Measuring Neutron Capture Cross Sections on s-Process Radioactive Nuclei

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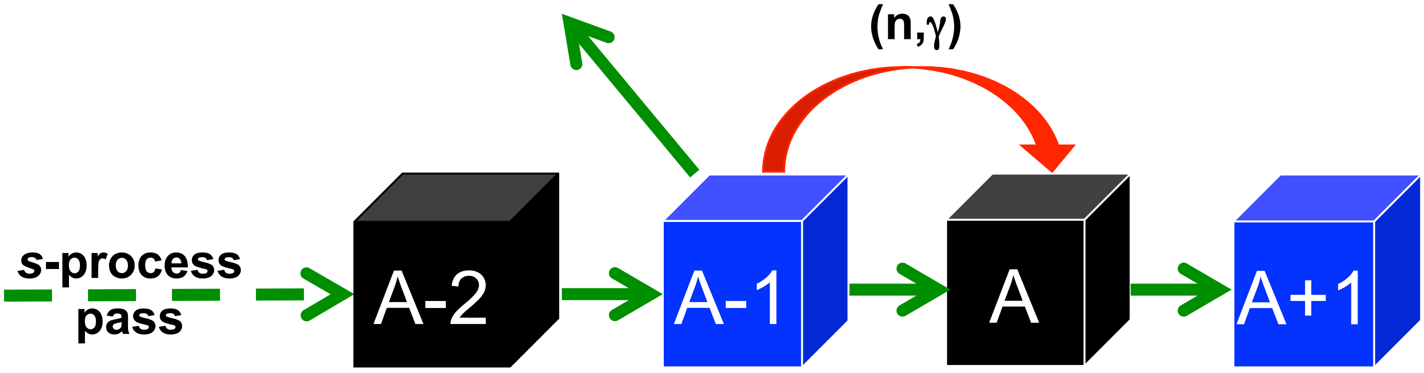
Outline

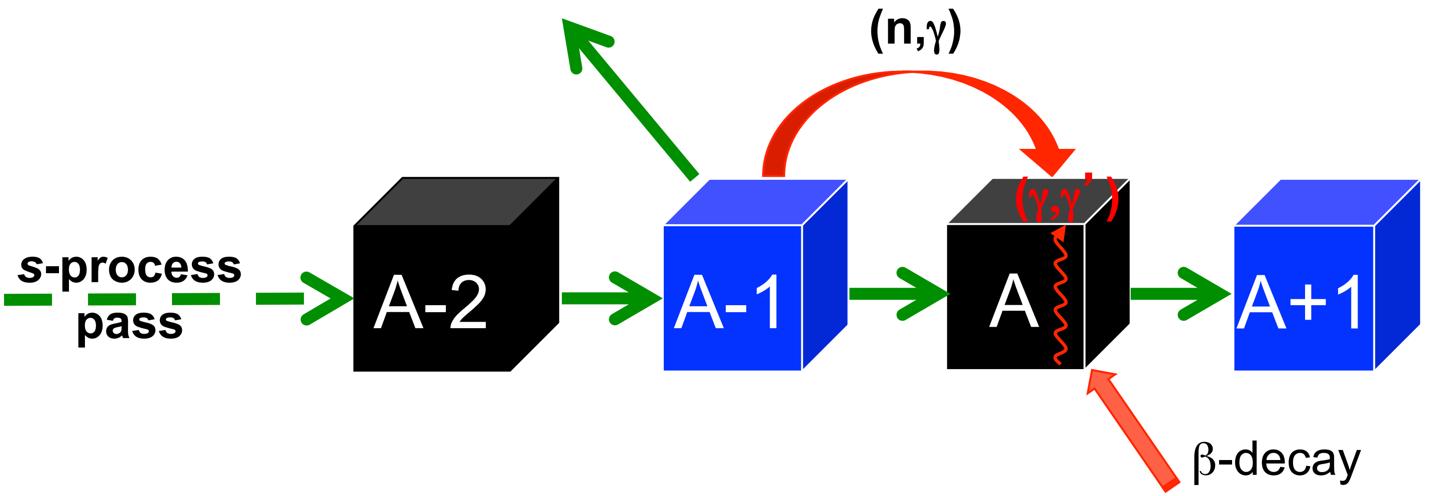
- ☐ Low-energy dipole strength: a key to understand decay mechanism for capture reactions
- ☐ Experimental techniques
- ☐ Experimental results for capture cross-section measurements on *s*-process branching point nucleus: ^{85}Kr, ^{75}Ge, and ^{205}Pb
- ☐ Summary

Neutron Capture on s-Process Nuclei



A is stable and A-1 is a *s*-process branching point nucleus

Neutron Capture on *s*-Process Nuclei



Leading indirect techniques:

- Nuclear Resonance Fluorescence (NRF)
- β-delayed γ and neutron spectra
- Surrogate method

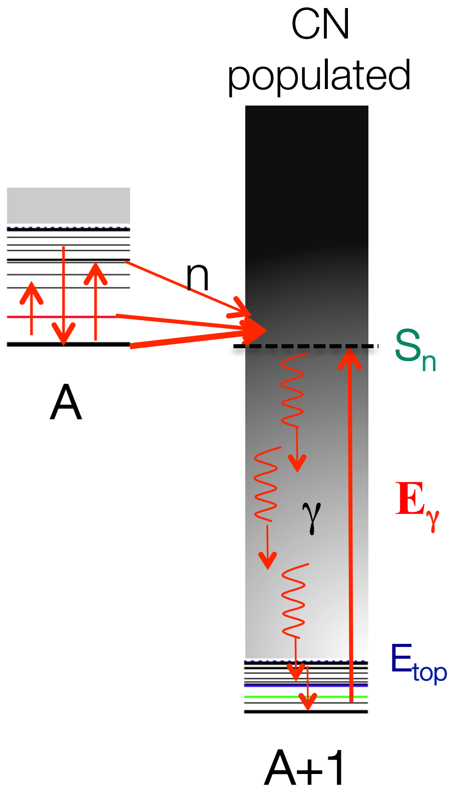
A is stable and A-1 is a s-process branching point nucleus

Calculating (n,γ) Cross Sections

Capture reaction

n+target ➔ population of compound nucleus (CN)

Subsequent decay by competition of γ emission and neutron evaporation



Theoretical description

Hauser-Feshbach (HF) formalism:

$$\sigma_{n\gamma} = \frac{\pi}{k_n^2} \sum_{J,\pi} g_J \frac{T_\gamma(E, J, \pi) T_n(E, J, \pi)}{T_{\text{tot}}}$$

where

T_γ is the gamma transmission coefficient

$$T_\gamma(E, J, \pi) = \sum_{X,\lambda} \int T_{X\lambda}(\epsilon_\gamma) \rho(E - \epsilon_\gamma) d\epsilon_\gamma$$

T_n is the neutron transmission coefficient

and $T_{tot} = T_n + T_p + T_d + T_t + T_\alpha + T_\gamma$

Challenge for calculations

Need accurate description of:

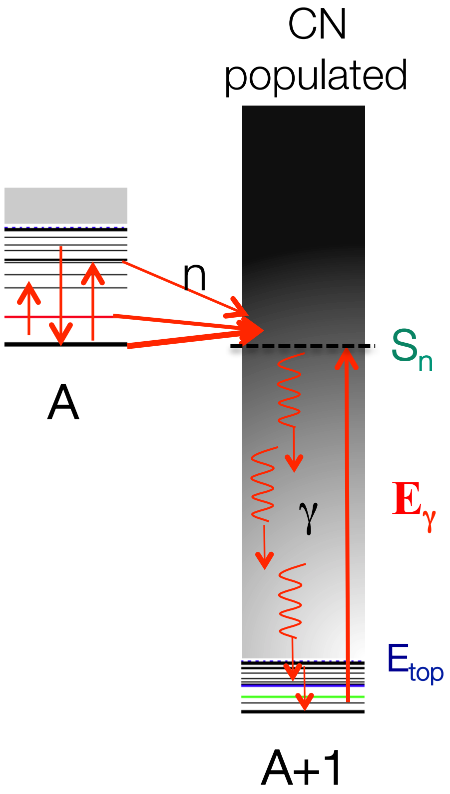
- γ–ray strength function (γSF)
- level densities (LDs)
- discrete low-lying levels with J^π, branching ratios – esp. important for isomers!
- optical model for n+target: (in decent shape ~10% below 1-2 MeV, 3-5% above)

Calculating (n,γ) Cross Sections from Photon Scattering

Capture reaction

n+target ➔ population of compound nucleus (CN)

Subsequent decay by competition of γ emission and neutron evaporation



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T_n is the neutron transmission coefficient

and $T_{tot} = T_n + T_p + T_d + T_t + T_\alpha + T_\gamma$

Constrain on γSF

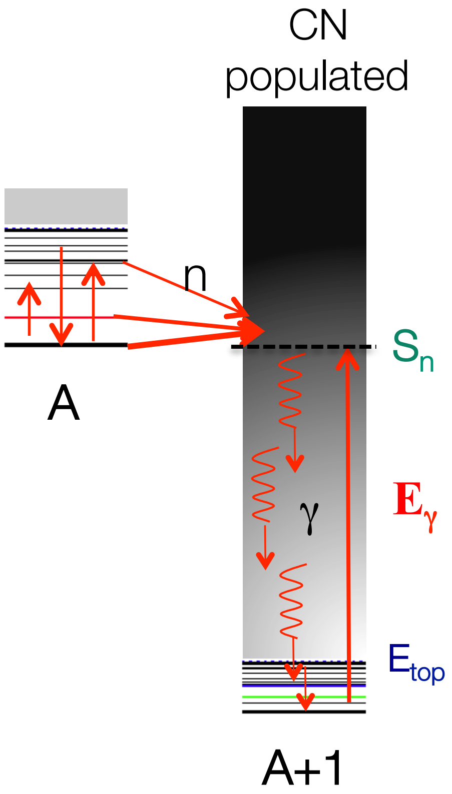
$$T_{X\lambda}(\epsilon_\gamma) = 2\pi\,\epsilon_\gamma^{(2\lambda+1)} f_{X\lambda}(\epsilon_\gamma)$$

