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

S. S. Belyshev[1], A. A. Kuznetsov[2], K. A. Stopani[2]

[1]Department of Physics, Lomonosov Moscow State University
[2]Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University

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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:

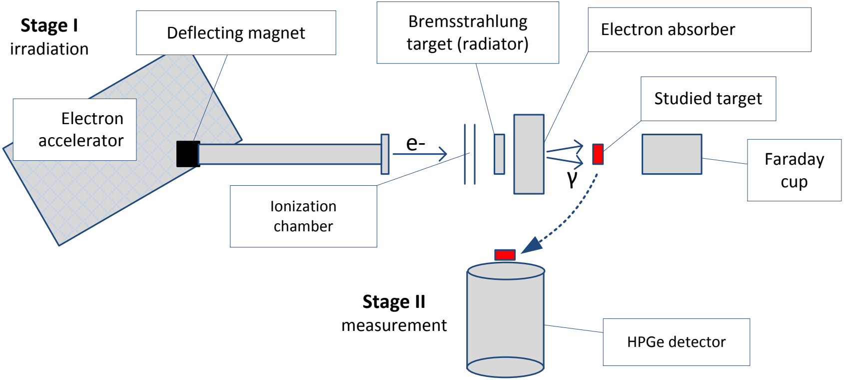
Reaction	Exp.	Theor.
^{106}Cd(γ, n)^{105}Cd	1.41 ± 0.05	2.8 ± 0.1
^{106}Cd(γ, p)^{105}Ag	1.5 ± 0.1	0.33 ± 0.02
^{108}Cd(γ, n)^{107}Cd	2.7 ± 0.2	2.8 ± 0.1

Photoproton reactions are very often underestimated by stat. models for $A > 40$, however, ^{106}Cd made interesting due to good agreement for other isotopes.
=> Repeat measurement with monoisotopic target to reduce background from ^{111}Cd.

Cadmium targets

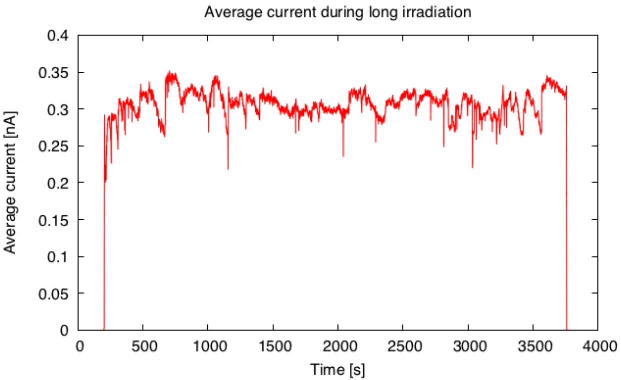
Target Irradiation	CdO 2013	Nat. Cd 2015	Enriched Cd (this work) 2016
Isotopes, at.%			
106	0.63	1.25	74.2 ± 0.4
108	0.44	0.89	0.52
110	6.25	12.49	4.16
111	6.4	12.80	3.70
112	12.07	24.13	6.6
113	6.11	12.22	3.10
114	14.37	28.73	6.6
116	3.75	7.49	1.12
Mass, g	0.3	0.64	0.25

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.

