Determination of the total neutron capture cross-section for $^{58}Ni(n,\gamma)^{59}Ni$ reaction

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OUTLINE

- Theoretical issues
  - Methods for determining the total neutron capture cross section
  - Determining the partial γ-ray production cross sections
  - Calculation of relative efficiency based on new intensities of $^{14}N(n,\gamma)^{15}N$ reaction
- $^{58}Ni(n,\gamma)^{59}Ni$ measurement and its evaluation
- Results and comparison with former measurements

Total neutron capture cross section

Method	Equation	Notes
PM	$\sigma_{th} = \sum_{f=1}^{n-1} (1+\alpha_f)(1+PCC_f) \cdot \sigma_{\gamma(CS \rightarrow f)}$	The sum of all primary transitions from the capture state can be used for nuclei with relative simple decay scheme. Conversion coefficients must be known.
GS	$\sigma_{th} = \sum_{i=2}^{n} (1+\alpha_i)(1+PCC_i) \cdot \sigma_{\gamma(i \rightarrow GS)}$	The sum of all ground state transitions can be used for nuclei with relative simple decay scheme. Conversion coefficients must be known.
Inv Q	$\sigma_{th} = \sum_{i} \frac{E_i}{B_n} \cdot (1+\alpha_i)(1+PCC_i) \cdot \sigma_{\gamma i}$	The energy weighted sum can be used for any nuclei with resolved gamma-transitions. *E_i* is the energy of the transition, *B_n* is the binding energy.

Key quantities: partial gamma-ray production cross sections (σ_γ)

Partial γ-ray production cross section

Comparator method (based on PGAA standardization):

partial gamma-ray production cross section for C (from standardization)

rate of counts at a given gamma energy for X and C

$$\sigma_{X\gamma} = \sigma_{C\gamma} \frac{A_{X\gamma}}{A_{C\gamma}} \frac{n_C}{n_X} \frac{\varepsilon(E_{C\gamma})}{\varepsilon(E_{X\gamma})} \frac{f(E_{C\gamma})}{f(E_{X\gamma})}$$

- number of atoms X and C must be known with high accuracy
- integers for chemical compounds (stochiometry)

- relative efficiency is needed only
- less uncertainty

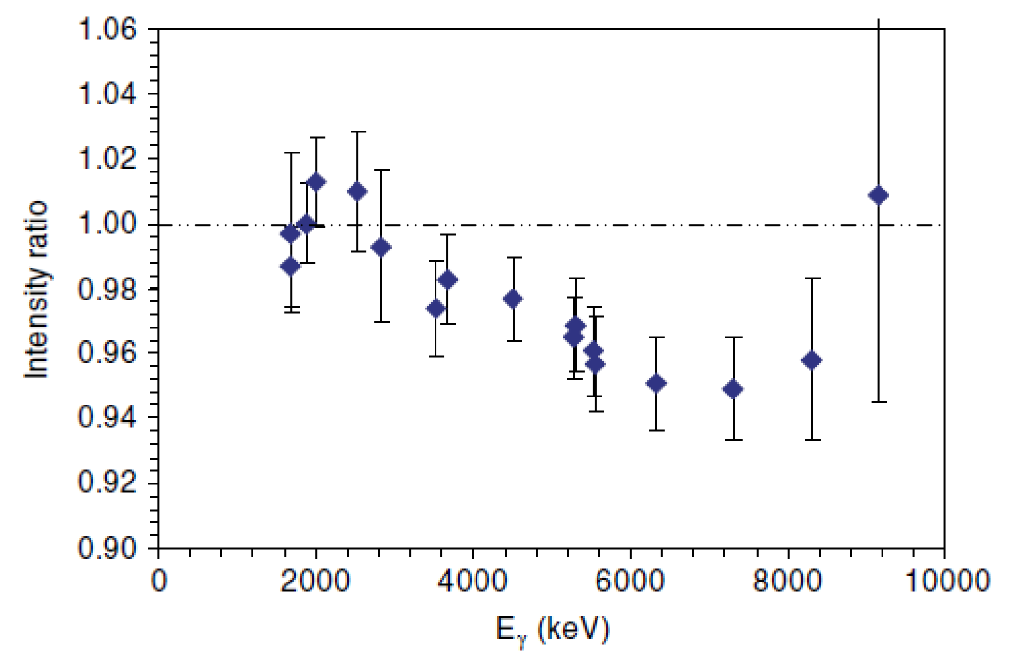
- different self-absorption for gammas
- same self-shielding for neutrons

