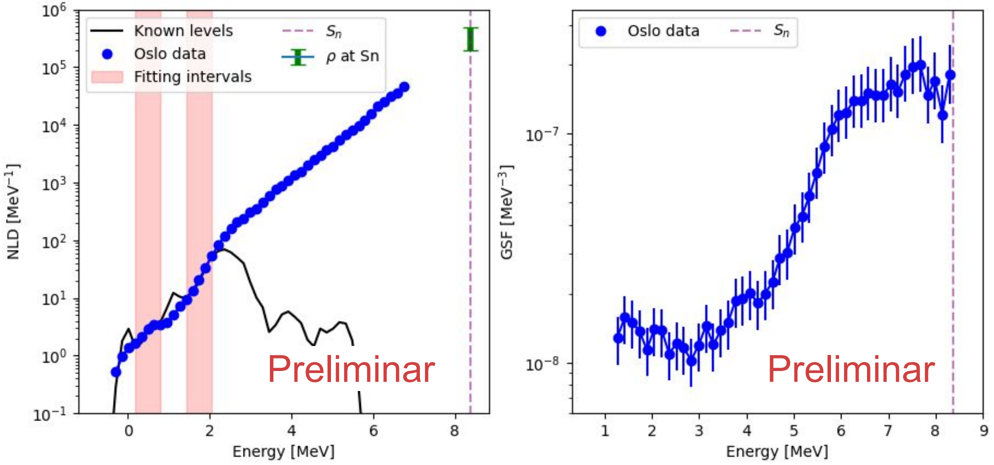
Closely modelled to experiment IS559 on ^{67}Ni

2.5e6 beam of 2005 might not be replicated

Can the experiment be carried out?

Normalization

Data for ^{127}Sb at OCL



The lower the beam yield, the higher the uncertainty -> risk of the experiment being inconclusive

Normalization

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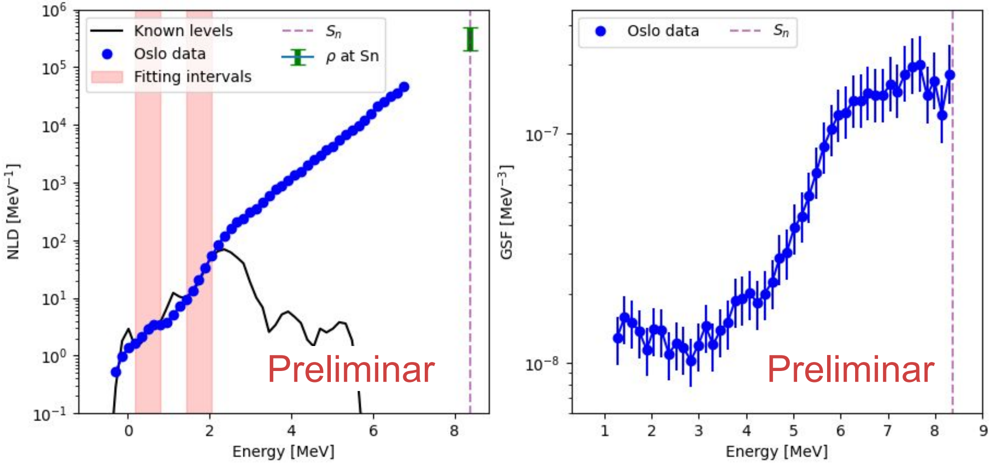
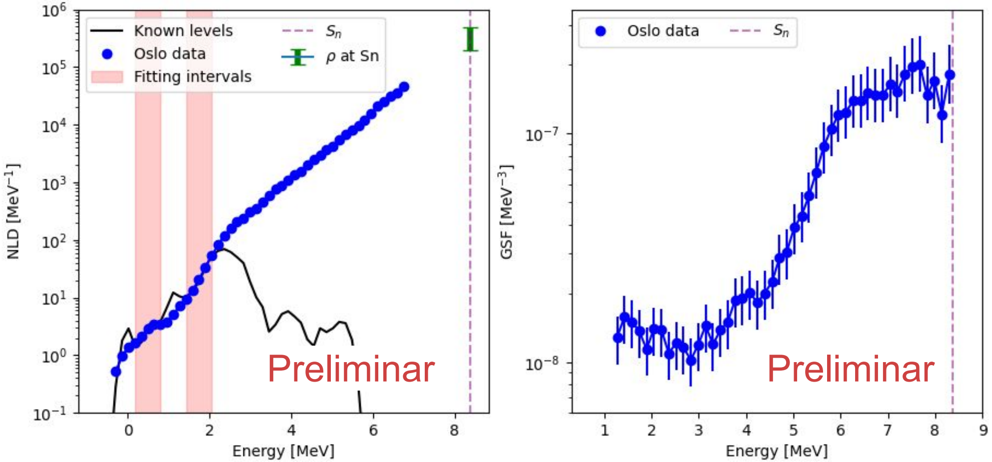