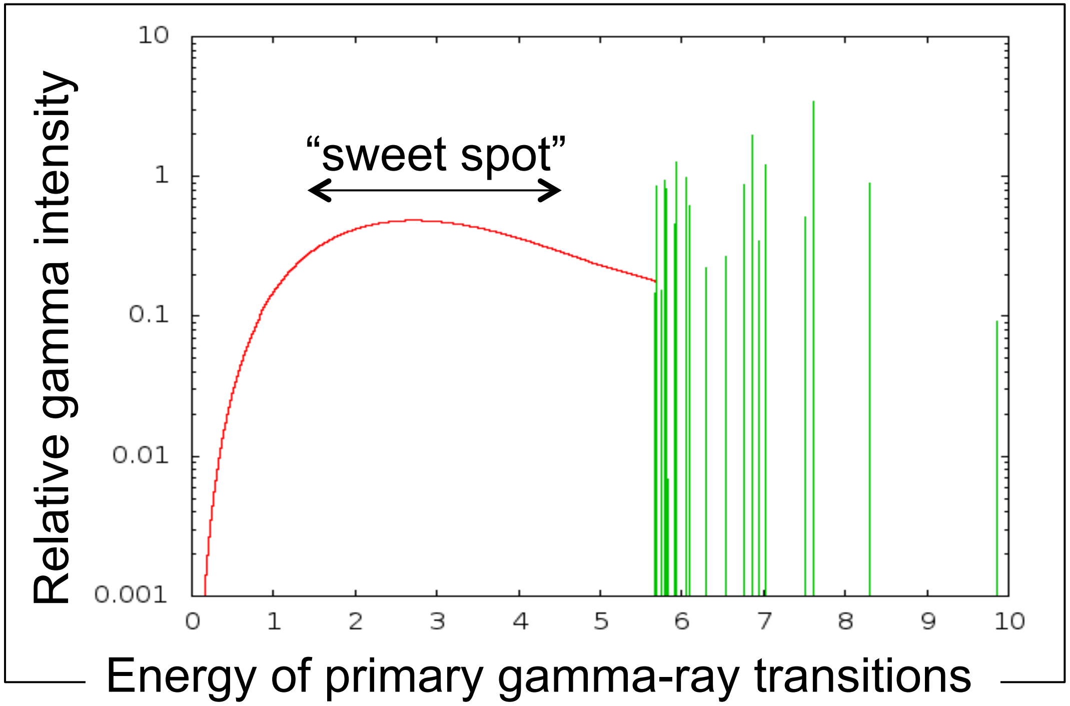
$$T_{E1}(E_\gamma) = 2\pi\, E_\gamma^3 f_{E1}(E_\gamma) \quad \text{(electric dipole)}$$

$\sigma_{abs}(E_\gamma)$: measured directly with real photons

$$\sigma_{\rm abs}(E_\gamma) = 3(\pi\hbar c)^2 E_\gamma f_{E1}^{\uparrow}(E_\gamma).$$

Direct measurement of the γ strength function via (γ,γ') measurement

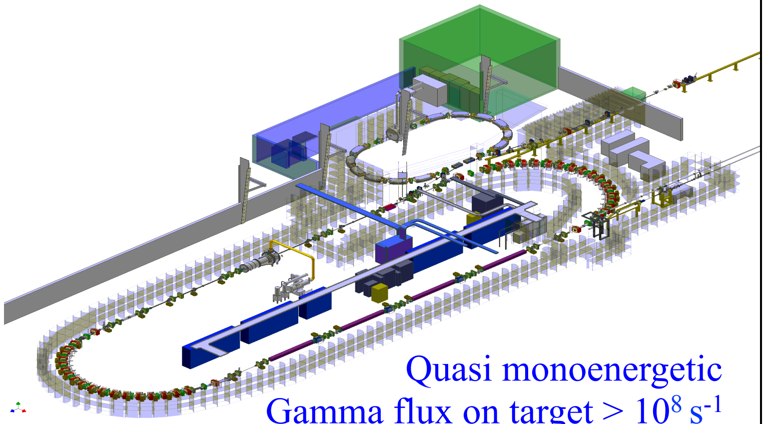




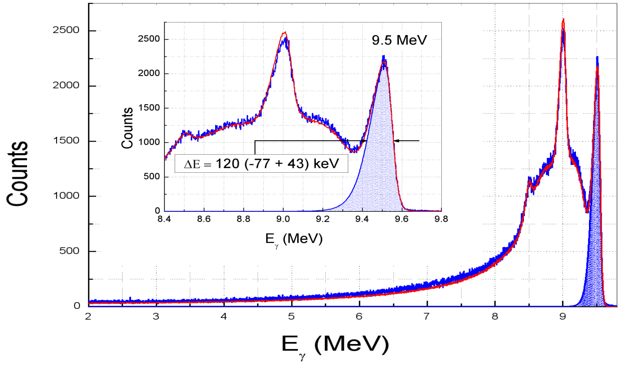
The *γ* strength function is governed by low-energy transitions !!!

Measuring the Nuclear Dipole Response using Real Photons

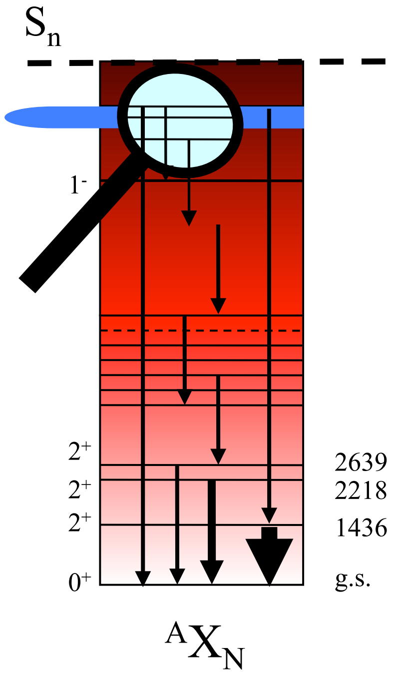
High-Intensity Gamma-Ray Source



Quasi monoenergetic
Gamma flux on target > 10^8 s^{-1}
Tunable beam from 1 – 100 MeV
100% linear or circular polarization



NRF Technique



Experimental observables

- Excitation energy E_x
- Spin and parity J, π
- Decay width Γ_0
- Branching ratio Γ_i/Γ

In a completely model independent way !

HIGS Advantages

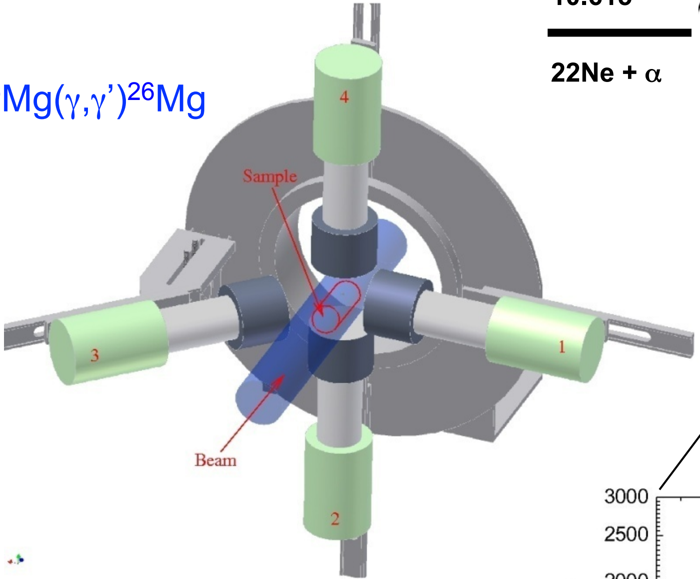
- $\sigma_{el} = f(E_\gamma)$ (from primary g.s. transitions)
- $\sigma_{inel} = f(E_\gamma)$ (from secondary transitions)
  - $\sigma_{tot} = \sigma_{el} + \sigma_{inel} = \sigma_{abs}$

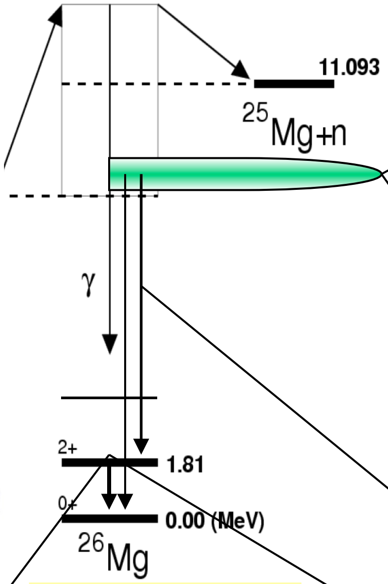
N. Pietralla, A. Tonchev at al. PRL **88** (2001) 012502

Photon Scattering from Light-Mass Nuclei

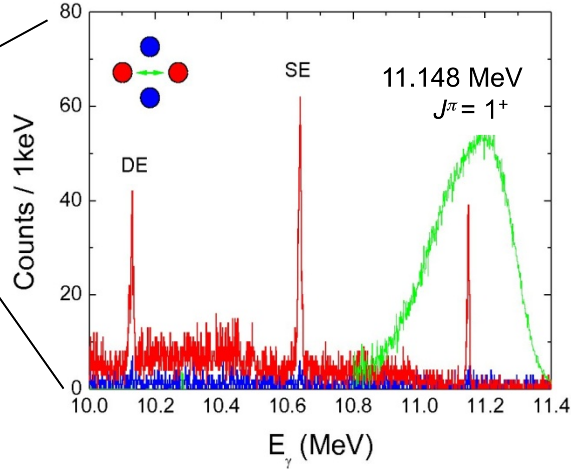
R.J. De Boer et al. Phys. Rev. **C 82**, 025802 (2010)
R. Longland et al. Phys. Rev. **C 80**, 055803 (2009)