Internal comparator method (in our case C = X = ^{58}Ni):

- C and X are the same → $n_C = n_X$
- Cross section by internal calibration (from standardization for γ = 464.9 keV)
- $\sigma_{C\gamma}(^{58}\text{Ni}) = \sigma_{C\gamma}(\text{elemental})$ / isotopic abundance × enrichment =
  = 0.843 b / 0.68077 × 0.995 = 1.232 b

Results of CIS method for intensities of $^{14}N(n,\gamma)^{15}N$

$$\text{Intensity ratio} = \frac{\text{Jurney, Phys.Rev. C56(1),118 (1997)}}{\text{Belgya, Phys.Rev. C74,024603 (2006)}}$$



Efficiency values according to which intensity set is used:

- if Jurney > Belgya → higher efficiency if using I_γ from Belgya
- if Jurney < Belgya → lower efficiency if using I_γ from Belgya

Relative efficiency and its uncertainty

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JUL08-2.EFF

121-10829 keV
CHSQ:          1.09
COEFFICIENTS:
(0)   -3436.457
±         3.912
(1)    -197.760
±         1.410
(2)     -64.548
±         1.090
(3)     -11.231
±         1.179
(4)      -9.623
±         1.182
(5)       3.725
±         1.150
(6)      -4.078
±         1.109
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122 keV  (7.95e-05 ±   2.1%)  Eu-152P CHI: 0.0
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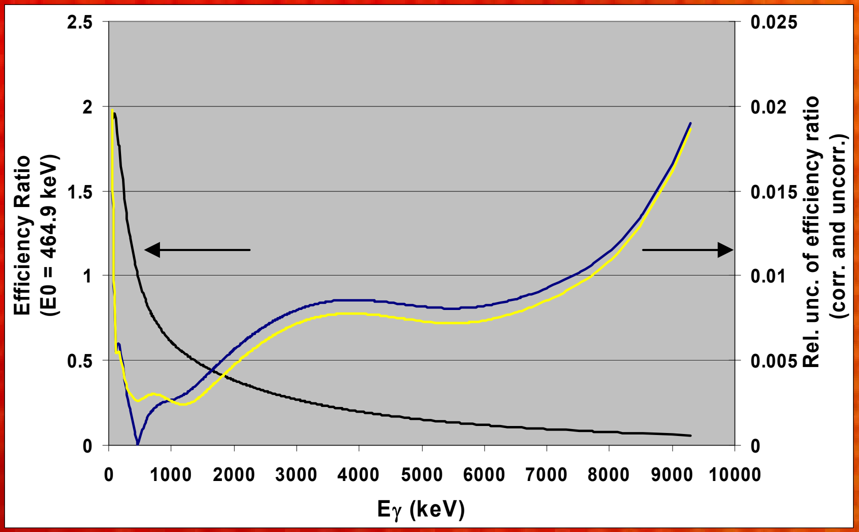


- efficiency is needed for a wide energy range:
  - ~50 keV — ~12 MeV
  - radioactive sources (^{226}Ra, ^{207}Bi, ^{152}Eu)
  - **(n,γ) reactions with well known intensities (e.g. ^{14}N)**
  - Hypermet-PC

- uncertainty of rel. efficiency:
  - below 1% for a wide range (85 keV – 7.5 MeV)
  - correlation between efficiency values
  - unc. of relative eff. is zero at the pivot energy (464.9 keV)

