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A Simple Estimate of Production of Medical Isotopes by Photo-Neutron Reaction at the Canadian Light Source

Barbara Szpunar

Collaboration with C. Rangacharyulu, S. Daté, H. Ejiri

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B.Szpunar@usask.ca

306-966-6462

Abstract

We employed FLUKA Monte Carlo code along with the simulated photon flux for a beamline at the Canadian Light Source in conjunction with a CO_2 laser system.

The photon intensity can not be modeled in FLUKA yet. S. Daté from Spring 8, Japan, simulated the photon flux for the laser back scatter systems at the CLS. Klein-Nishina formula was used to calculate back scattered photons energy distribution.

This calculated parabolic shape of photon energy distribution is not included as a standard shape of source in Fluka. Therefore user routine needs to be used in modeling transmutations for this source. Alternatively one can use FLUKA to calculate transmutations for a narrow energy width (for which the standard source can be used) and integrate them over the whole energy range. The induced activities (of ^{99}Mo, ^{192}Ir and ^{196}Au) were calculated using Bateman equations (implemented in EXCEL) and weighted according to the shape of the source residuals (obtained by FLUKA).

Content

- Purpose of this work and introduction
- FLUKA simulation
  - Photon induced artificial transmutation
    - medical isotope production
    - photofission
- Summary and conclusions

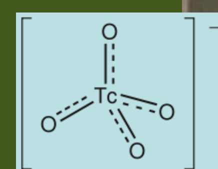
Purpose of this work and introduction

- Shortage of medical isotopes – call for alternative production methods
- Most widely used $^{99}Mo \rightarrow {}^{99m}Tc$ (~35 common radiopharmaceuticals)

$^{99m}Tc \rightarrow {}^{99}Tc + \gamma$

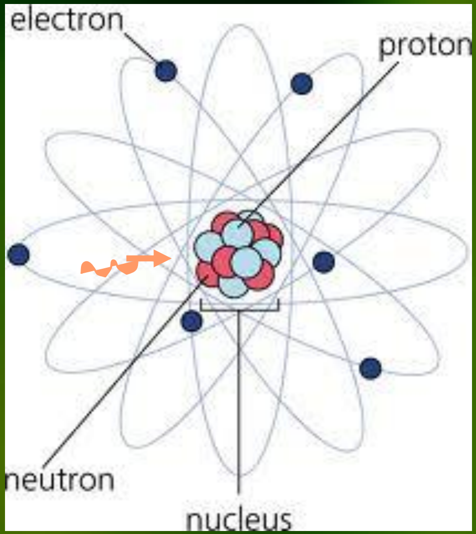
Each diagnostic uses few GBq

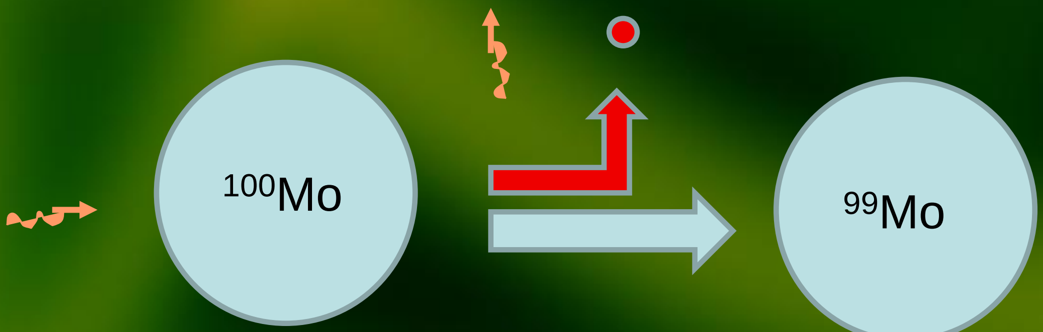
(1GBq = 0.027 Ci)