^{26}Mg(γ,γ')^{26}Mg

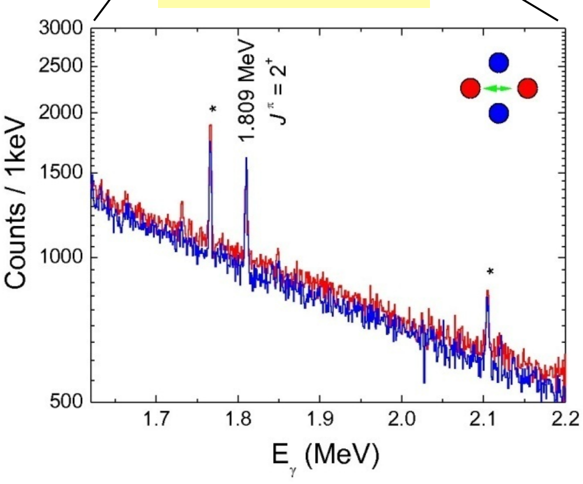




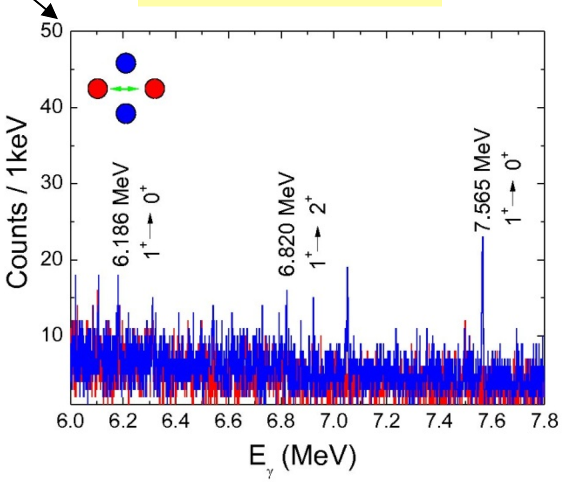
Ground state transitions Γ_0



Secondary transitions



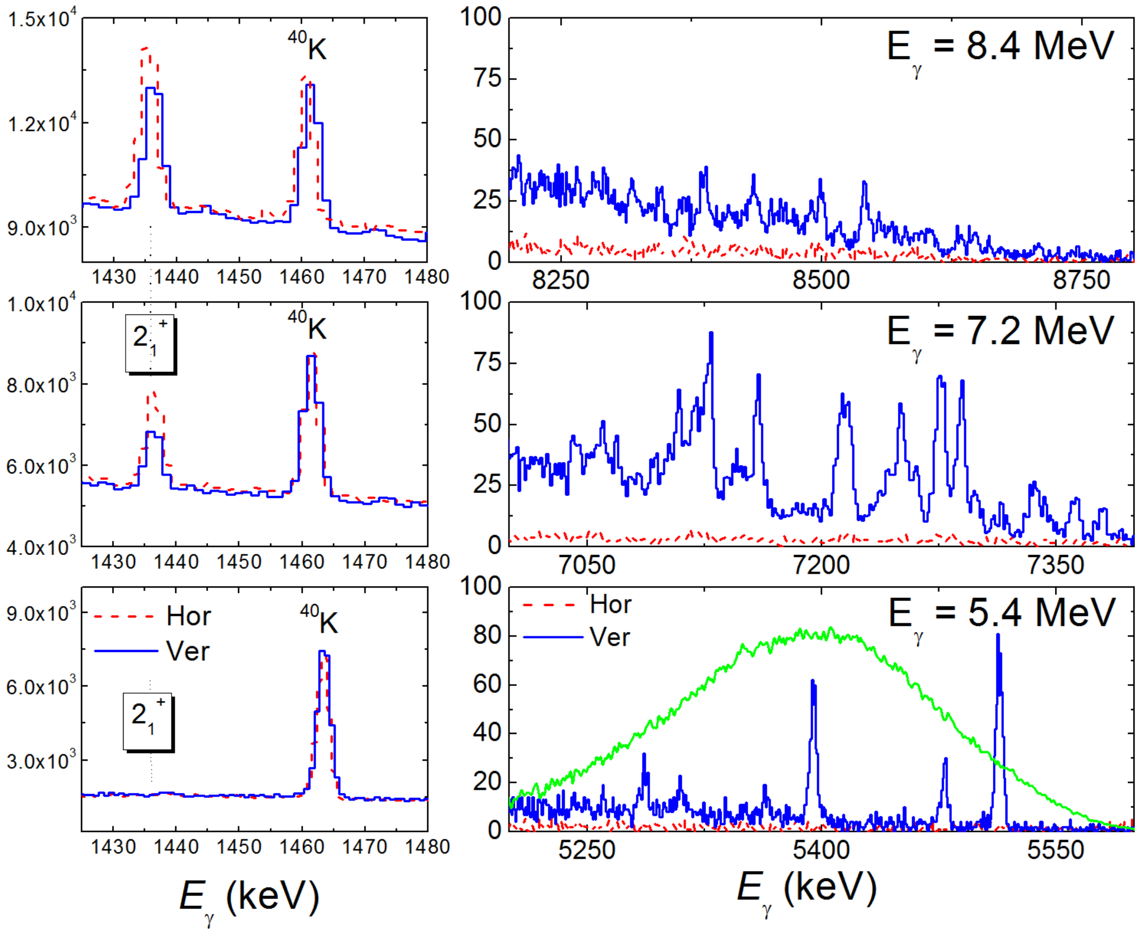
Branching transitions Γ_f

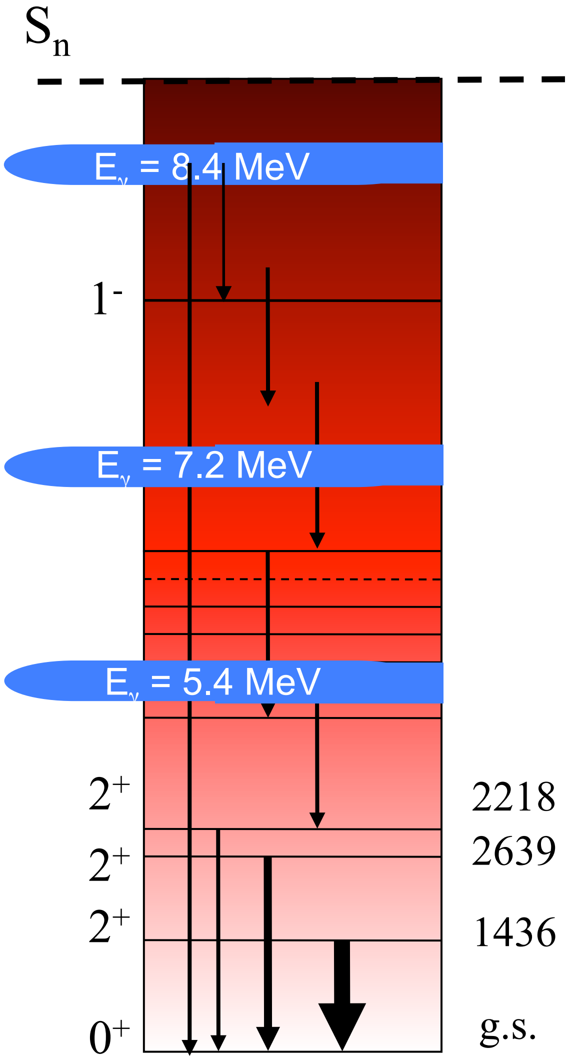


HIGS detection sensitivities:

resonance states with
$\Gamma_{tot} \geq 1\text{meV}$

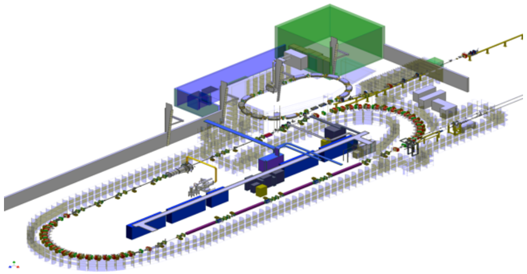
Photon Scattering from Mid- and Heavy-Mass Nuclei

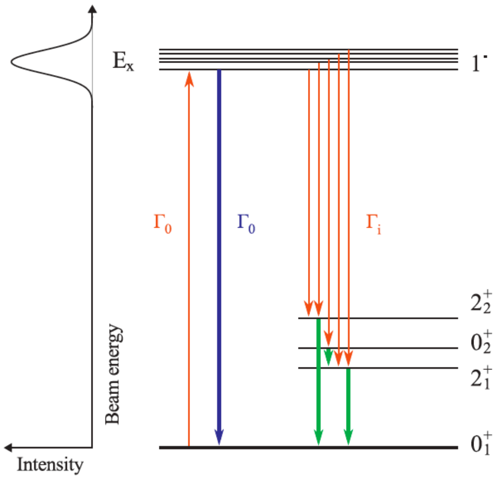




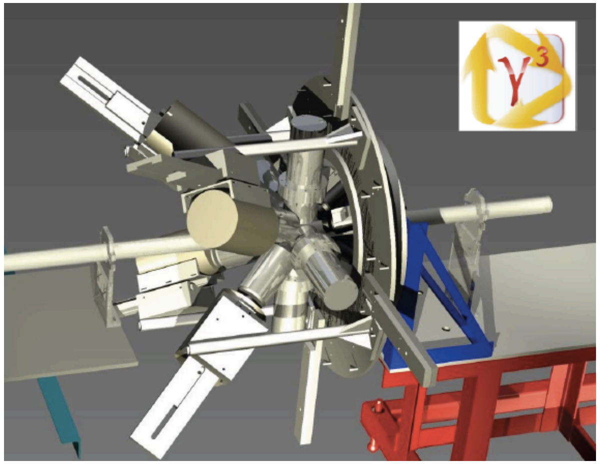
Constructed the New γ^3 Setup at the High Intensity Gamma-Ray Source Facility (HIGS) at Duke University

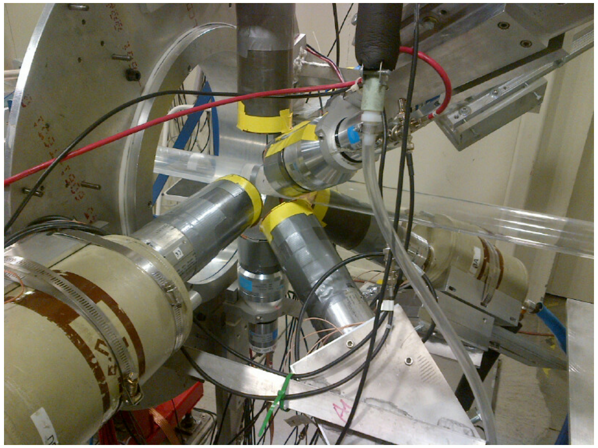
HIGS facility





Schematic drawing of the γ^3 experimental setup





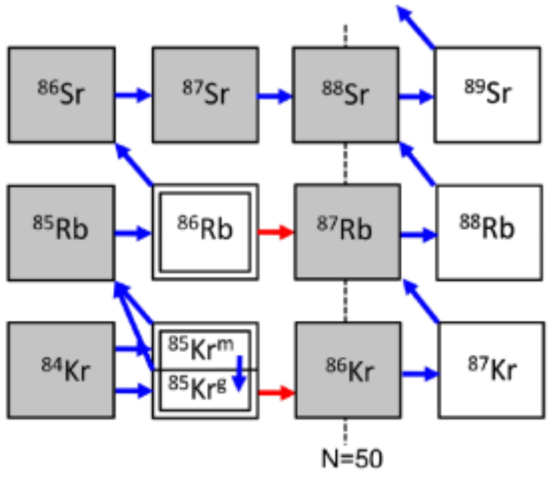
γ^3 Setup:
Array of four LaBr, four HPGe, and four neutron detectors.

Provides:

Absolute and model independent cross-section measurements below or above the neutron separation energy, hence direct measurement of the gamma-ray strength function.

B. Loher, V. Derya et al. NIMA **723,** 136 (2013)

Cross-Section Measurements of the ^{86}Kr(γ,n) Reaction to Probe the *s*-Process Branching at ^{85}Kr



- The branching at ^{85}Kr is significant for *s*-process modeling.
- This branching is independent of temperature and depends only on the neutron density.
- Helps to constrain the neutron density parameter in models of AGB stars.
- ^{85}Kr ($T_{1/2}$ = 10.76 y) neutron capture not measured.