Ni-58 measurement

- Sample description
- Measurement conditions
- Data evaluation
- Results
- Comparison

Recent sample for ^{58}Ni(n,γ)^{59}Ni experiment

- Pressed metal target
- Enriched in ^{58}Ni : 99.5 %
- m = 2.0679 g
- Diam = 20 mm
- Thickness = 0.77-0.78 mm
  - some surface depression

Experimental conditions at the PGAA station

- Beam cross section (max): $\leq 2 \times 2$ cm^2,
- Beam cross section (used): 10 mm^2
- Thermal-eq. flux at target: $\sim 1.2 \times 10^8$ cm^{-2}s^{-1}

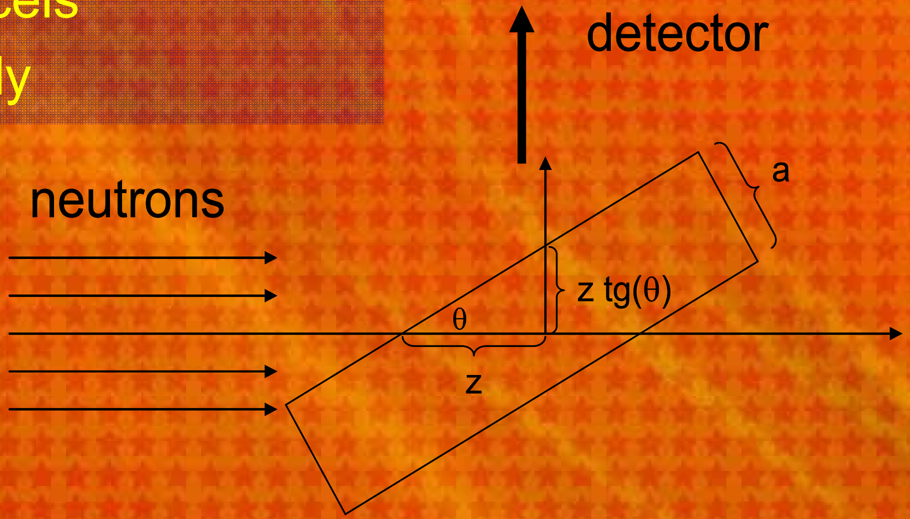
- Vacuum in target chamber: $\sim$1 mbar

- γ-ray detector: n-type coax. HPGe, with BGO shield in Compton-suppr. mode

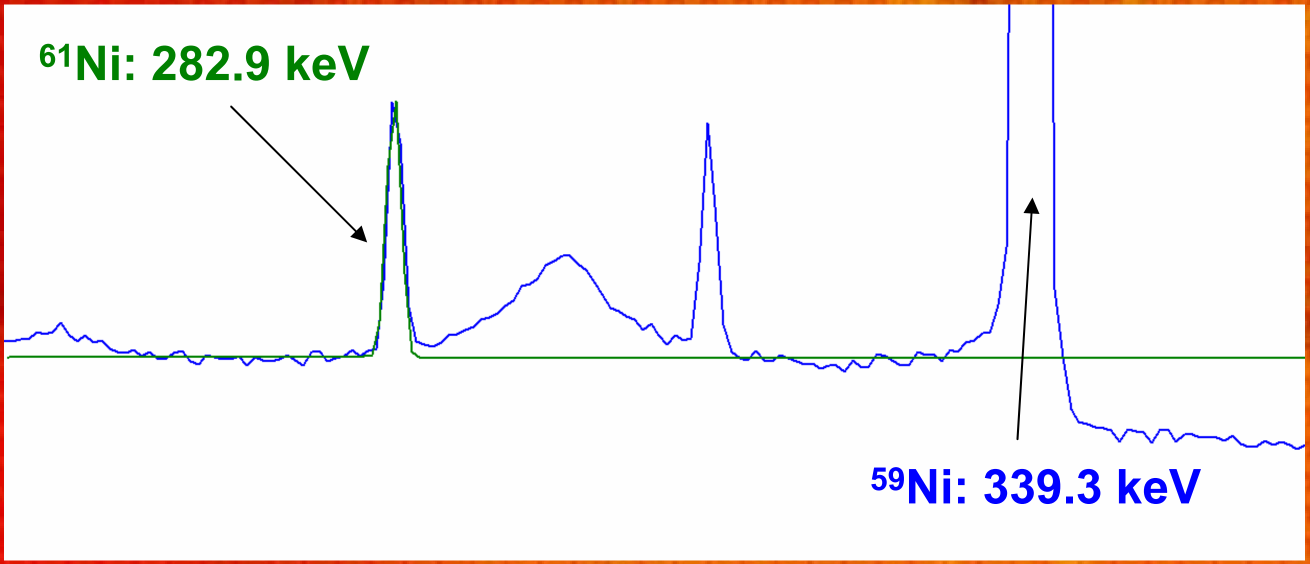
Identification of peaks and attenuation correction