  - EPAC 2000 Vienna, world uses: 150,000 Ci/year
  - Proton cyclotrons located close to hospital can supply average usage: e.g. at CHUS, Sherbrooke 10 Ci/week of ^{99m}Tc
- ^{99m}Tc is short-lived ($T_{1/2}$ = 6.0058 h) therefore ^{99}Mo ($T_{1/2}$ = 65.94 h) needed for remote, small hospitals

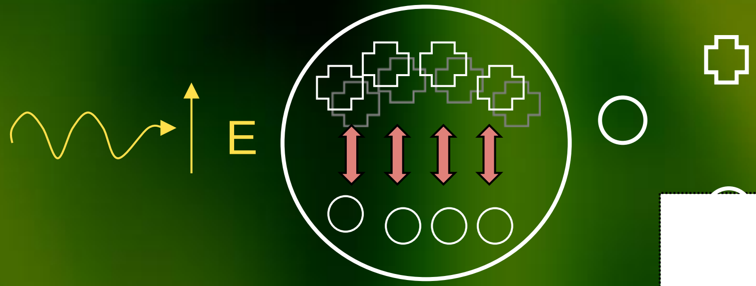
Artificial transmutation (photons)

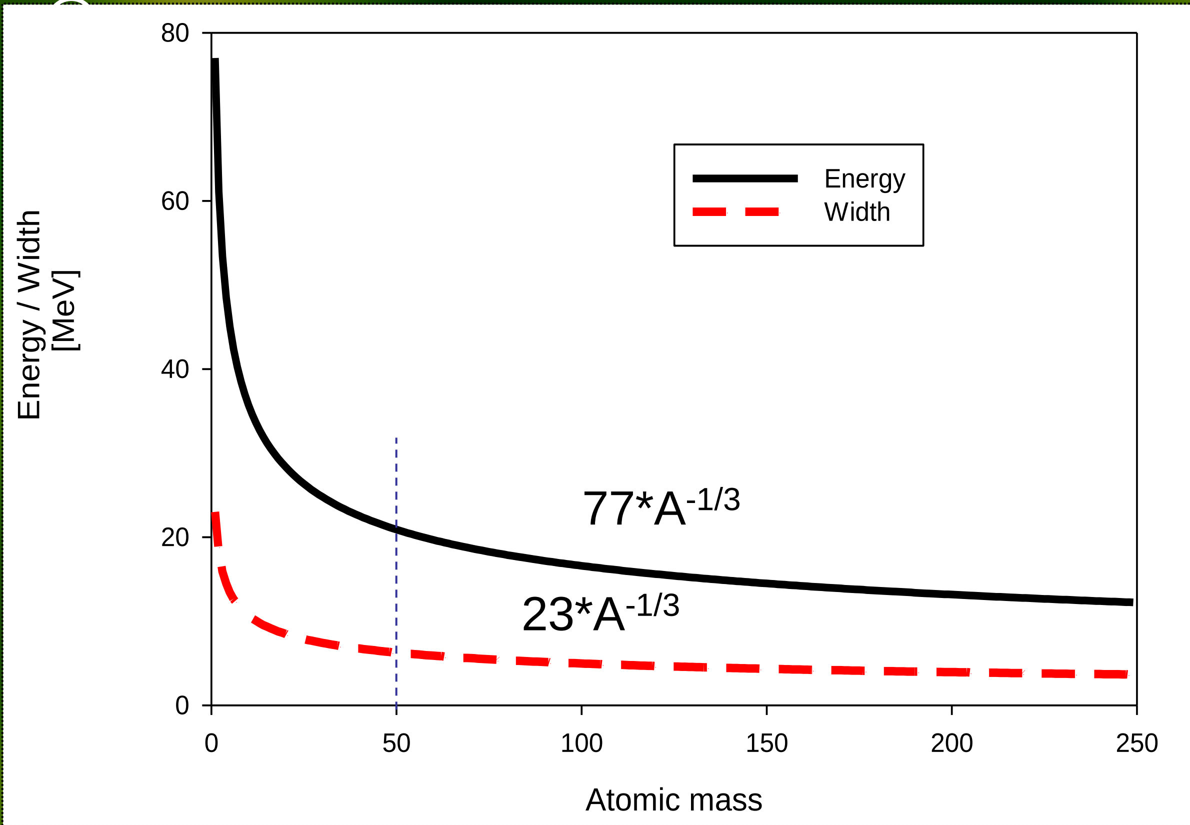




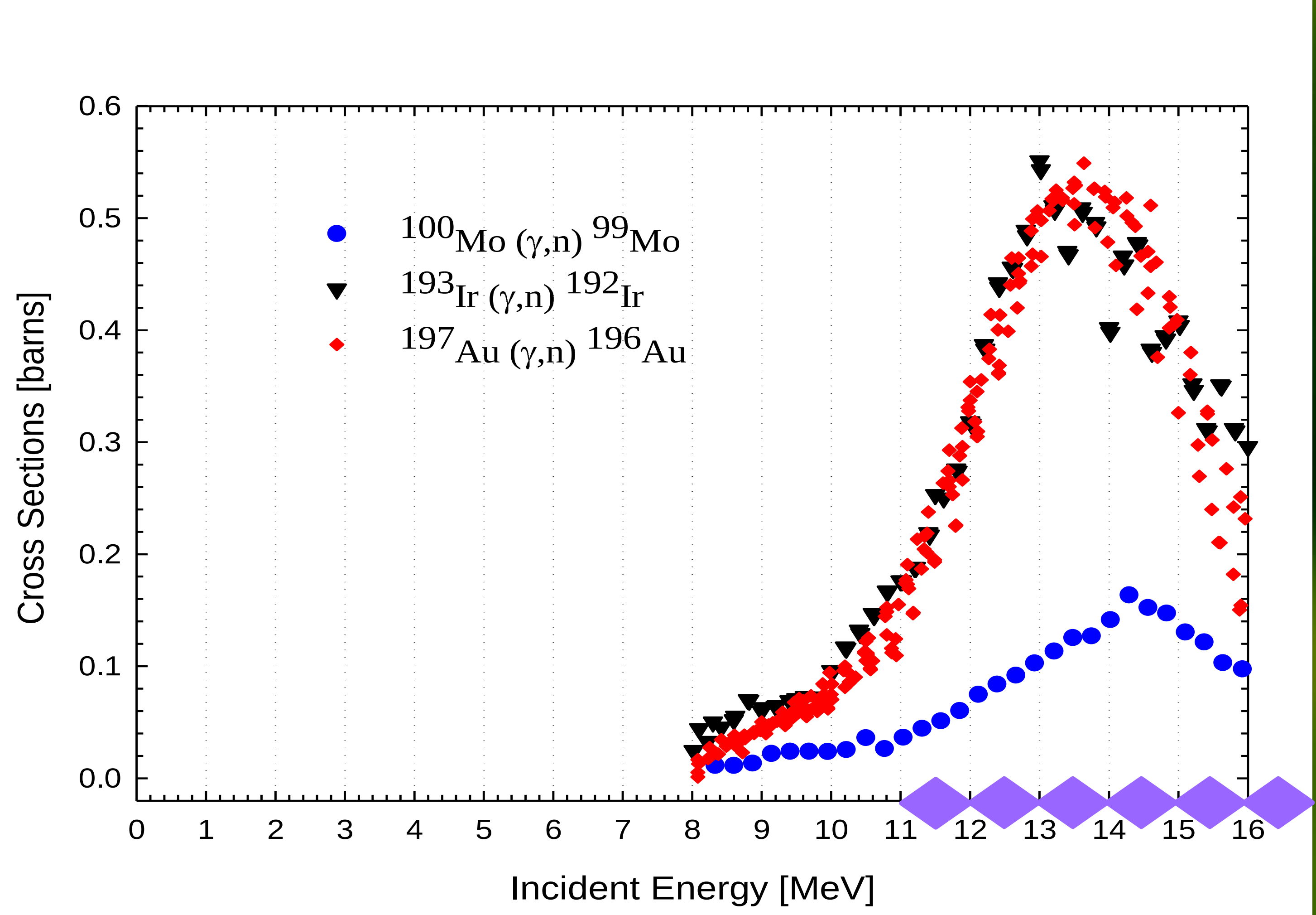
$$^{99}_{42}Mo \rightarrow {}^{99m}_{43}Tc + {}^{0}_{-1}e + \overline{\nu}$$