Solution

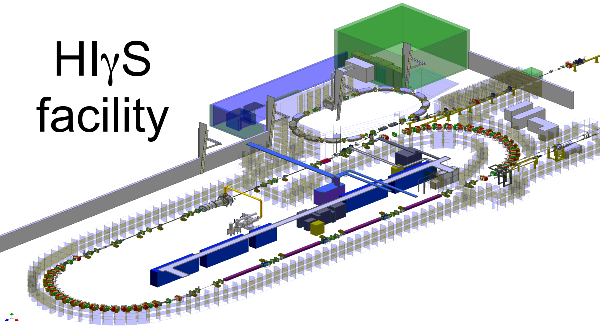
Measure ^{86}Kr(γ,γ')^{86}Kr and inverse ^{86}Kr(γ,n)^{85}Kr reaction

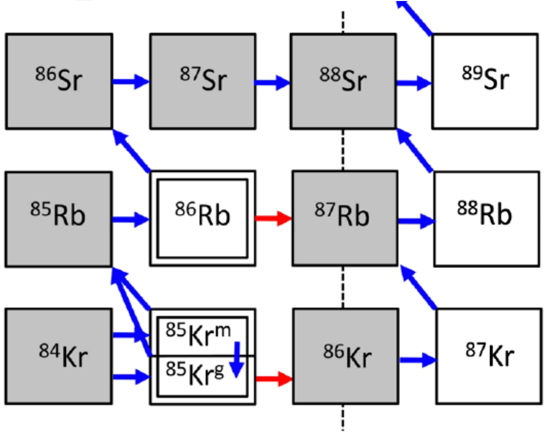
Reproduce experimental results with the statistical model calculations

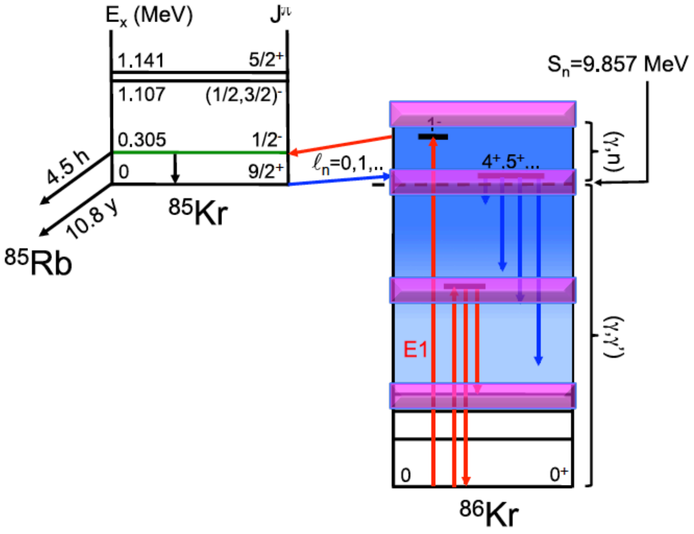
Apply same parameter set for (n, γ) cross section

Proof-of-Principle Experiment on ^{85}Kr radioactive target

HIγS facility







PRL **111,** 112501 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Cross-Section Measurements of the ^{86}Kr(γ, n) Reaction to Probe the *s*-Process Branching at ^{85}Kr

R. Raut,[1,2,*] A. P. Tonchev,[1,2,†] G. Rusev,[1,2,‡] W. Tornow,[1,2] C. Iliadis,[3,2] M. Lugaro,[4] J. Buntain,[4] S. Goriely,[5]
J. H. Kelley,[2,6] R. Schwengner,[7] A. Banu,[8] and N. Tsoneva[9,10]
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[2]*Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708, USA*
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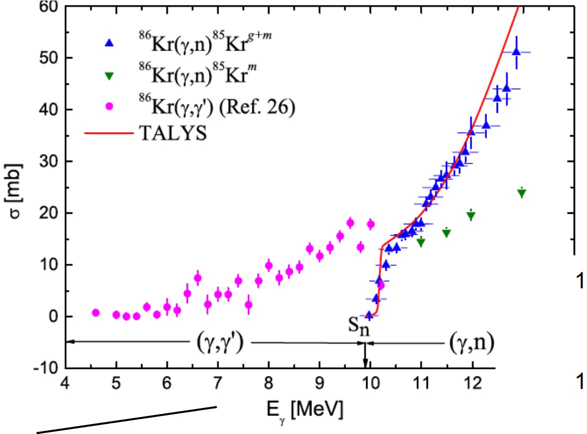
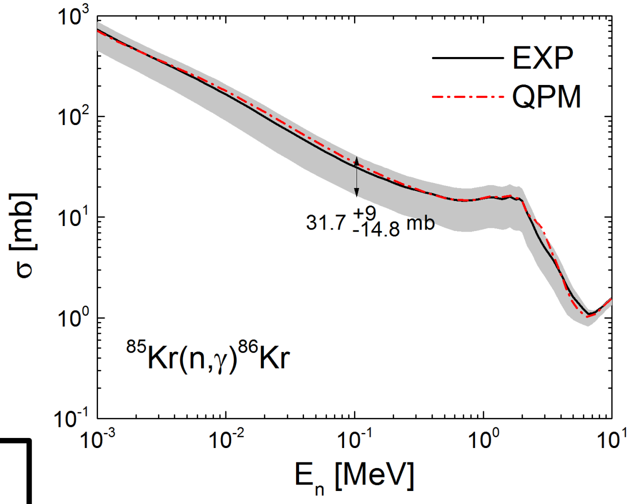
[5]*Institut d' Astronomie et d' Astrophysique, Université Libre de Bruxelles, CP 226, 1050 Brussels, Belgium*
[6]*Department of Physics, North Carolina State University, Raleigh, North Carolina 27695, USA*
[7]*Institut für Strahlenphysik, Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany*
[8]*Department of Physics and Astronomy, James Madison University, Harrisonburg, Virginia 22807, USA*
[9]*Institut für Theoretische Physik, Universität Gieβen, Gieβen D-35392, Germany*
[10]*Institute of Nuclear Research and Nuclear Energy, 1784 Sofia, Bulgaria*



Obtained by statistical (HF) model



Measured directly with monoenergetic photon beams at HIGS

R. Schwengner *et al.*, PRC 87, 024306 (2013)

Proof-of-Principle Experiment on ^{85}Kr radioactive target

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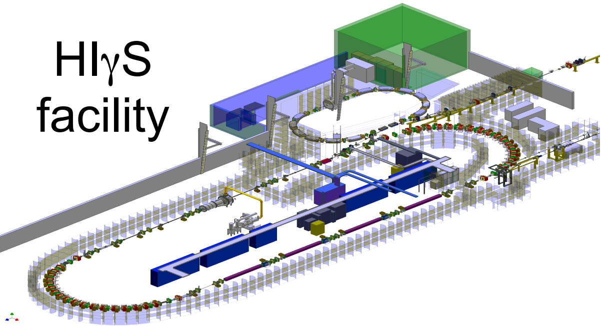

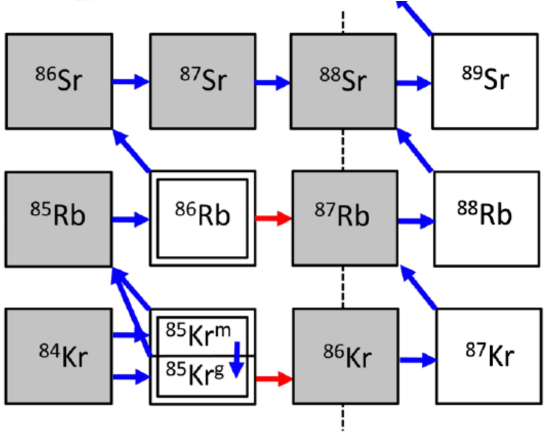

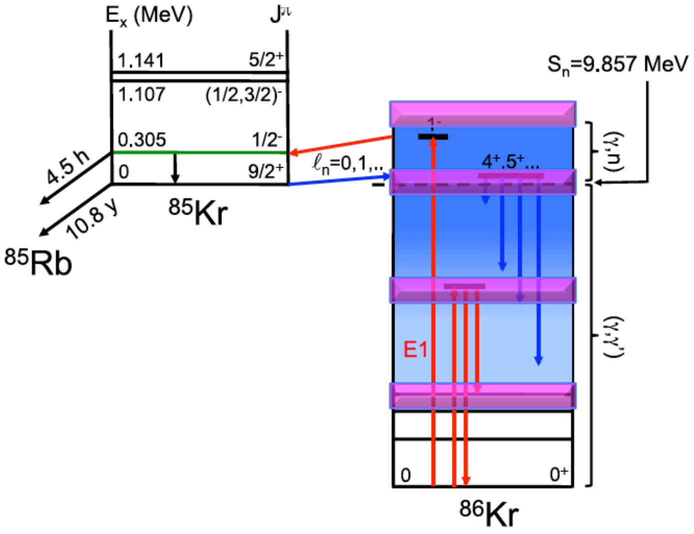

PRL **111,** 112501 (2013) PHYSICAL REVIEW LETTERS week ending 13 SEPTEMBER 2013

Cross-Section Measurements of the ^{86}Kr(*γ, n*) Reaction to Probe the *s*-Process Branching at ^{85}Kr

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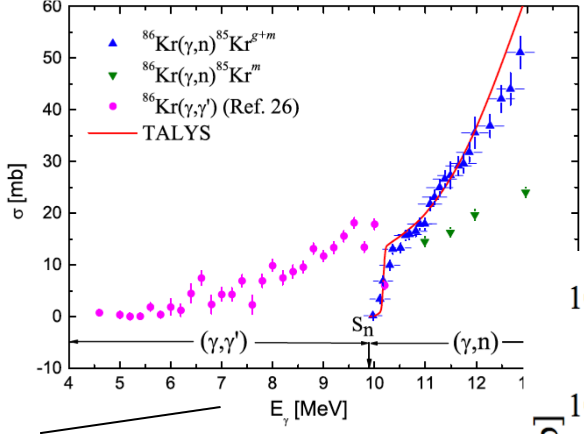
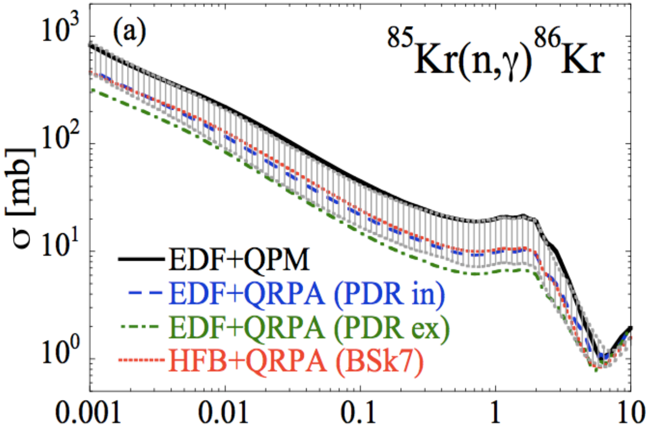


Measured directly with monoenergetic photon beams at HIGS

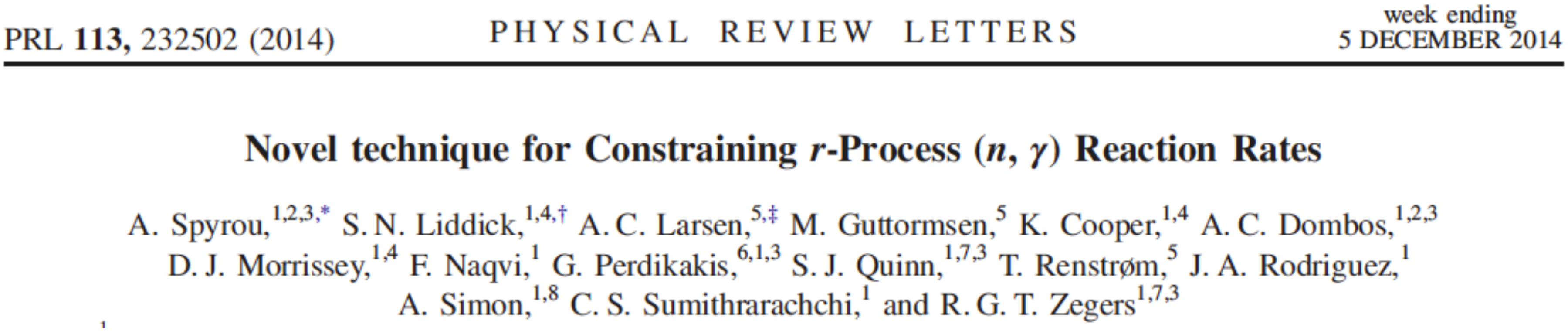
R. Schwengner *et al.*, PRC 87, 024306 (2013)