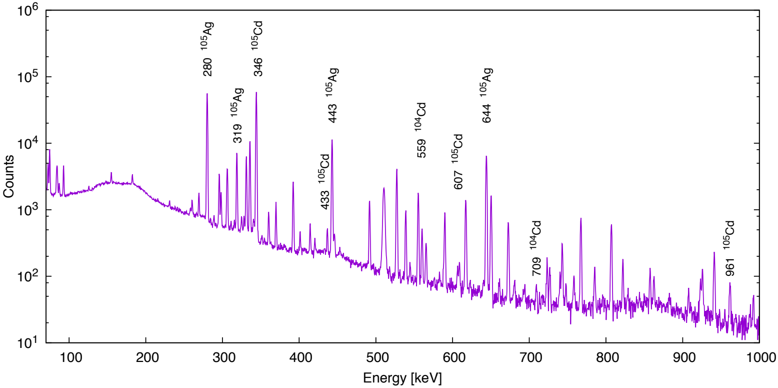
Measurement



- 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

	$(\gamma,\ n)^{105}Cd$	$(\gamma,\ p)^{105}Ag$
	Experiment	
σ_q, mb	31 ± 1	46 ± 4
Y, $1/\mu C$	$(3.0 \pm 0.1) \cdot 10^7$	$(4.4 \pm 0.4) \cdot 10^7$
	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	$(6.61 \pm 0.09) \cdot 10^7$	$(1.27 \pm 0.02) \cdot 10^7$

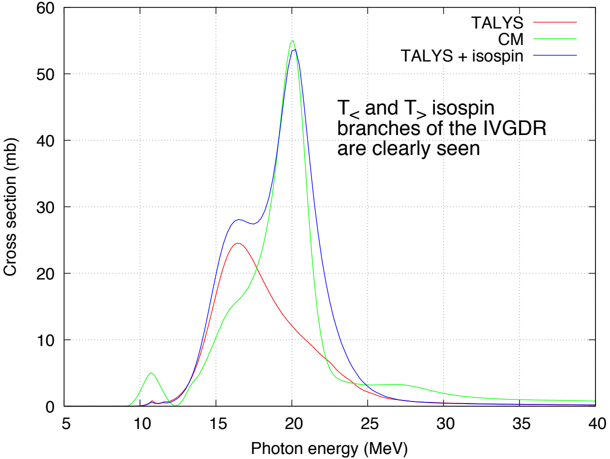
$(\gamma,\ n) + (\gamma,\ p)$ in agreement with dipole sum rule in all cases.

*)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

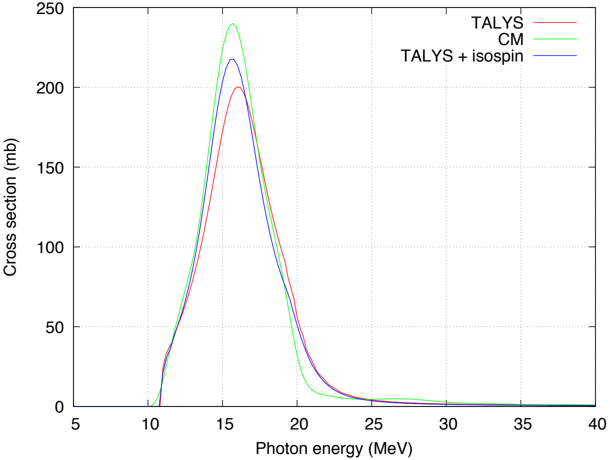
^{106}Cd(γ, p) reaction



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

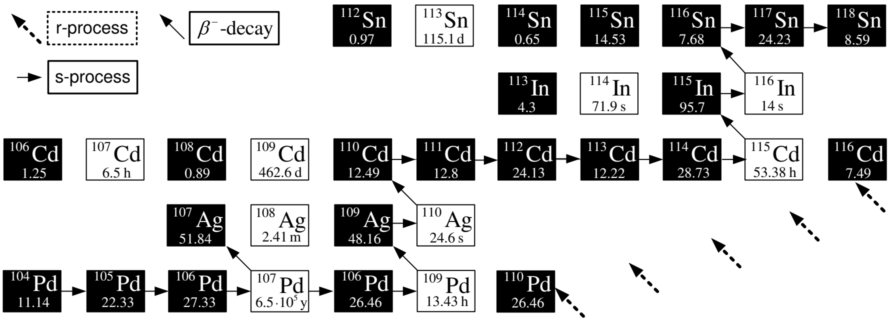
Model cross sections

^{106}Cd(γ,n) reaction



Photoneutron cross sections are almost equally overestimated by all models.