Giant Dipole Resonance



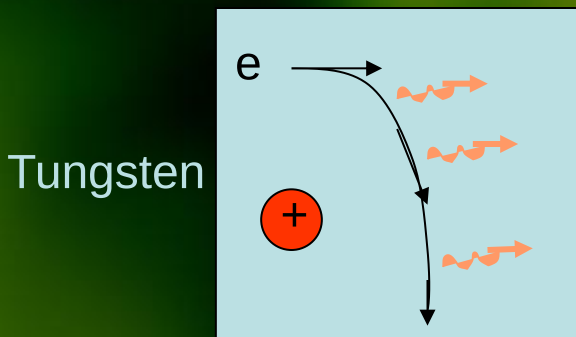


Medical Isotopes (photons)



http://www.nndc.bnl.gov

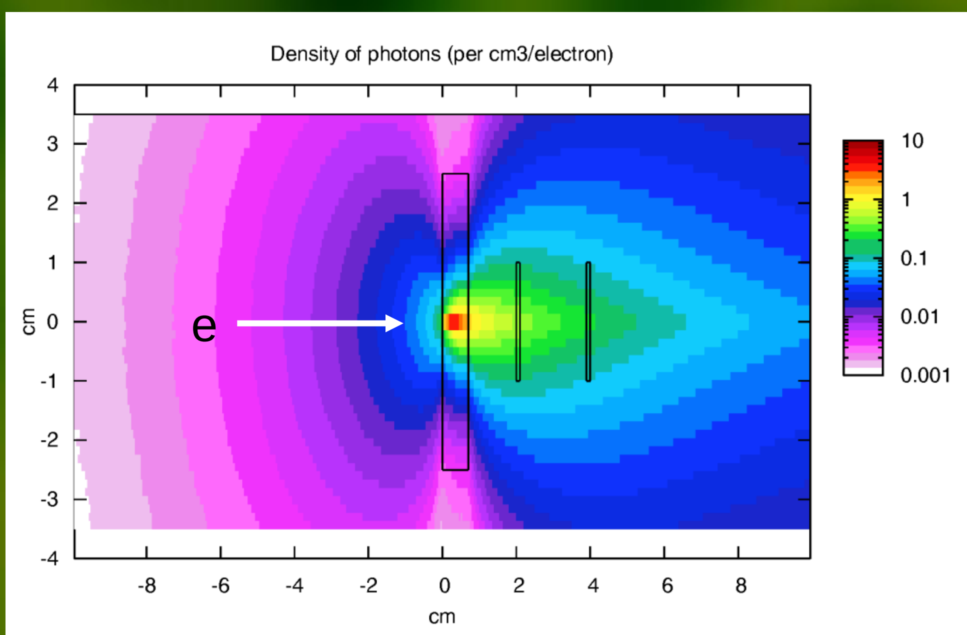
LINAC ~ NRC (Bremsstrahlung)