Obtained by statistical (HF) model



N. Tsoneva *et al.*, PRC 91, 044318 (2015)

β-Delayed γ Spectra from Total Absorption Spectrometer (TAS)



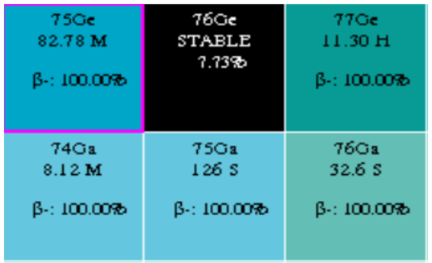
PRL **113,** 232502 (2014) PHYSICAL REVIEW LETTERS week ending 5 DECEMBER 2014

Novel technique for Constraining *r*-Process (*n*, *γ*) Reaction Rates

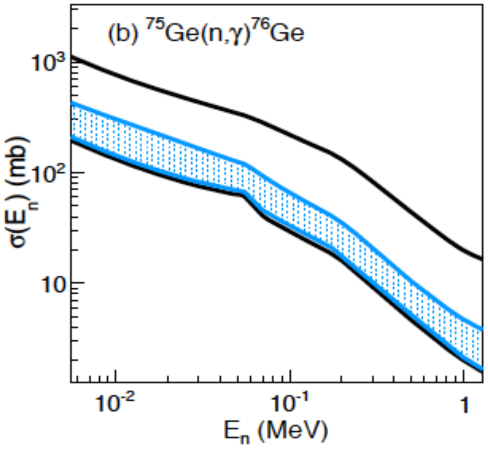
A. Spyrou,[1,2,3,*] S. N. Liddick,[1,4,†] A. C. Larsen,[5,‡] M. Guttormsen,[5] K. Cooper,[1,4] A. C. Dombos,[1,2,3]
D. J. Morrissey,[1,4] F. Naqvi,[1] G. Perdikakis,[6,1,3] S. J. Quinn,[1,7,3] T. Renstrøm,[5] J. A. Rodriguez,[1]
A. Simon,[1,8] C. S. Sumithrarachchi,[1] and R. G. T. Zegers[1,7,3]

TECHIQUE USED:

Combine β-decay and γ-emission measurements using γ-ray total absorption spectrometer (TAS). Analyse γ-ray spectra using the 'Oslo'-method.



75Ge 82.78 M β-: 100.00%	76Ge STABLE 7.73%	77Ge 11.30 H β-: 100.00%
74Ga 8.12 M β-: 100.00%	75Ga 126 S β-: 100.00%	76Ga 32.6 S β-: 100.00%



OBJECTIVE:

"Experimental" determination of the nuclear level density (NLD) and the γ-ray strength function (γSF). These two quantities (and the nucleon-nucleus optical model potential) are essential for calculating the neutron-capture cross section.

RESULT:

Proof-of-principle application to ^{75}Ge(n,γ) shows good agreement with known result.

OPEN QUESTIONS:

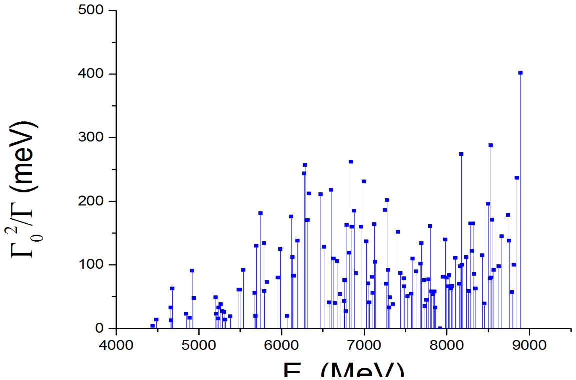
1. Approach made heavy use of available nuclear structure information. How much independent information does this type of measurement yield?
2. Only the functional form of the NLD and γSF are obtained from the primary γ-ray spectra from 1.2 – 5.8 MeV.
3. **The slope and absolute value must be determined by other means.**

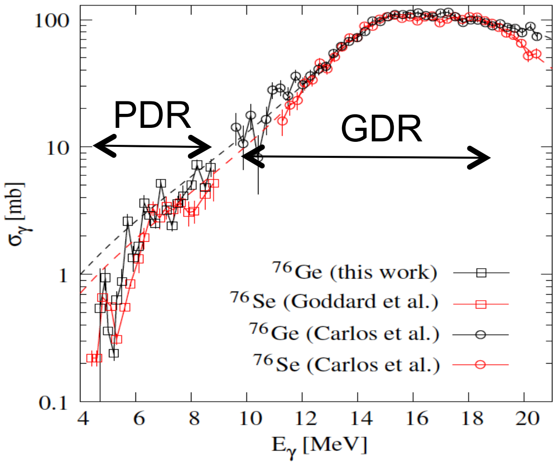
Nuclear Resonance Fluorescence technique (NRF) to measure the nuclear dipole response

Dipole response of ^{76}Ge between 4.5 and 9 MeV

R. S. Ilieva,[1,2] P. Humby,[1,2,*] N. Cooper,[1] V. Werner,[1,3] G. Rusev,[4,5,†] C. Bernards,[1] J. Beller,[3] J. Bliss,[3] B. P. Crider,[6] P. M. Goddard,[2] J. Isaak,[3] J.H. Kelly,[5] B. Löher,[7] E. E. Peters,[8] N. Pietralla,[3] C. Romig,[3] D. Savran,[7] M. Scheck,[3,‡] A. P. Tonchev,[4,§] W. Tornow,[4,5] S. W. Yates,[6,8] and M. Zweidinger[3]

(Submitted to PRC)





TECHIQUE USED:

Nuclear resonance fluorescence technique.

OBJECTIVE:

Direct measurements of the ptotoabsorption cross section below the neutron separation energy, hence direct measure of the γ-ray strength function (γSF) needed for inversed (n,γ) calculations.

RESULT:

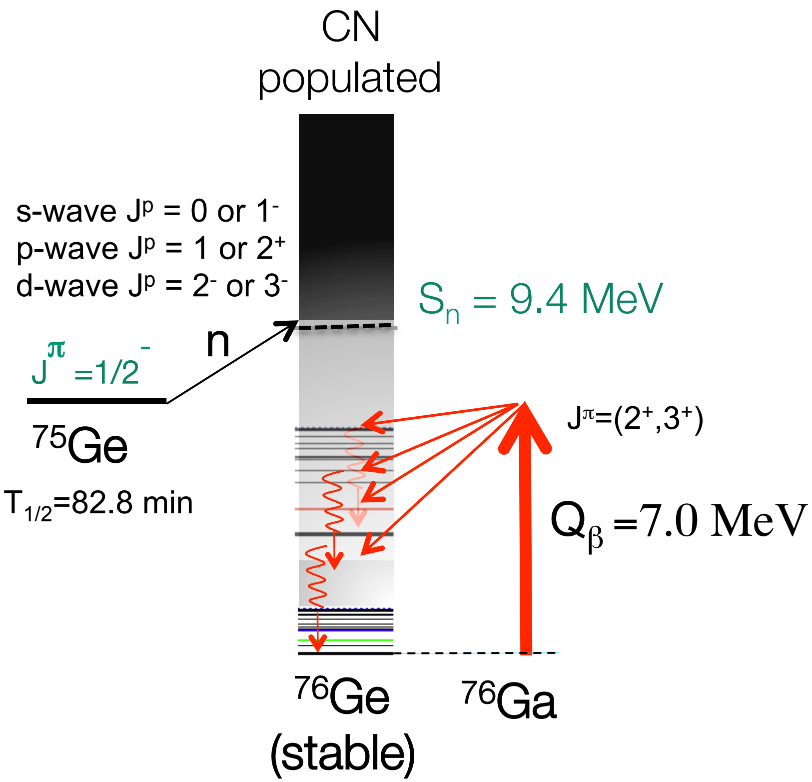
Photoabsorption cross section of ^{76}Ge(γ,γ’) from 4 to Sn (9.4 MeV).

OPEN QUESTIONS:

This approach is applicable for systems where A is stable and A-1 is a radioactive nucleus.

Reaction Mechanism

β-delayed neutron emission
(β-Oslo)



CN populated

s-wave $J^p = 0$ or 1^-
p-wave $J^p = 1$ or 2^+
d-wave $J^p = 2^-$ or 3^-

$S_n = 9.4$ MeV

$J^\pi = 1/2^-$

n

^{75}Ge

$T_{1/2}$=82.8 min

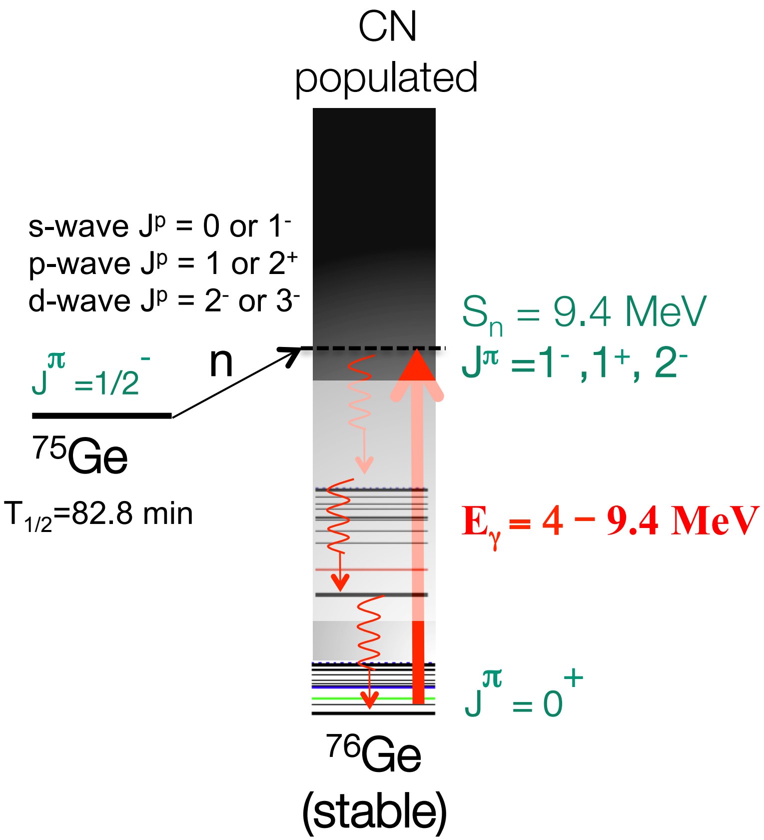
J^π=(2^+,3^+)