- Identifying peaks from $^{58}Ni(n,\gamma)^{59}Ni$:
  - elimination: SE, DE, bkg and other nuclides
  - other isotopes of Ni: ^{60}Ni found, but only in low amount
  - trace elements (not found)

- Correction for attenuation
  - comparator method + homogeneous sample:
  - self-shielding for neutrons cancels
  - self-absorption for gammas only



Identification of peaks from other nuclides in the sample



- comparison of two spectra with GammaView:
  - separate spectra for **^{58}Ni(n,γ)^{59}Ni** and **^{60}Ni(n,γ)^{61}Ni**
  - strongest line of ^{60}Ni is at 282.9 keV
  - scale factor: 0.004
  - amount of ^{60}Ni in the ^{58}Ni sample is about 0.4 n%
- others < 0.1 n%

Results for σ_{th} using the two sets of ^{14}N intensities

- Primary transitions:
  - 55 of 57 (Raman’s) primary found
  - not found:
    - σ_γ(5585.2 keV) = 0.70 mb
    - σ_γ(7050.1 keV) = 0.43 mb
- Ground state transitions:
  - 42 of 44 (Raman’s) ground state found
  - not found:
    - σ_γ(6279 keV) = 0.38 mb
    - σ_γ(6872.8 keV) = 0.63 mb
- Inverse Q-value test (pri + sec):
  - 430 transitions found > 414 (Raman’s)

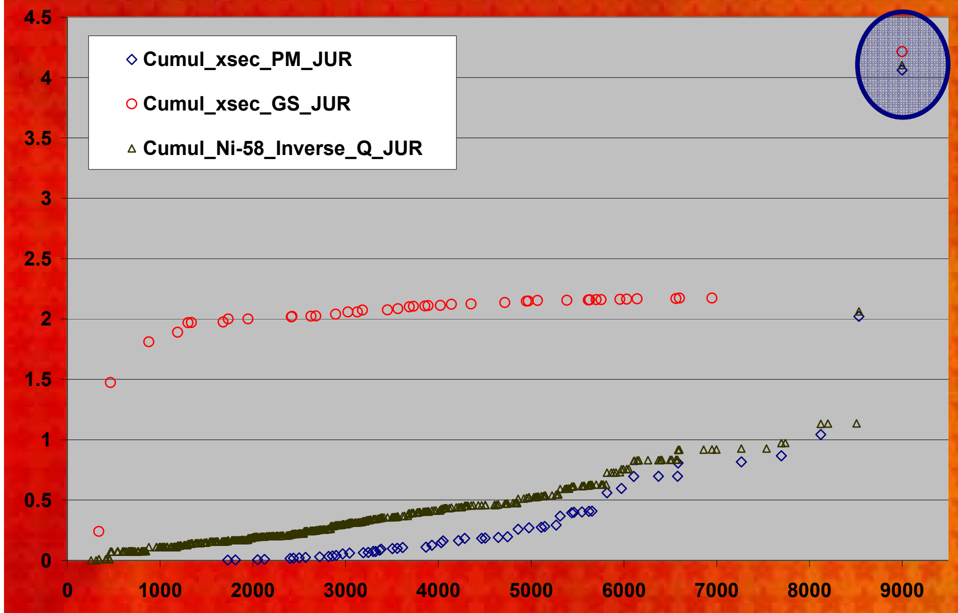
^{58}Ni(n,γ)^{59}Ni	σ_{th} (b)	
	Jurney ^{14}N	Belgya ^{14}N
Primary	**4.06 ± 0.05**	**4.24 ± 0.05**
Ground state	**4.21 ± 0.05**	**4.31 ± 0.05**
Inverse Q	**4.10 ± 0.05**	**4.27 ± 0.05**

