Empirical estimation of astrophysical photodisintegration rates of ^{106}Cd and ^{108}Cd

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Introduction

Previous photon activation experiments (at the SINP MSU microtron):

1. 2013 [S. S. Belyshev *et al.*, Phys. At. Nucl. **77**, 809 (2014)]
   1.1 relative yields on CdO target:

Reaction	Exp.	Theor.
^{106}Cd(γ, n)^{105}Cd	0.57 ± 0.02	0.97–1.06
^{106}Cd(γ, p)^{105}Ag	0.47 ± 0.06	0.12–0.143
^{108}Cd(γ, n)^{107}Cd	1.15 ± 0.08	1.04–1.2

   1.2 reactions on other isotopes: good agreement
2. 2015 [S. S. Belyshev *et al.*, Phys. At. Nucl. **79**, 5 (2016)]
   2.1 absolute yields (in $10^6 \times$ 1 /μC) on natural Cd:

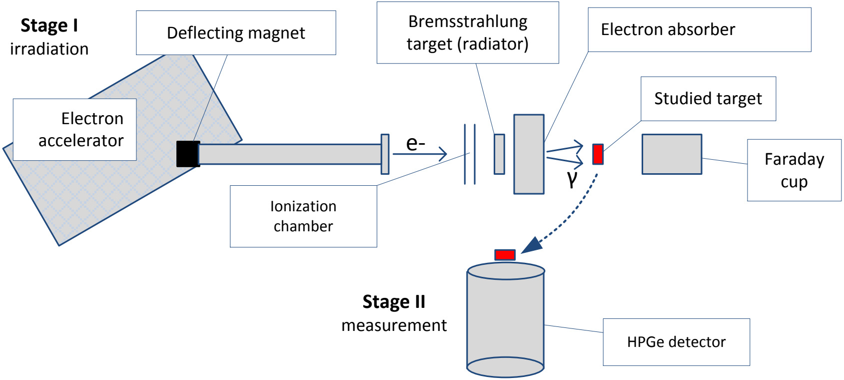
Reaction	Exp.	Theor.
^{106}Cd(γ, n)^{105}Cd	1.41 ± 0.05	2.8 ± 0.1
^{106}Cd(γ, p)^{105}Ag	1.5 ± 0.1	0.33 ± 0.02
^{108}Cd(γ, n)^{107}Cd	2.7 ± 0.2	2.8 ± 0.1

Photoproton reaction on ^{106}Cd almost equal to (γ,n) which is unusual for $A > 40$.
=> Repeat measurement with monoisotopic target to reduce background from ^{111}Cd.

Cadmium targets

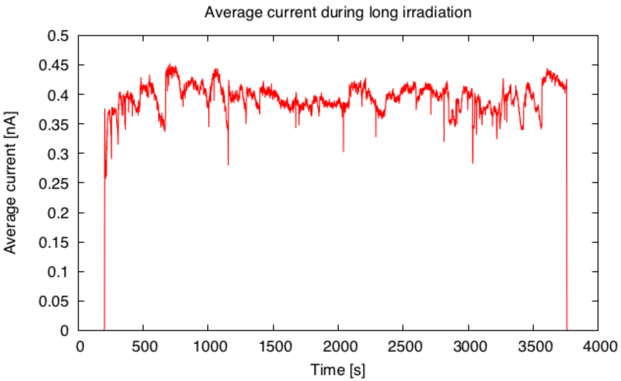
Target Irradiation	CdO 2013	Nat. Cd 2015	Enriched Cd 2016
Isotopes, at.%			
106	0.63	1.25	74.2 ± 0.4
108	0.44	0.89	0.52
110	6.25	12.49	4.16
111	6.4	12.80	3.70
112	12.07	24.13	6.6
113	6.11	12.22	3.10
114	14.37	28.73	6.6
116	3.75	7.49	1.12
Mass, g	0.3	0.64	0.25

Photon activation technique



- RTM-55 racetrack microtron, $E_e = 55.5$ MeV, 10 mA pulsed current, no. of orbits: 11.
- Average current measured by a Faraday cup and charge collected from the target. Normalized using a copper monitor target.