Q_β =7.0 MeV

^{76}Ge
(stable)

^{76}Ga

Photoabsorption
(NRF)



CN populated

s-wave $J^p = 0$ or 1^-
p-wave $J^p = 1$ or 2^+
d-wave $J^p = 2^-$ or 3^-

$S_n = 9.4$ MeV

$J^\pi = 1^-, 1^+, 2^-$

$J^\pi = 1/2^-$

n

^{75}Ge

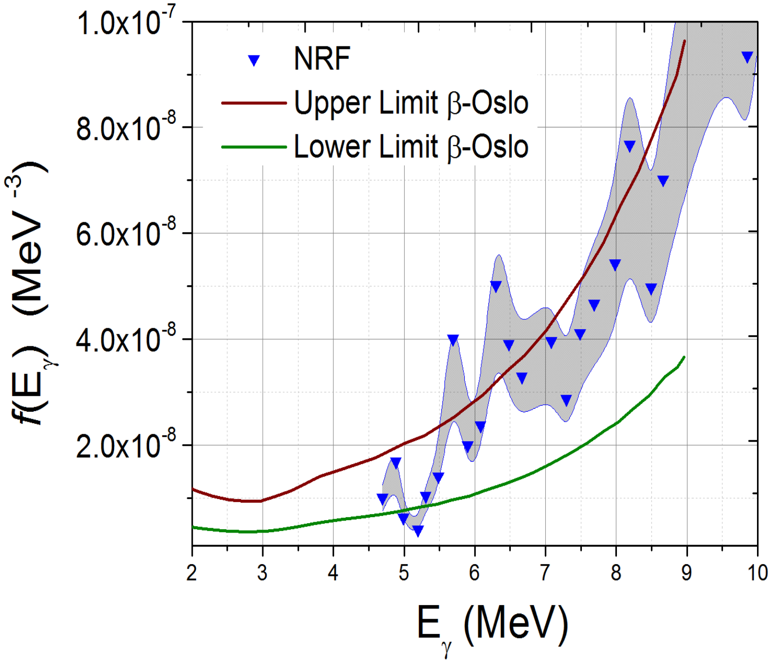
$T_{1/2}$=82.8 min

$E_\gamma = 4 - 9.4$ MeV

$J^\pi = 0^+$

^{76}Ge
(stable)

First Results



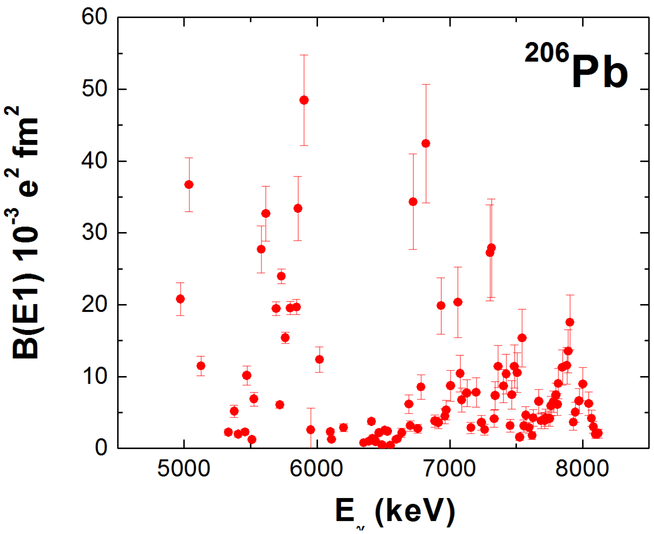
1. γ-ray strength function of ^{76}Ge measured by the β-Oslo methods is slightly lower compared to the photonscattering or NRF experiment.

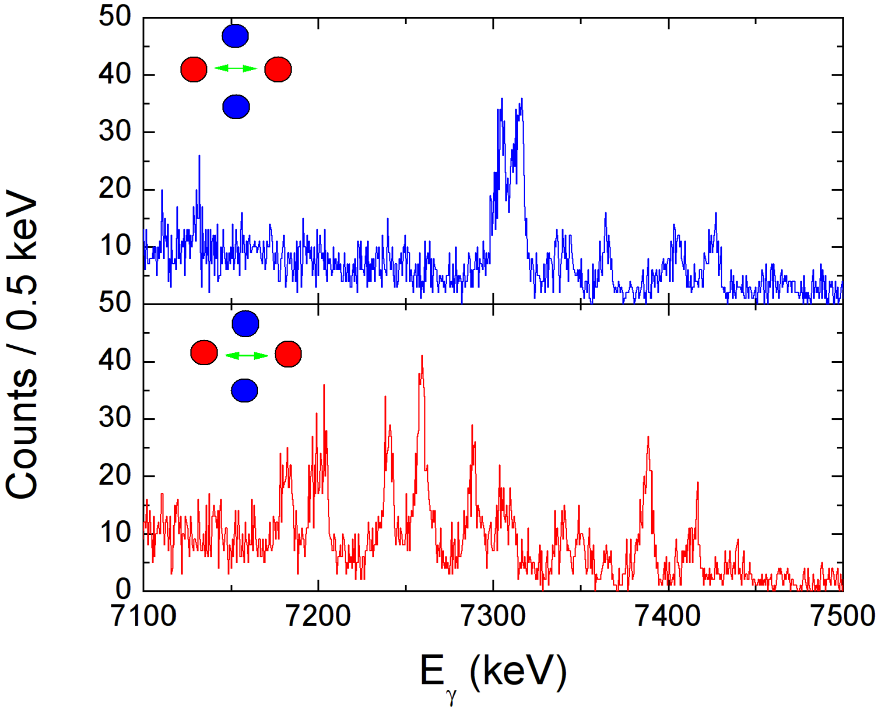
2. γ-strength function obtained by the photonscattering method show more structural effect compared to the one obtained via the β-Oslo methods.

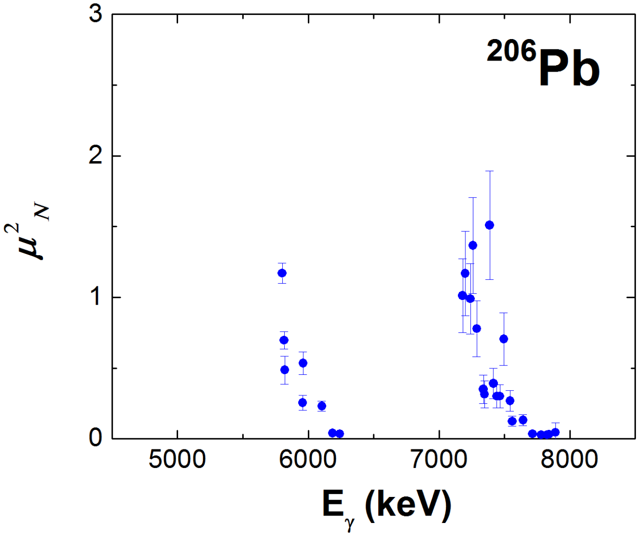
Fine Structure of the Electromagnetic Dipole Strength in ^{206}Pb

Measured:

- 99 E1 levels (40 new)
- 28 M1 levels (23 new)