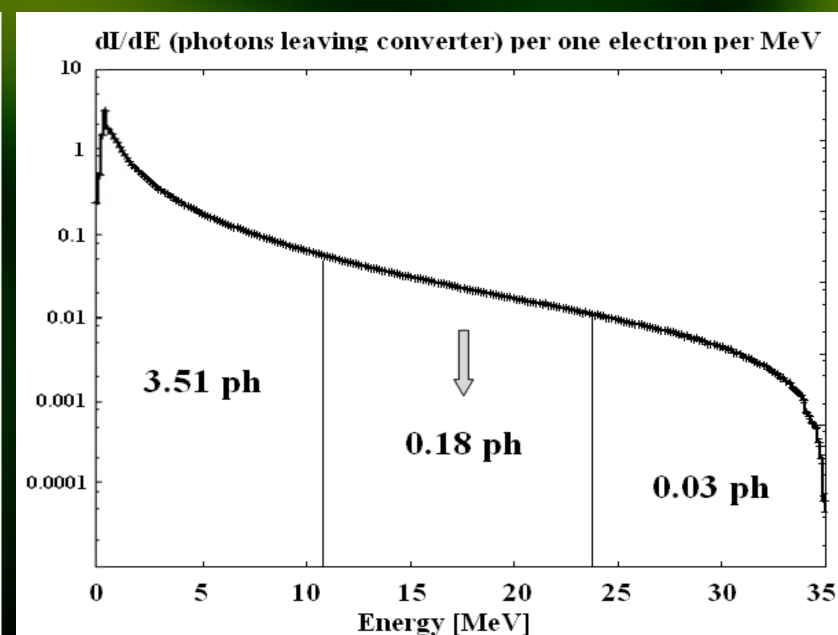


Electron's current:

43 μA: 27×10^{13} e/s

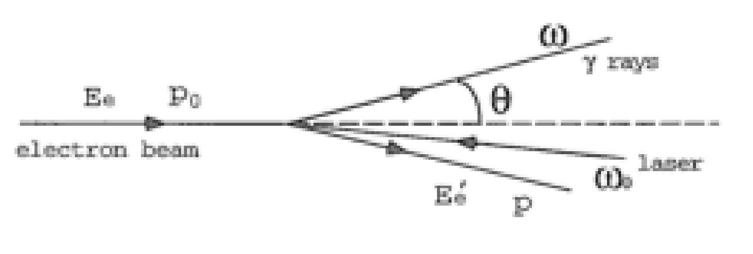
Pin beam 35 MeV





April 2010, Canadian Light Source, workshop

http://physics.usask.ca/~chang/department/index.html



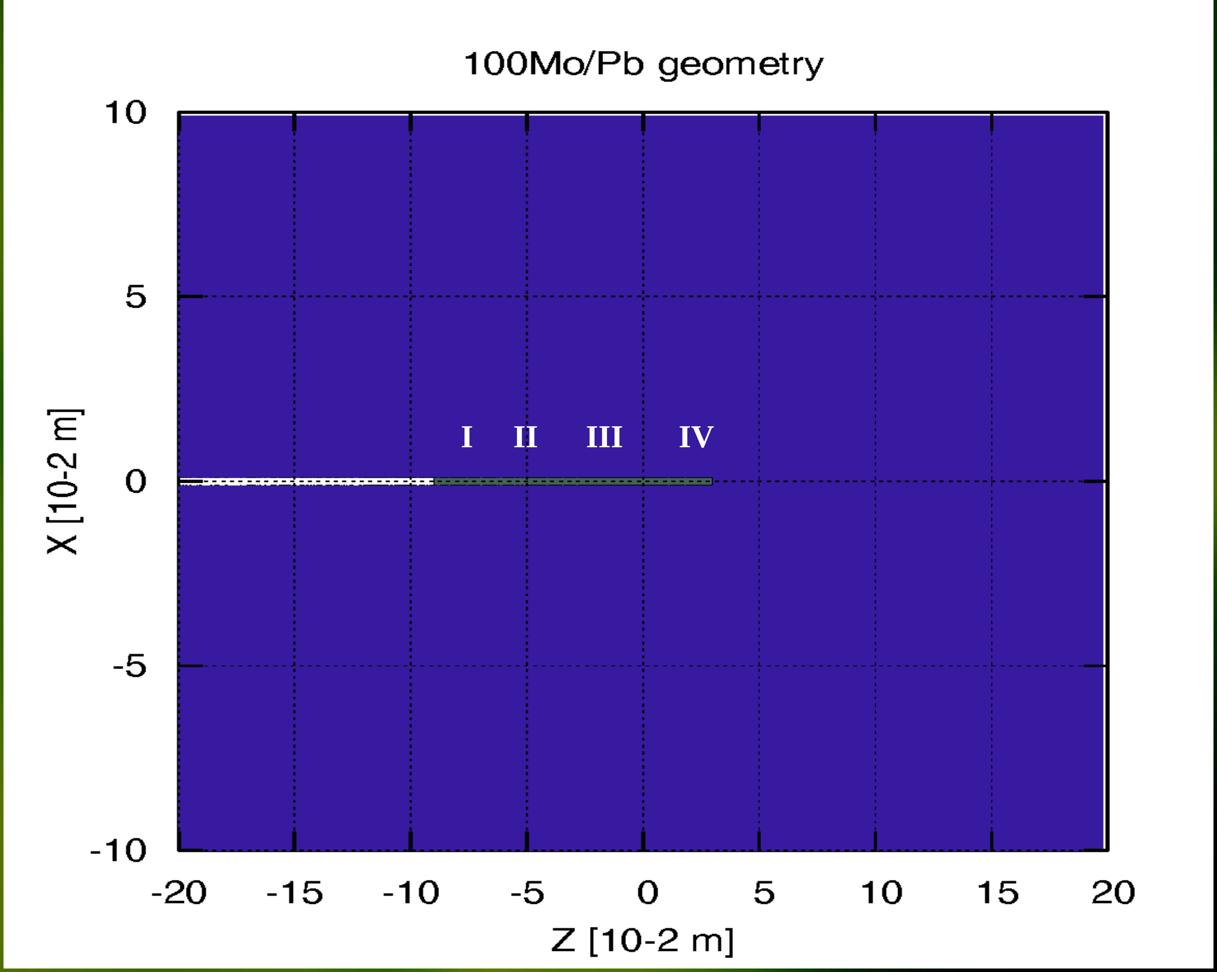
- CLS equipped with a CO_2 laser back scatter system to test the feasibility of application of photo-nuclear transmutations.
- Discussion and collaboration with international community (Japan (JAEA), USA).
- Achievable at CLS maximum photon energy (Compton back-scattering at 0 degree incident angle): 15 MeV for 2.9 GeV electron beam energy.
- Intensity (Date'): 10^{10}/s for 1 kW CO_2 laser, 250 mA electron beam current; maximal ($\sim P_L I_e$): 10^{12}/s (50 kW, 500 mA). The highest ever reached by Duke HIGS FEL: $2x10^9/s$.