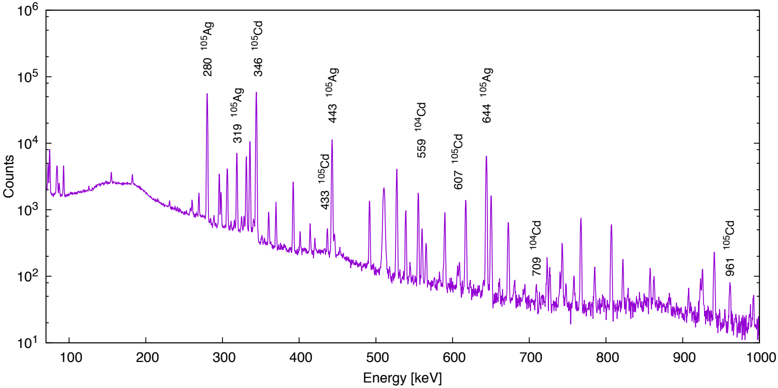
Measurement



- Perfromed 4 irradiations for 10 min–1 h for short and long $T_{1/2}$ at average current 0.2–0.3 μA
- Bremsstrahlung target: 2.1 mm W
- After irradiation target transferred to low-background HPGe detector
- Initial count rate 27000 s^{-1} at 15 cm from detector.
- Continuous spectrum measurement by automatic database for two days after irradiation and 26 days in 4 months after irradiation.

Spectrum analysis

Sample spectrum 12 hr after irradiation



Unstable reaction products identified by peak energies and intensities and by $T_{1/2}$ obtained by fitting decay curves.
The following peaks were used for ^{105}Cd: 346.87, 433.24, 607.22, 961.84, 1302.459, 1388.48, 1693.34.
For ^{105}Ag: 63.98, 280.41, 319.14, 331.51, 344.52, 443.37, 644.55, 1087.94
Decay of ^{105}Ag to ^{105}Cd taken into account by calculating the independent yield.

Obtained yields

	$(\gamma,\ \mathrm{n})^{105}\mathrm{Cd}$	$(\gamma,\ \mathrm{p})^{105}\mathrm{Ag}$
	Experiment	
σ_q, mb	$(3.0 \pm 0.1) \cdot 10^7$	$(4.4 \pm 0.4) \cdot 10^7$
Y, $1/\mu$C	$(3.0 \pm 0.1) \cdot 10^7$	$(4.6 \pm 0.7) \cdot 10^7$
	Models	
Y, TALYS	$(6.4 \pm 0.9) \cdot 10^7$	$(0.73 \pm 0.01) \cdot 10^7$
Y, CM	$(7.0 \pm 0.1) \cdot 10^7$	$(1.04 \pm 0.01) \cdot 10^7$
Y, TALYS+isospin	$(6.61 \pm 0.09) \cdot 10^7$	$(1.27 \pm 0.02) \cdot 10^7$

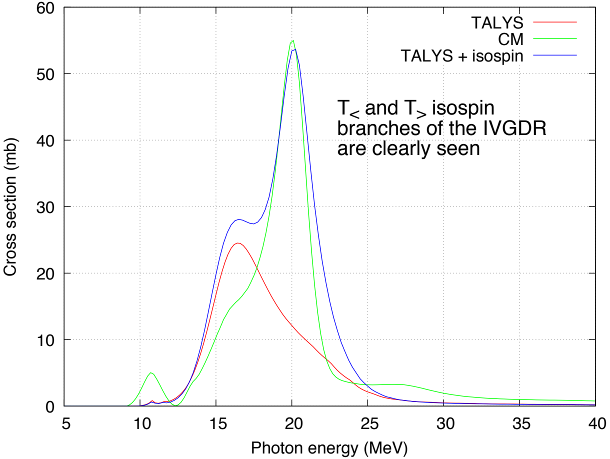
$(\gamma,\ \mathrm{n}) + (\gamma,\ \mathrm{p})$ in agreement with dipole sum rule in all cases.