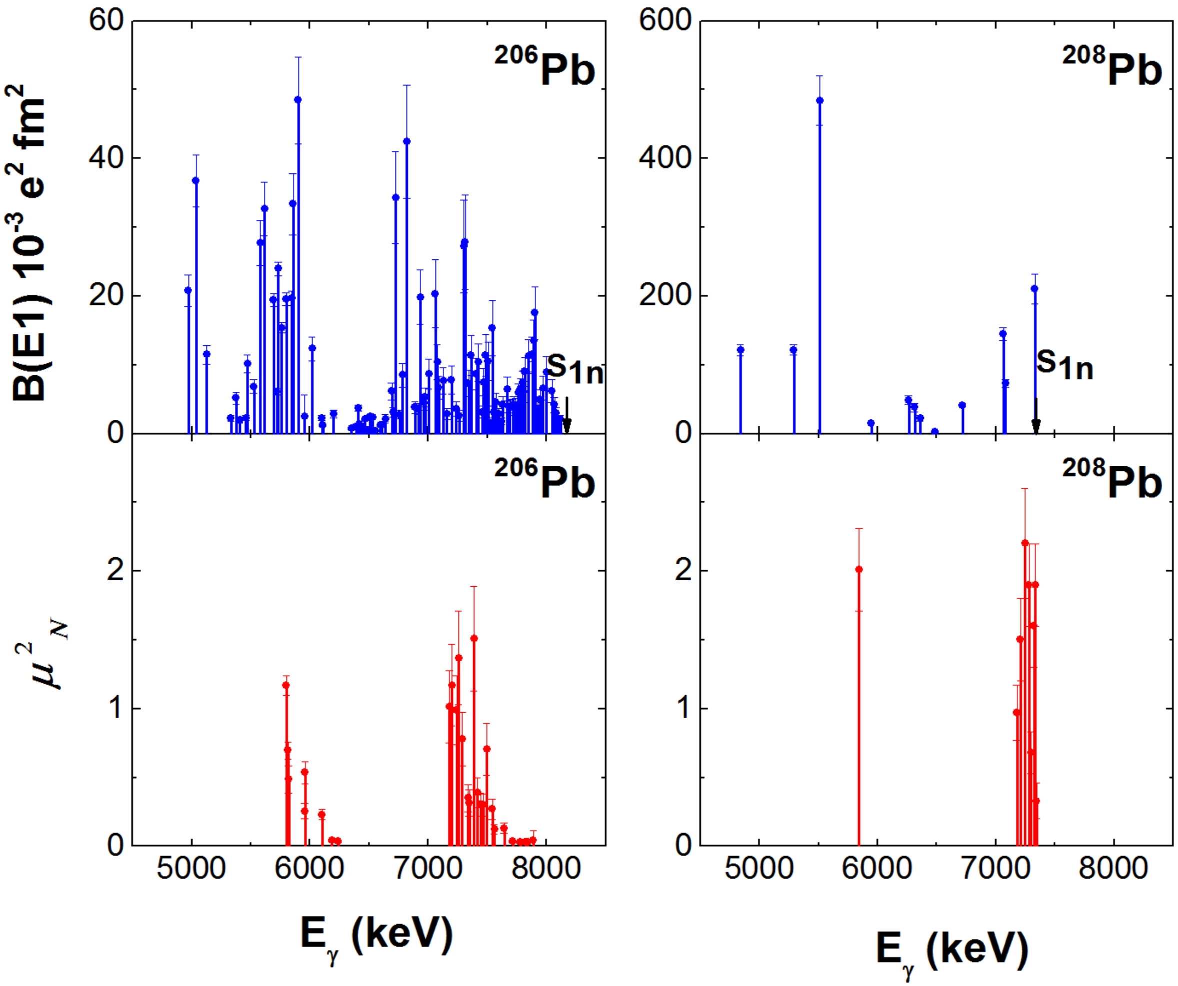






Fine Structure of the Electromagnetic Dipole Strength in ^{206}Pb

C. Bhatia et al. In preparation



^{208}Pb

Number of E1 states = 12

$\Sigma B(E1)\uparrow = 1.23 \pm 0.11\ e^2fm^2$

$\Sigma B(E1)_{QRPA} = 1.13\ e^2fm^2$

^{206}Pb

Number of E1 states = 99

$\Sigma B(E1)\uparrow = 0.91 \pm 0.17\ e^2fm^2$

$\Sigma B(E1)_{QPM} = 1.03\ e^2fm^2$

^{208}Pb

Number of M1 states = 9

$\Sigma B(M1)\uparrow = 13.09 \pm 0.30\ m_N^2$

^{206}Pb

Number of M1 states = 28

$\Sigma B(M1)\uparrow = 13.3 \pm 3.0\ m_N^2$

N. Tsoneva, Preliminary QPM calculations

Summary and Future Work

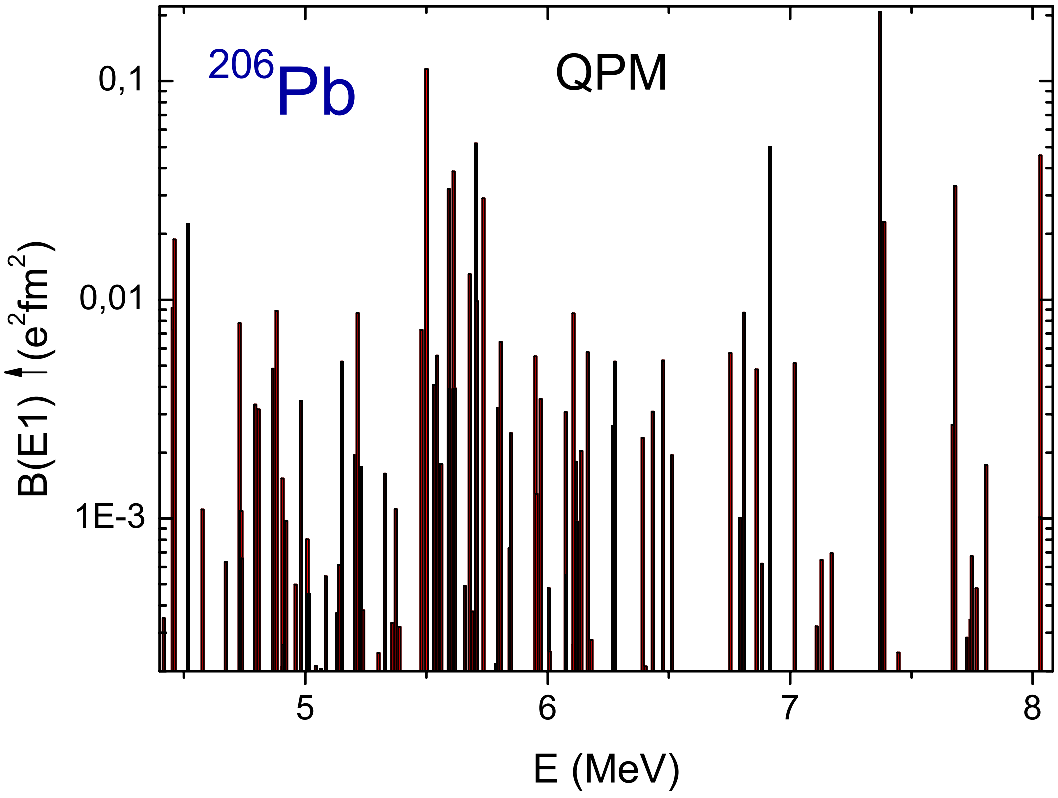
1. Good agreement is obtained for capture cross-section measurement on ^{75}Ge from the NRF and β-Oslo methods.

2. Constraining the level density of ^{76}Ge by using the discrete levels at low excitation energy and information from neutron-resonance experiments at the neutron separation energy Sn on neighboring germanium isotopes. Use the same normalization data as in the β-Oslo approach.

3. Plug the γ-ray strength function of ^{76}Ge directly into the Hauser-Feshbach calculations to compare with the capture cross section on ^{75}Ge nucleus obtained by the β-Oslo methods. Define the uncertainty of the predicted capture cross section based on both methods.

Spare Slides

B(E1) Strength in ^{206}Pb from QPM Calculations



^{206}Pb: QPM Calculations

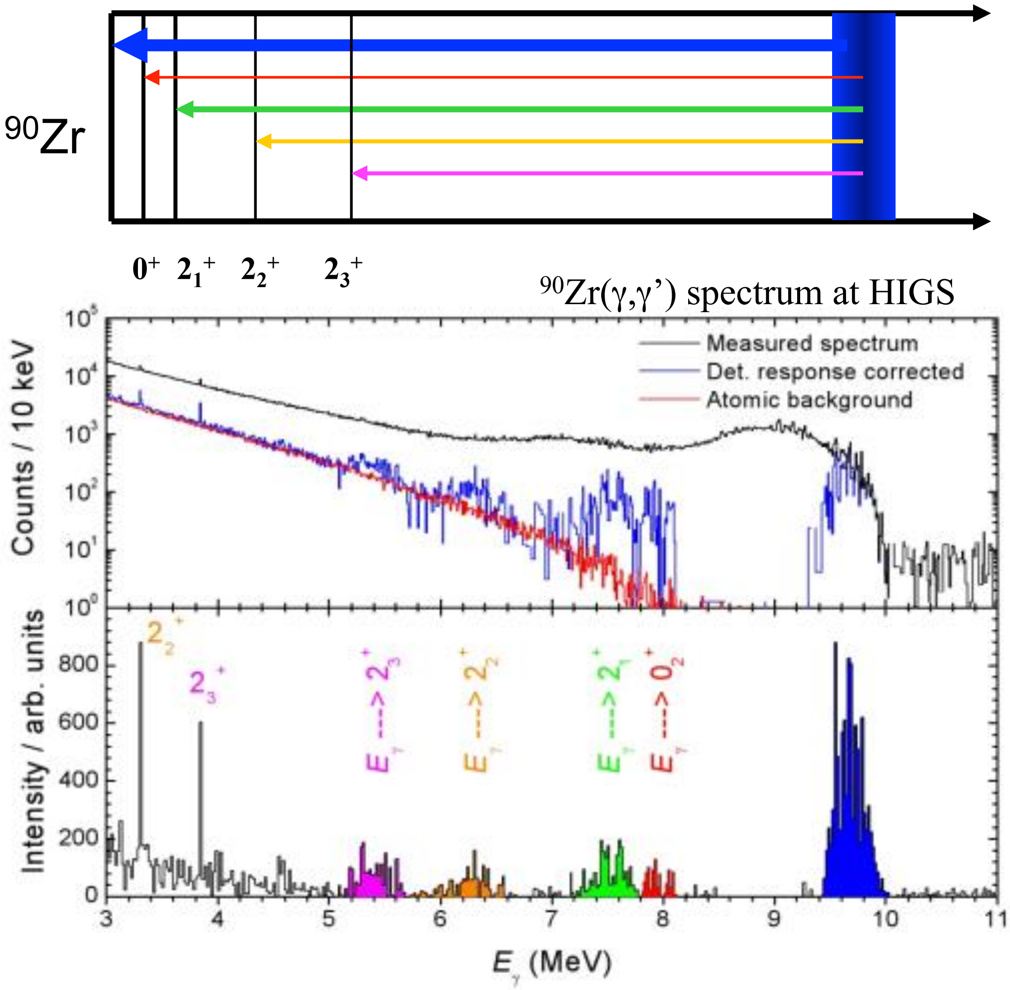
Number of E1 states = 430

$\Sigma B(E1)_{QPM} \uparrow = 2.18\ e^2fm^2$

Includes 2 and 3 phonon states

N. Tsoneva, preliminary results

Investigation of Photon-Strength Functions: ^{90}Zr case



- Photon-strength function describes energy distribution of photon emission from high-energy states.

$$f(E_\gamma) = \langle \Gamma_\gamma / D\, E_\gamma^3 \rangle$$

- Importance: Astrophysical network calculations; new fast nuclear reactors, statistical models.

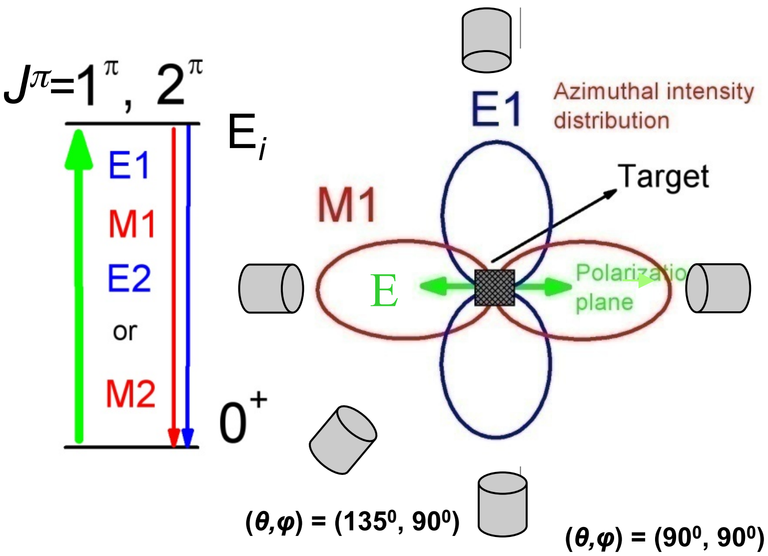
Preliminary results

- E1 is the dominant multipolarity transition
- Primary transitions are strongly dictated by the microscopic properties o the low-lying levels.
  - PSF is not smooth curve below the B_n and $E_\gamma > 4$ MeV.