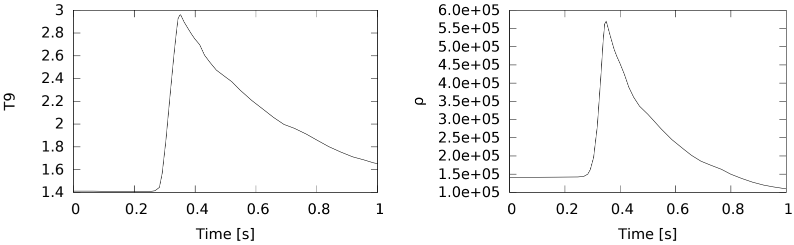
p-nuclei



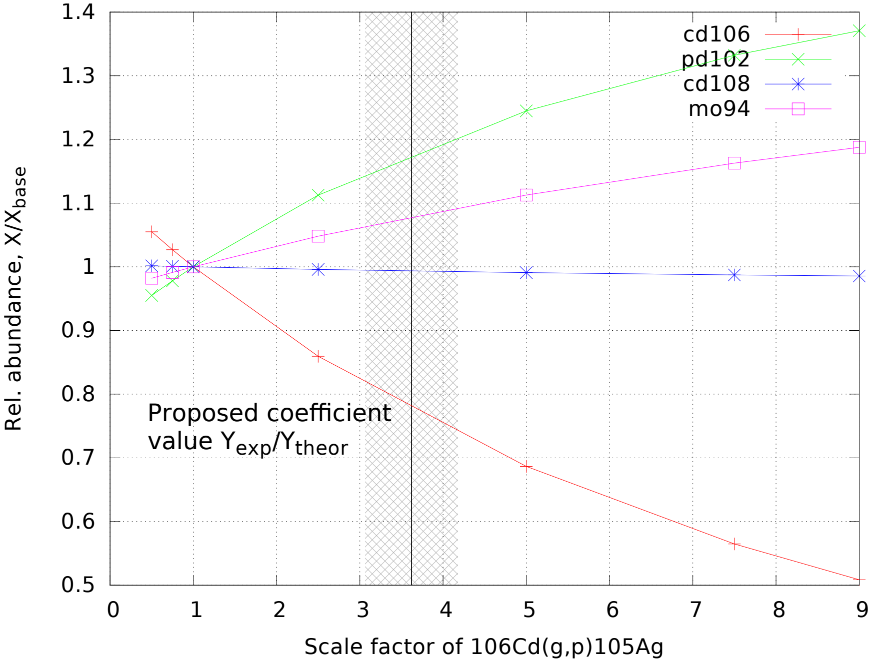
^{106,108}Cd belong to a group of 35 nuclei from ^{74}Se to ^{196}Hg far from the *s*- and *r*-process trajectories.
Produced in the *p*-process of nucleosynthesis, mainly photodisintegrations in core-collapse supernova at several GK.
(γ,p) especially important for ^{106}Cd: $B_p = 7.4$ MeV, $B_n = 10.9$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