*)CM = Combined model of photonuclear reactions (semi-microscopic description of photoabsorption followed by HF, preeq. or QD decay with global optical potential) [B. S. Ishkhanov and V. N. Orlin, Phys. At. Nucl. **74**, 19 (2011)]

**)"TALYS + isospin" = modified TALYS to artificially include isospin splitting effect of the IVGDR

Model cross sections

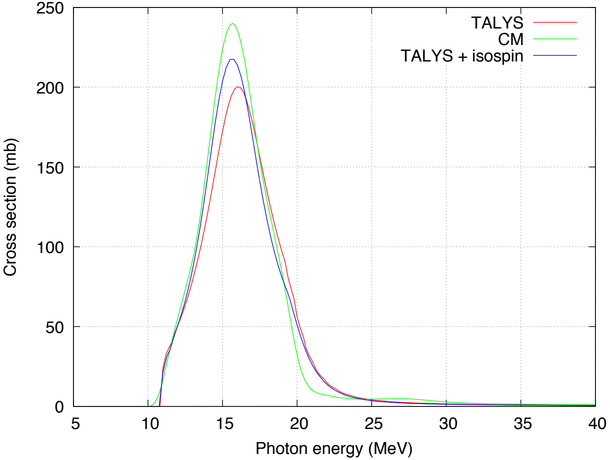
(γ, p) reaction



Other potential sources of $\sigma(\gamma,\mathrm{p})$ enhancement: GQR (included in CM, low), direct proton emission (expected at about 34 MeV), competition with (γ,γ') at 7–10 MeV.

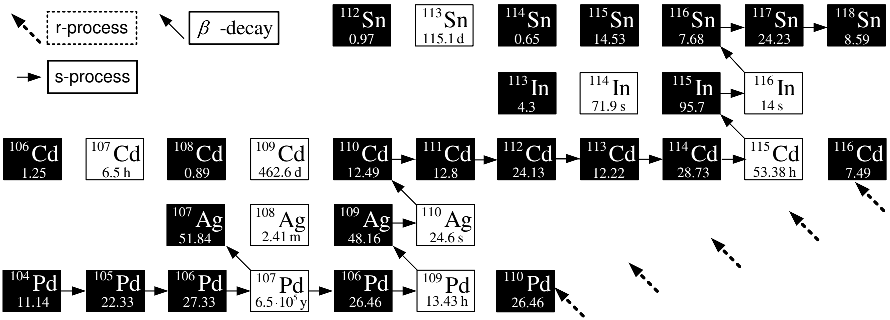
Model cross sections

(γ,n) reaction



Photoneutron cross sections are almost equally overestimated by all models.