GDR transmutation (CLS): maximum intensity limitation

6×10^{21} atoms in 1g of Mo

Even maximal 10^{12}/s photon intensity can only transmute very small fraction of atoms, therefore one can neglect interaction between particles produced in each transmutation!

FLUKA; Photon induced activity (multiple targets by H. Ejiri)



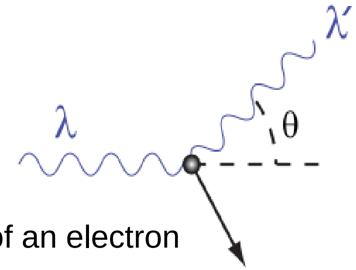
Chary's safe parameters for CLS used: 200 mA electrons and 1kW laser

S. Date' photon flux simulations

Compton e-ph elastic scattering from resting electron

(Partially from Wikpedia)

Compton scattering formula:



$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta),$$

λ is the initial wavelength, λ' is the wavelength after scattering, m_e is the mass of an electron

Klein-Nishina formula (differential cross section of photons over solid angle: $d\Omega = 2\pi\sin\theta d\theta$):

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\alpha^2 r_c^2 P(E_\gamma,\theta)^2 (P(E_\gamma,\theta) + P(E_\gamma,\theta)^{-1} - 1 + \cos^2(\theta))$$

where α is the fine structure constant, $r_c = \hbar / m_e c$ is the compton radius of the electron, θ is the scattering angle .

$$P(E_\gamma,\theta) = \frac{1}{1 + \frac{E_\gamma}{m_e c^2}(1 - \cos\theta)}$$

is the ratio of photon energy after and before (E_γ,) the collision

By combining the Compton's and Klein-Nishina's formulas one can calculate the energy (E'=hc/λ') distribution of scattered photons.