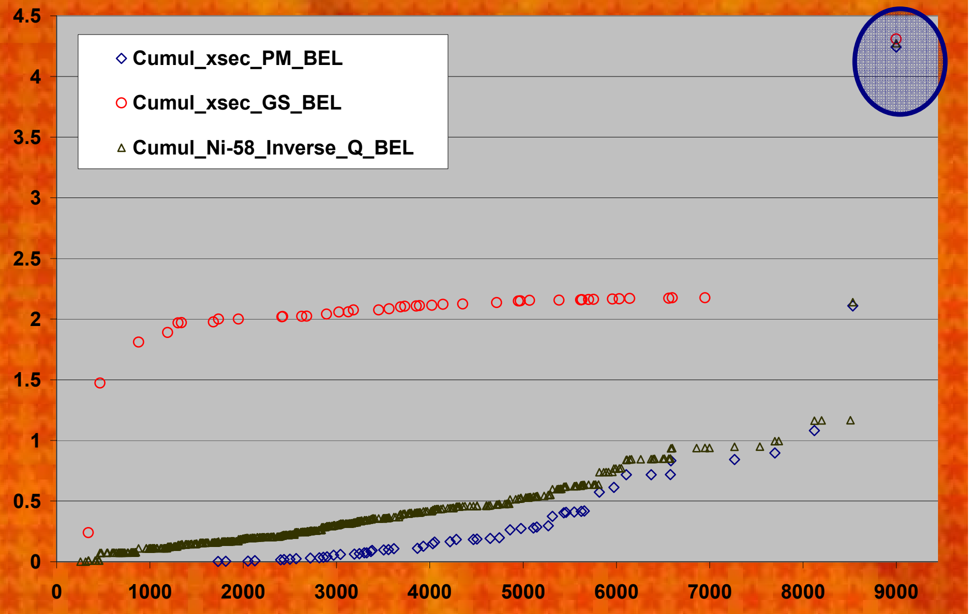
more fluctuation

less fluctuation

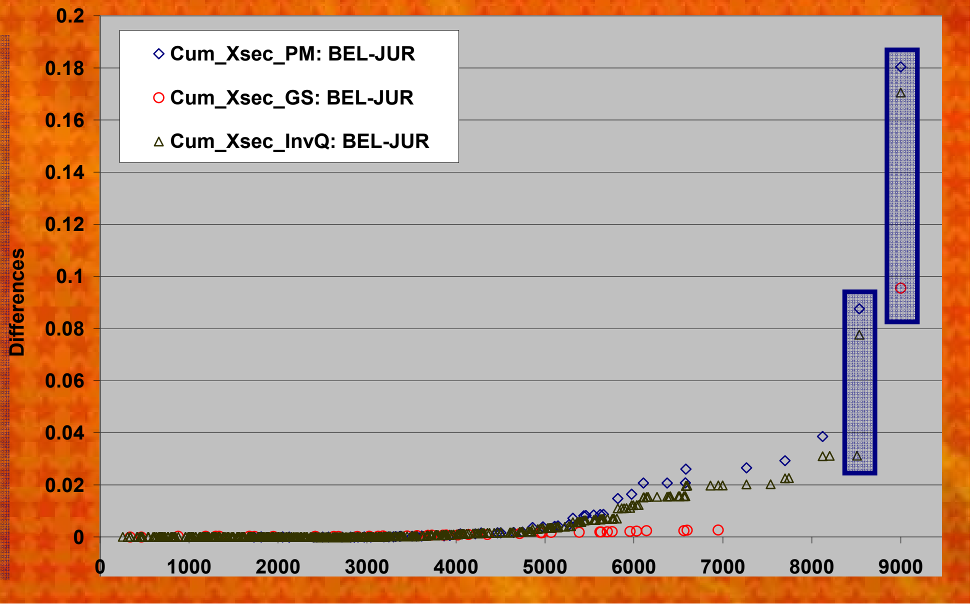
Identifying PM and GS transitions:
Raman, Phys Rev C 70, 044318 (2004)