p-nuclei

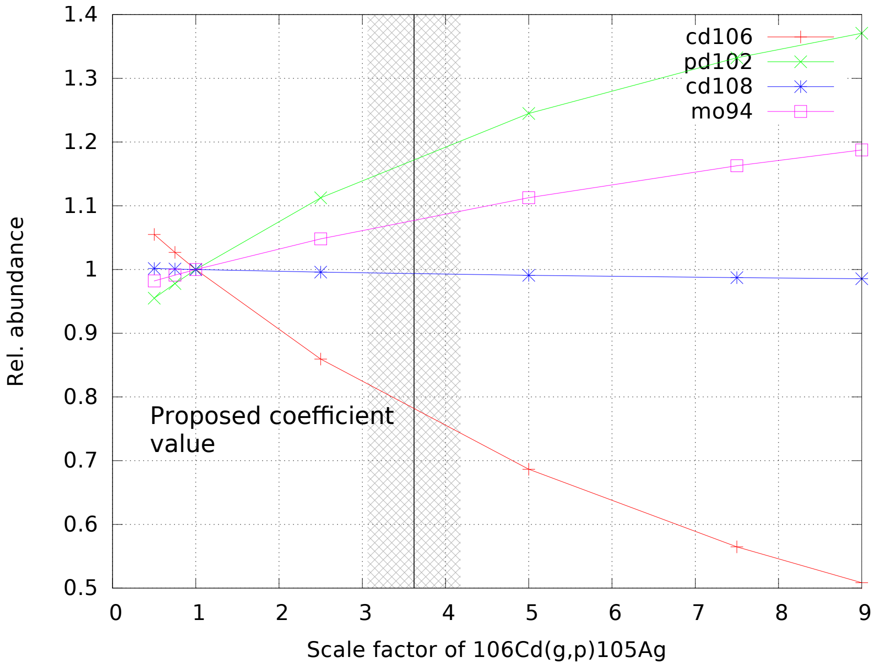


^{106,108}Cd belong to a group of 35 nuclei from ^{74}Se to ^{196}Hg far from the s- and r-process trajectories.
Produced in the p-process of nucleosynthesis, mainly photodisintegrations in core-collapse supernova at several GK.
(γ,p) especially important for ^{106}Cd: $B_p = 7.4$ MeV, $B_n = 10.9$ MeV.

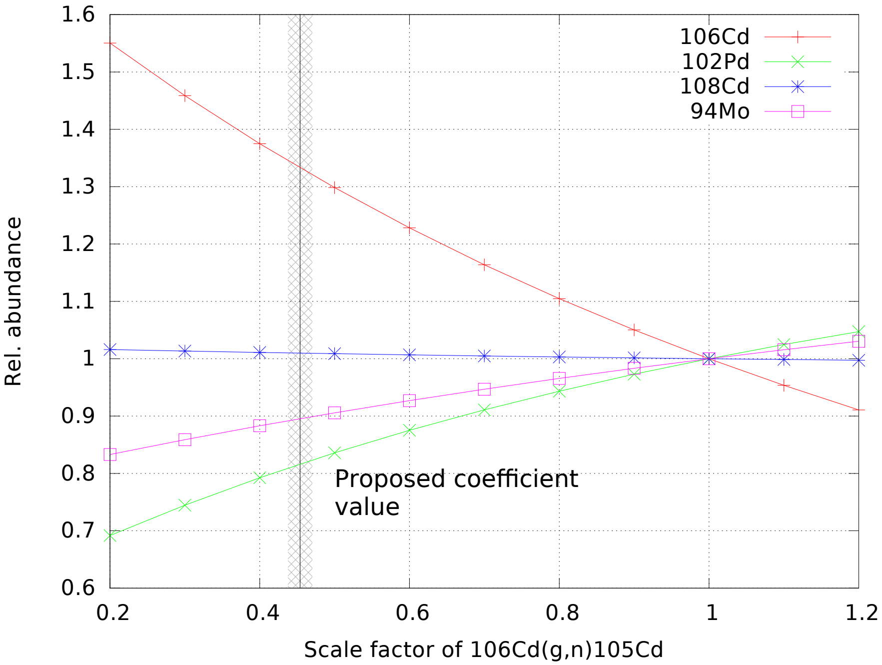
Nuclear network calculations

- ^{106}Cd(γ, n) and (γ,p) rates calculated with TALYS with isospin effect
- A slightly modified burning routine from the MESA star evolution package used to calculate final abundances as a function of scaling factors applied to the rates
- Other reaction rates from JINA REACLIB
- Initial abundances, temperature and density profiles of a $25 M_\odot$ SNII as in [Rapp *et al.*, ApJ 653, 474 (2006)]