Nuclear network calculations

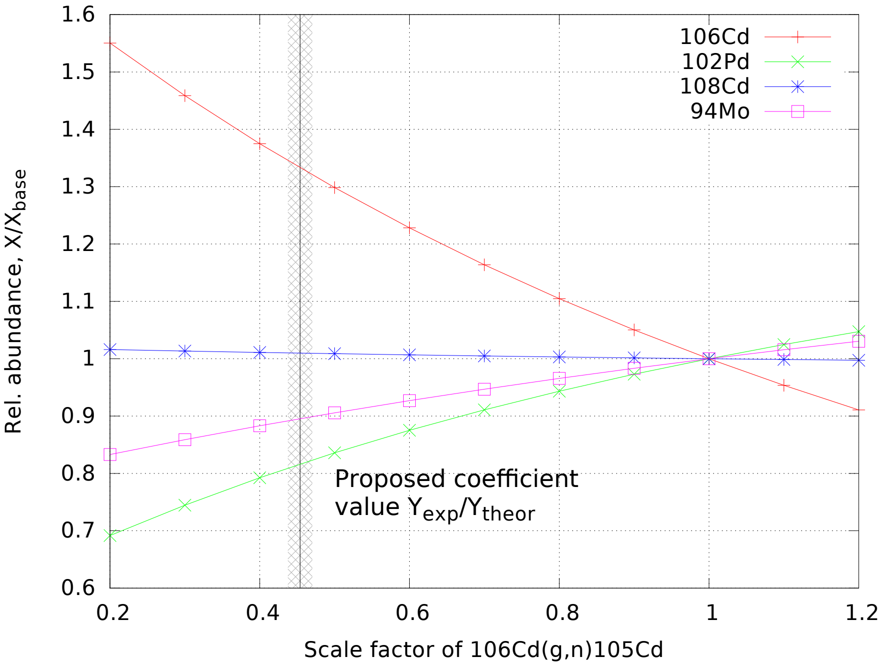
- ^{106}Cd(γ, n) and (γ,p) rates calculated with "TALYS+isospin"
- A slightly modified burning routine from the MESA star evolution package used to calculate final abundances as a function of scaling factors applied to the rates
- Other reaction rates from JINA REACLIB
- Initial abundances, temperature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



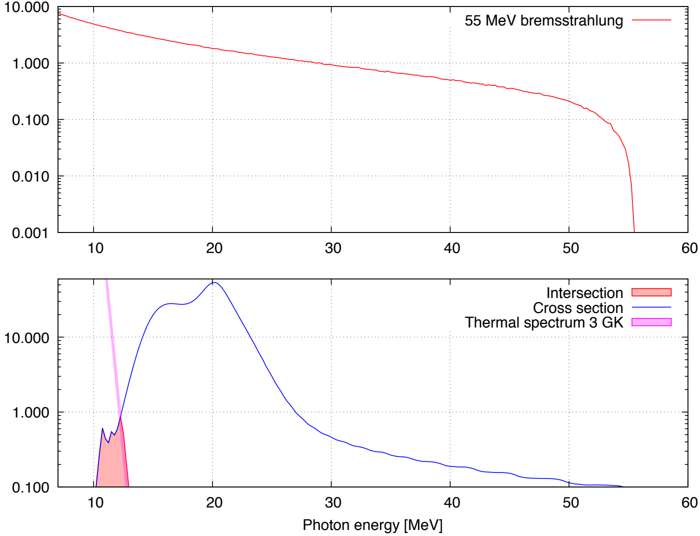
Impact of rate normalization of the ^{106}Cd(γ,p) reaction



Impact of rate normalization of the ^{106}Cd(γ,n) reaction

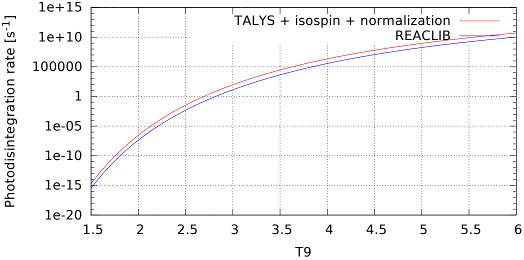


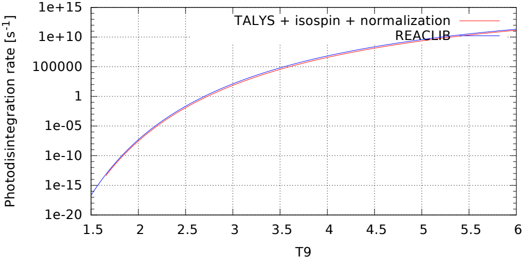
Bremsstrahlung and stellar photon spectrum



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

Photodisintegration rates on ^{106}Cd





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

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

- ^{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!