Cumulative Xsecs of inverse Q, GS and PM transitions using Jurney's and Belgya's $^{14}N(n,\gamma)$ intensities





- Reasons of fluctuation:
  - energy sampling of methods:
    - PM: more in *higher* energy range
    - GS: more in *lower* energy range
    - InvQ: more *uniform*
  - diff. mainly at higher energy when cumulating (e.g. @ 8999 keV)
  - differences: PM > InvQ > GS



Former results

Mughabghab (evaluated): σ_{th}(Ni-58) = 4.37 ± 0.1 b

Xsec (b)	Err (b)	Author	Source	Sample	Monitor
4.13	**0.05**	Raman, 2004	MXW th n flux: 6E11	99.93 % enriched 58NiO	•en cal: melamine ($C_3H_6N_6$) •int cal: rad sources and $^{14}N(n,\gamma)^{15}N$
4.4	**0.2**	Venturini, 1997	MXW th n flux: 5E11	Mixture: melanine + nat Ni	•en cal: melamine ($C_3H_6N_6$) •int cal: rad. sources and $^{14}N(n,\gamma)^{15}N$
4.6	**0.3**	Weselka, 1991	MXW th n flux: 3.9E17	Foil of 4.8 mg/cm2	Activation: Ni-58 and Fe-54
4.52	**0.1**	Carbonari, 1988	MXW th n flux: 5.2E11	Mixture: melanine + natural Ni	en and int cal: $^{14}N(n,\gamma)^{15}N$ and $^{35}Cl(n,\gamma)^{36}Cl$
4.5	**-**	Ishaq, 1977	MXW th n flux: 5E12		en and int cal: $^{14}N(n,\gamma)^{15}N$
4.4	**-**	Gippner, 1971	Th beam. No details	Natural nickel	-
4.2	**0.34**	Pomerance, 1952	Pile oscillator	Enriched Ni, NiO	Activation: Au-197

All results but Pomerance and Weselka were based on $^{14}N(n,\gamma)^{15}N$ intensities: e.g. Jurney et al., Phys.Rev. C56(1) (1997)

Estimation for total capture cross section

- σ_{th} is a lower limit:
  - we cannot claim that we have detected all possible γ-rays
- Estimation for missing part of σ_{th} based on primaries:
  - Max. value of transitions not seen among primaries?
    - Smallest $\sigma_{\gamma i}$ measured: ~0.00053 b („worst case scenario”: overestimation)
  - Number of transitions not seen among primaries?
    - E1 transitions from 1/2+ to 1/2- and 3/2- are the most probable
    - Based on theoretical level densities, the number of 1/2- and 3/2- levels: ~350
  - Max. part of σ_{th} not seen: 350 × 0.00053 b = ~0.19 b
  - More sophisticated: e.g. Dicebox

Estimation for total σ_{th} based on primaries:

$$\sigma_{th} = \sigma_{th}\text{ (seen)} + \sigma_{th}\text{ (not seen)} = 4.24 + 0.19 = 4.43\text{ b}$$

- Thank you for your attention!