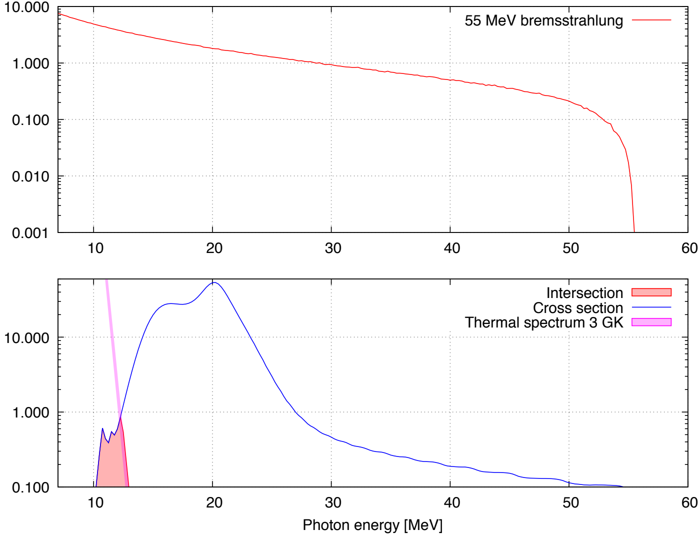
Impact of rate normalization of the (γ,p) reaction



Impact of rate normalization of the (γ,n) reaction

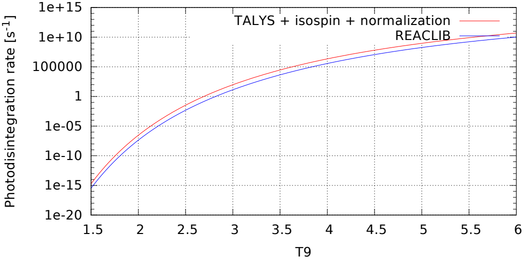


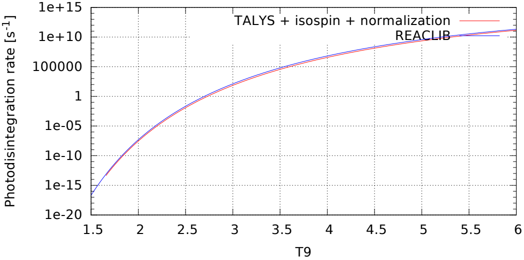
Bremsstrahlung and stellar photon spectrum



Very wide bremsstrahlung spectrums gives only rough estimates of rates normalization. However, no other experimental data on ^{106} available.
More reliable at *p*-process sites with higher temperatures (accretion disks, ...).

Photodisintegration rates





Almost an order of magnitude difference for (γ,p). (γ, n) is within 2 times difference from the DB value.

Rates in REACLIB format

Parameterization of the proposed rates

$$\lambda = \exp\left(a_0 + \sum_{i=1}^{5} a_i T_9^{\frac{2i-5}{3}} + a_6 \ln T_9\right) \qquad [1/\mathrm{sec}]$$

- ^{106}Cd(γ,p)^{105}Ag reaction rate
  a_0 = -2.278902e+03, a_1 = -5.612792e+02, a_2 = 7.767336e+03,
  a_3 = -5.150742e+03, a_4 = 1.580728e+02, a_5 = -5.632337e+00,
  a_6 = 3.708693e+03
- ^{106}Cd(γ,n)^{105}Cd reaction rate
  a_0 = -3.167238e+03, a_1 = -7.286351e+02, a_2 = 8.503323e+03,
  a_3 = -4.819095e+03, a_4 = 1.304085e+02, a_5 = -4.259804e+00,
  a_6 = 3.735719e+03

Conclusions and outlook

- Experimental measurement of yields and cross sections per equivalent quantum on enriched ^{106}Cd target is performed.
- Good agreement with theory is seen for photodisintegration reactions on ^{108}Cd, but large difference on ^{106}Cd.
- Cross sections of ^{106}Cd(γ, n) and (γ, p) calculated with addition of the isospin splitting effect of the IVGDR are most close to the experimental results.
- The cross sections are used to calculate photodisintegration rates and examine effects of their variation on the produced *p*-nuclei abundances.
- Estimated photodisintegration rates on ^{106}Cd are obtained by applying experimental scaling factors.
- Experiments with monochromatic photons on Cd are needed.
- Also on ^{102}Pd, as indications of large photodisintegration yields were seen.

Thanks!