G. Rusev *et al*. PRC 77, 064321 (2008)

Parity Measurements with a Linear Polarized Photon Beams

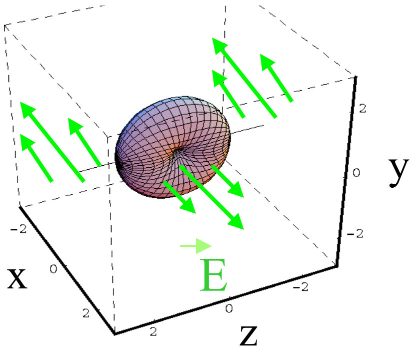
Azimuthal distribution



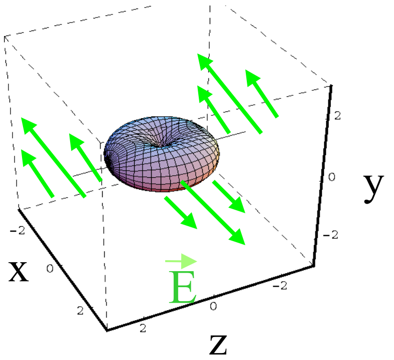
$$\Sigma = \frac{W(90^0,0^0)-W(90^0,90^0)}{W(90^0,0^0)+W(90^0,90^0)} = \pi_1 = \begin{cases} +1 & for \quad J^\pi = 1^+, 2^+ \\ -1 & \quad J^\pi = 1^-, 2^- \end{cases}$$

Experimental Asymmetry of 0.96

Dipole

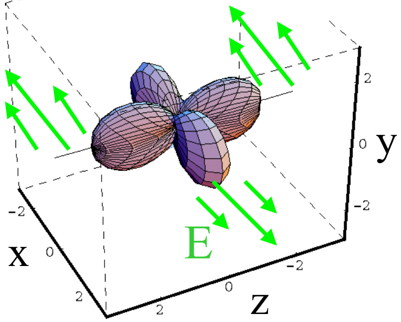

E1

$0^+ \to 1^- \to 0^+$

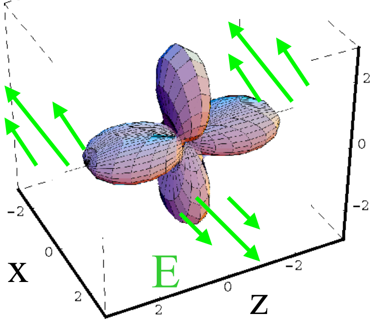

M1

$0^+ \to 1^+ \to 0^+$

Quadruple


E2

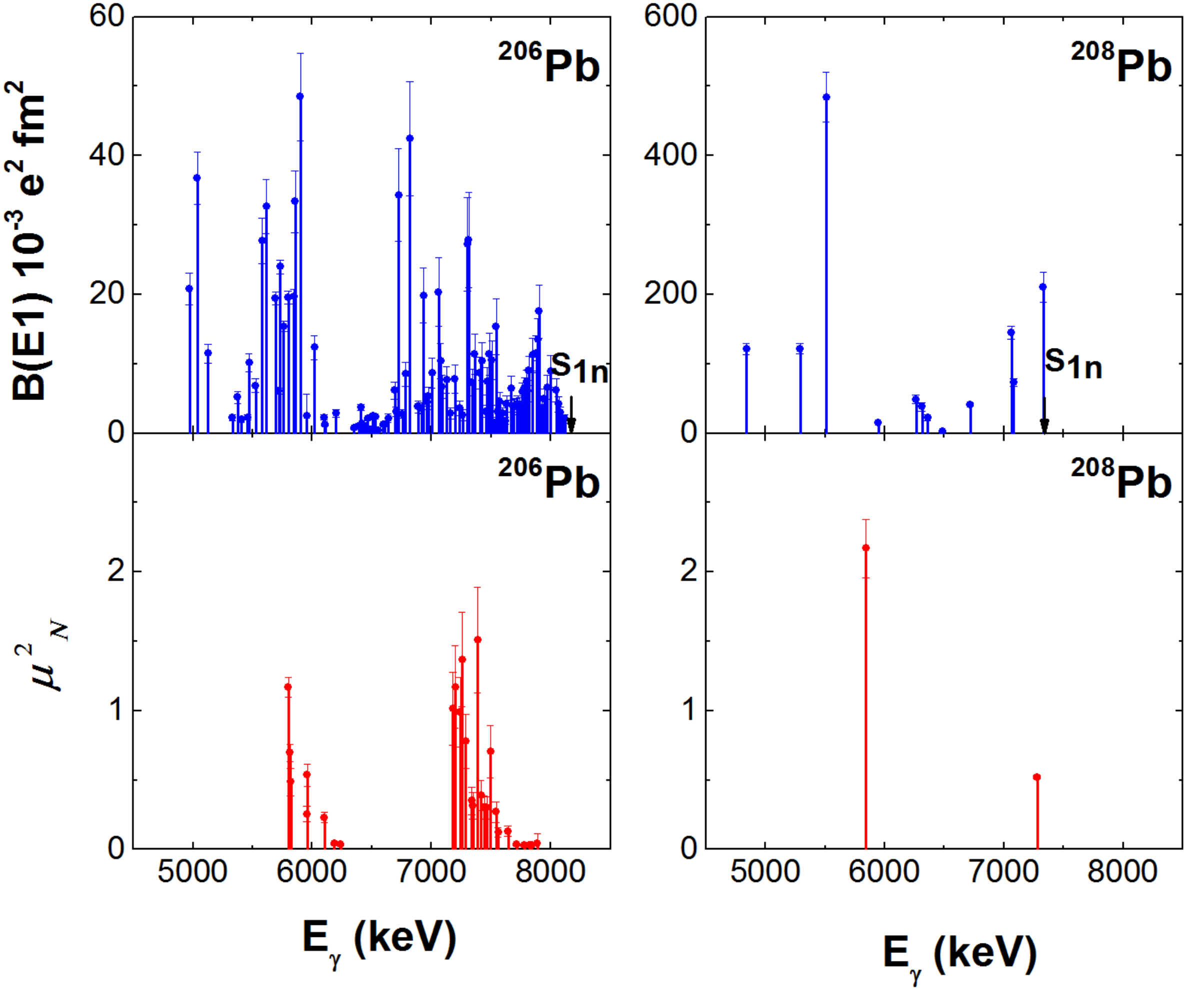
$0^+ \to 2^+ \to 0^+$


M2

$0^+ \to 2^- \to 0^+$

N. Pietralla et al. NIMA **483,** 556 (2002), A. Tonchev, NIM **B 241** (2005) 51474, G. Rusev et al. Phys. Rev**. C 79**, 047601 (2009), B. Löher et al. NIMA **723**, 136 (2013)

Fine Structure of the Electromagnetic Dipole Strength in ^{206}Pb



^{208}Pb

$\Sigma B(E1)\uparrow = 1.23 \pm 0.11\ e^2 fm^2$

$B(E1)_{min} = 0.003\ e^2 fm^2$

$B(E1)_{max} = 0.484\ e^2 fm^2$

Number of states = 12

^{206}Pb

$\Sigma B(E1)\uparrow = 0.91 \pm 0.17\ e^2 fm^2$

$B(E1)_{min} = 0.37xE\text{-}3\ e^2 fm^2$

$B(E1)_{max} = 48.5xE\text{-}3\ e^2 fm^2$

Number of states = 99

208Pb

$\Sigma B(M1)\uparrow = 2.7 \pm 0.3\ m_N{}^2$

Number of states = 2

206Pb

$\Sigma B(M1)\uparrow = 13.3 \pm 3.0\ m_N{}^2$

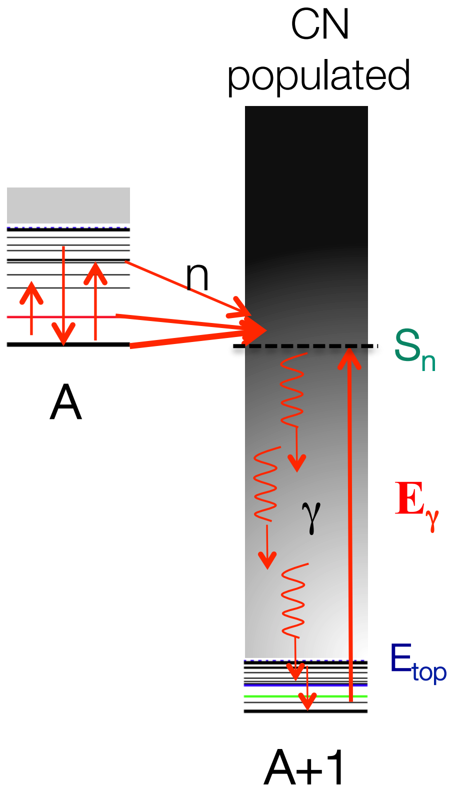
Number of states = 28

V. Ponomarev et al. J. Phys. G **13** (1987) 1523

Calculating (n,g) Cross Sections

Capture reaction

n+target ➔ population of compound nucleus (CN)
Subsequent decay by competition of γ emission and



Theoretical description

Hauser-Feshbach (HF) formalism:

$$\sigma_{n\gamma} = \frac{\pi}{k_n^2}\sum_{J,\pi} g_J \frac{T_\gamma(E,J,\pi)T_n(E,J,\pi)}{T_{\text{tot}}}$$

where

T_γ is the gamma transmission coefficient

$$T_\gamma(E,J,\pi) = \sum_{X,\lambda}\int T_{X\lambda}(\epsilon_\gamma)\rho(E-\epsilon_\gamma)d\epsilon_\gamma$$

T_n is the neutron transmission coefficient

and $T_{tot} = T_n + T_p + T_d + T_t + T_\alpha + T_\gamma$

In the case of (n,γ):

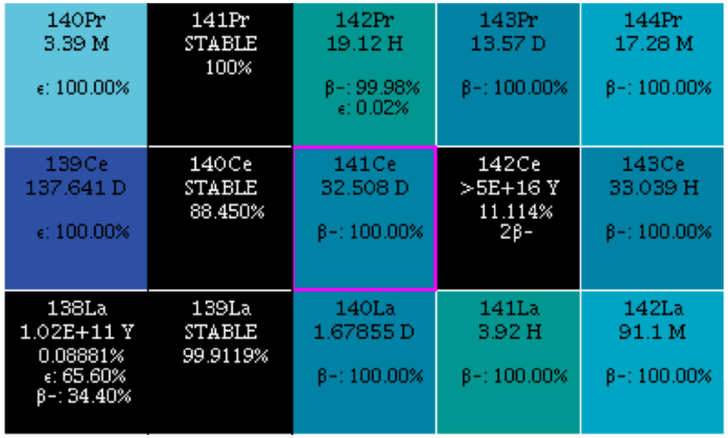
- $T_\gamma << T_n + T_p + T_d + T_t + T_\alpha$, ignore T_γ in T_{tot}
- T_p, T_d, T_t, T_α all small below thresholds

So $T_n T_\gamma / T_n$ reduces to T_γ

$$\sigma_{n\gamma} = \frac{\pi}{k_n^2}\sum_{J,\pi} g_J \sum_{X,\lambda}\int \underbrace{T_{X\lambda}(\epsilon_\gamma)\rho(E-\epsilon_\gamma)d\epsilon_\gamma}_{\text{Product of }\gamma\text{SF and LD}}$$

Measuring the ^{142}Ce(g,n) reaction to infer the inverse ^{141}Ce(n, g) reaction

Proof-of-Principle Experiment on ^{141}Ce radioactive target



140Pr 3.39 M ε: 100.00%	141Pr STABLE 100%	142Pr 19.12 H β-: 99.98% ε: 0.02%	143Pr 13.57 D β-: 100.00%	144Pr 17.28 M β-: 100.00%
139Ce 137.641 D ε: 100.00%	140Ce STABLE 88.450%	141Ce 32.508 D β-: 100.00%	142Ce >5E+16 Y 11.114% 2β-	143Ce 33.039 H β-: 100.00%
138La 1.02E+11 Y 0.08881% ε: 65.60% β-: 34.40%	139La STABLE 99.9119%	140La 1.67855 D β-: 100.00%	141La 3.92 H β-: 100.00%	142La 91.1 M β-: 100.00%

PHYSICAL REVIEW C 89, 035803 (2014)

Determination of the ^{142}Ce(γ,n) cross section using quasi-monoenergetic Compton backscattered γ rays

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Knowing the energy dependence of (γ,n) cross sections is mandatory to predict the abundances
of heavy elements using astrophysical models. The data can be applied directly or used to constrain the cross section of the inverse (n,γ) reaction.