The lower the beam yield, the higher the uncertainty -> risk of the experiment being inconclusive

Oslo method: technically ok with only ~100k coincidences for non-exotic nuclei

Normalization

Data for ^{127}Sb at OCL

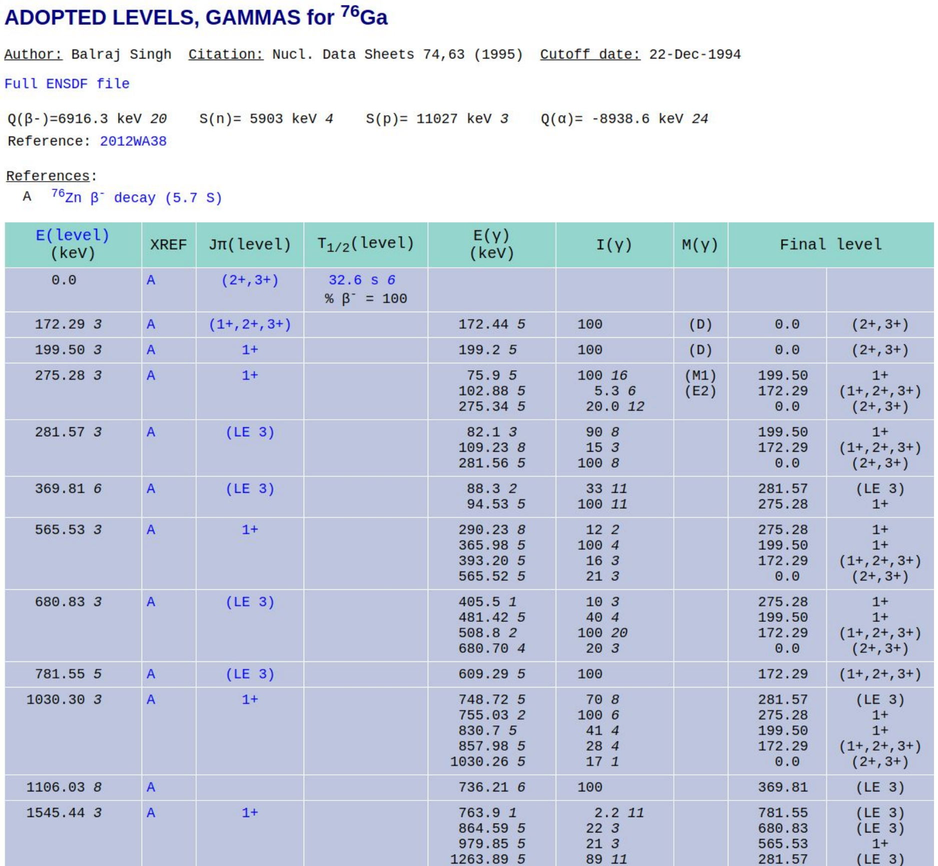


The lower the beam yield, the higher the uncertainty -> risk of the experiment being inconclusive

Oslo method: technically ok with only ~100k coincidences for non-exotic nuclei

Require low energy states for normalization

Convert Proposal to LoI



ADOPTED LEVELS, GAMMAS for ^{76}Ga

Author: Balraj Singh Citation: Nucl. Data Sheets 74,63 (1995) Cutoff date: 22-Dec-1994

Full ENSDF file

Q(β-)=6916.3 keV *20* S(n)= 5903 keV *4* S(p)= 11027 keV *3* Q(α)= -8938.6 keV *24*
Reference: 2012WA38

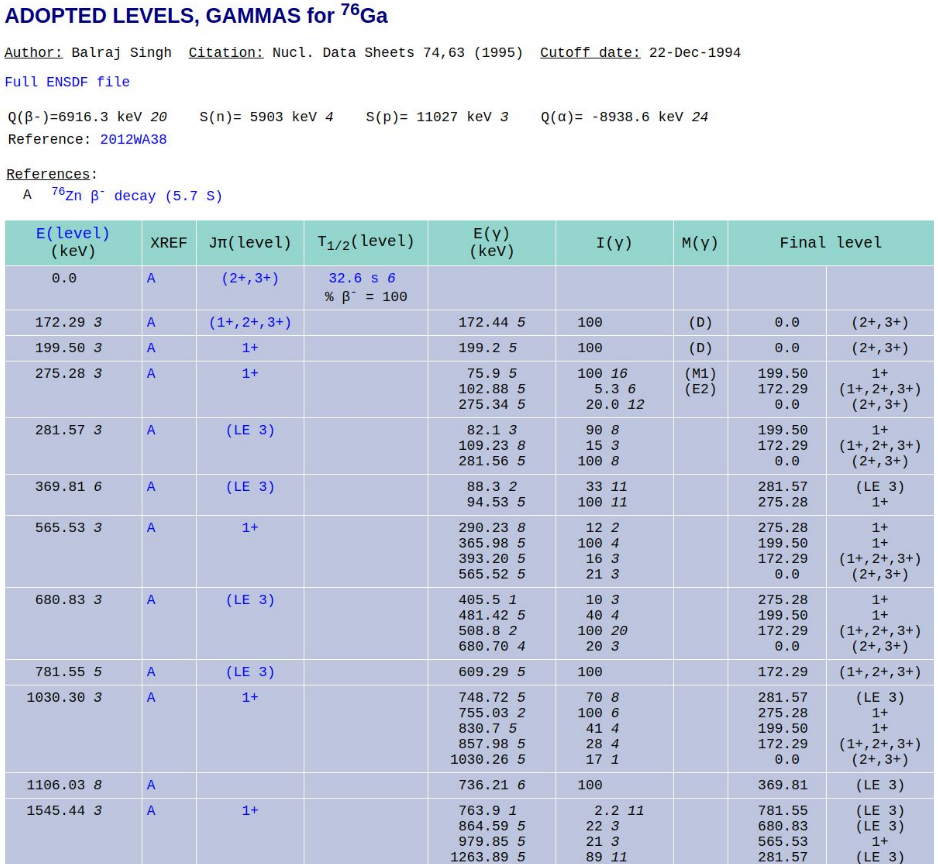
References:
A ^{76}Zn β^- decay (5.7 S)

E(level) (keV)	XREF	Jπ(level)	$T_{1/2}$(level)	E(γ) (keV)	I(γ)	M(γ)	Final level	
0.0	A	(2+,3+)	32.6 s *6* % β^- = 100					
172.29 *3*	A	(1+,2+,3+)		172.44 *5*	100	(D)	0.0	(2+,3+)
199.50 *3*	A	1+		199.2 *5*	100	(D)	0.0	(2+,3+)
275.28 *3*	A	1+		75.9 *5* 102.88 *5* 275.34 *5*	100 *16* 5.3 *6* 20.0 *12*	(M1) (E2)	199.50 172.29 0.0	1+ (1+,2+,3+) (2+,3+)
281.57 *3*	A	(LE 3)		82.1 *3* 109.23 *8* 281.56 *5*	90 *8* 15 *3* 100 *8*		199.50 172.29 0.0	1+ (1+,2+,3+) (2+,3+)
369.81 *6*	A	(LE 3)		88.3 *2* 94.53 *5*	33 *11* 100 *11*		281.57 275.28	(LE 3) 1+
565.53 *3*	A	1+		290.23 *8* 365.98 *5* 393.20 *5* 565.52 *5*	12 *2* 100 *4* 16 *3* 21 *3*		275.28 199.50 172.29 0.0	1+ 1+ (1+,2+,3+) (2+,3+)
680.83 *3*	A	(LE 3)		405.5 *1* 481.42 *5* 508.8 *2* 680.70 *4*	10 *3* 40 *4* 100 *20* 20 *3*		275.28 199.50 172.29 0.0	1+ 1+ (1+,2+,3+) (2+,3+)
781.55 *5*	A	(LE 3)		609.29 *5*	100		172.29	(1+,2+,3+)
1030.30 *3*	A	1+		748.72 *5* 755.03 *2* 830.7 *5* 857.98 *5* 1030.26 *5*	70 *8* 100 *6* 41 *4* 28 *4* 17 *1*		281.57 275.28 199.50 172.29 0.0	(LE 3) 1+ 1+ (1+,2+,3+) (2+,3+)
1106.03 *8*	A			736.21 *6*	100		369.81	(LE 3)
1545.44 *3*	A	1+		763.9 *1* 864.59 *5* 979.85 *5* 1263.89 *5*	2.2 *11* 22 *3* 21 *3* 89 *11*		781.55 680.83 565.53 281.57	(LE 3) (LE 3) 1+ (LE 3)

We need a (more) complete level scheme

^{76}Ga is odd-odd: many levels, high statistics needed

Convert Proposal to LoI



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^{76}Ga is odd-odd: many levels, high statistics needed

Might be inconclusive for less than 750k coincidences (corresponding to ~1.2e6 pps @ MINIBALL under the same conditions)

Convert Proposal to LoI

Updated estimates on the production of ^{75}Ga may be needed to guarantee useful statistics

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Thank you

Questions

Angle distribution