Compton e-ph backscattering from relativistic electrons (CLS)

Using invariant differential cross section for Compton scattering (Mandelstam variables) the energy distribution of backscattered photons was calculated by S. Date' (Spring 8, Japan).

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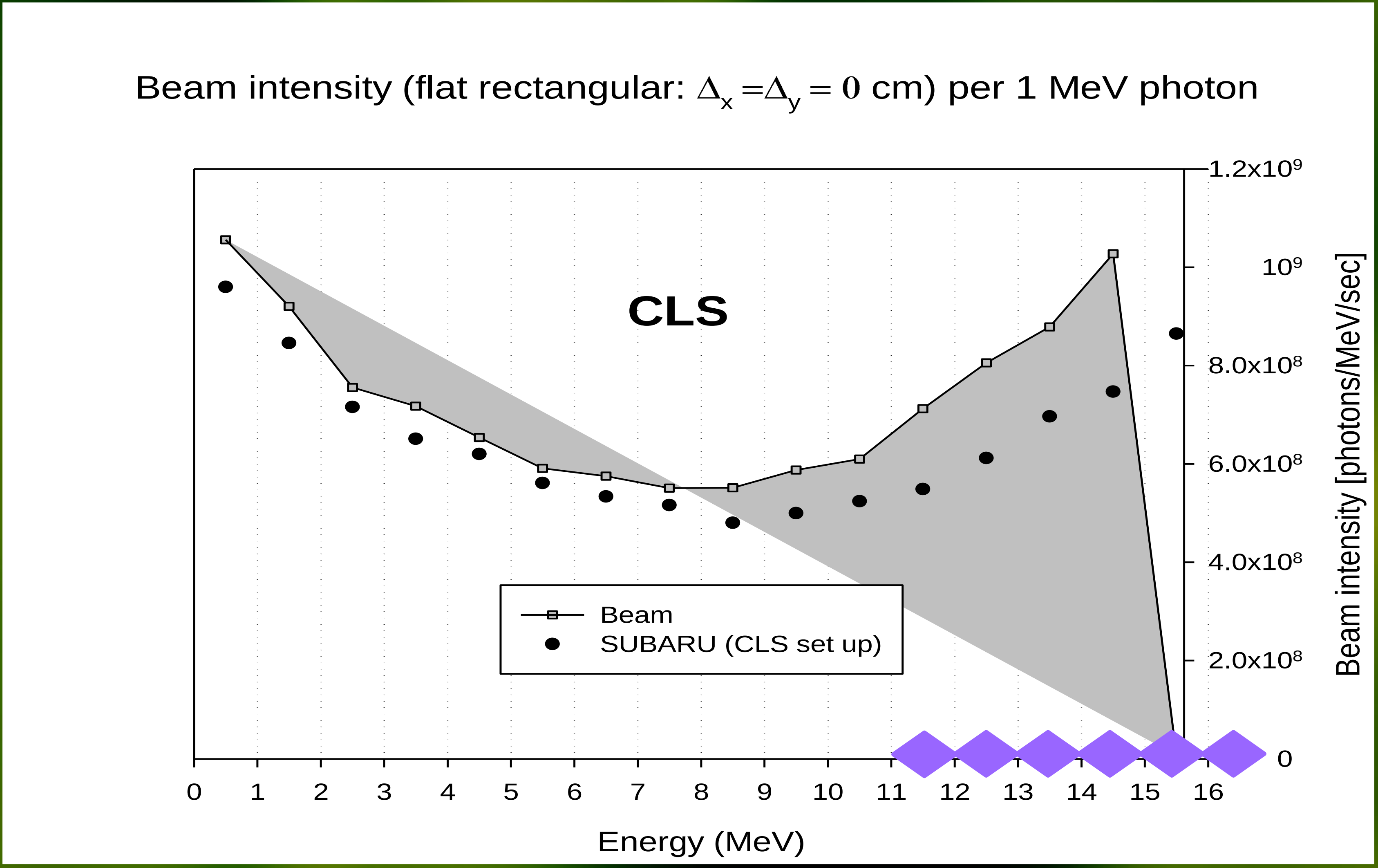
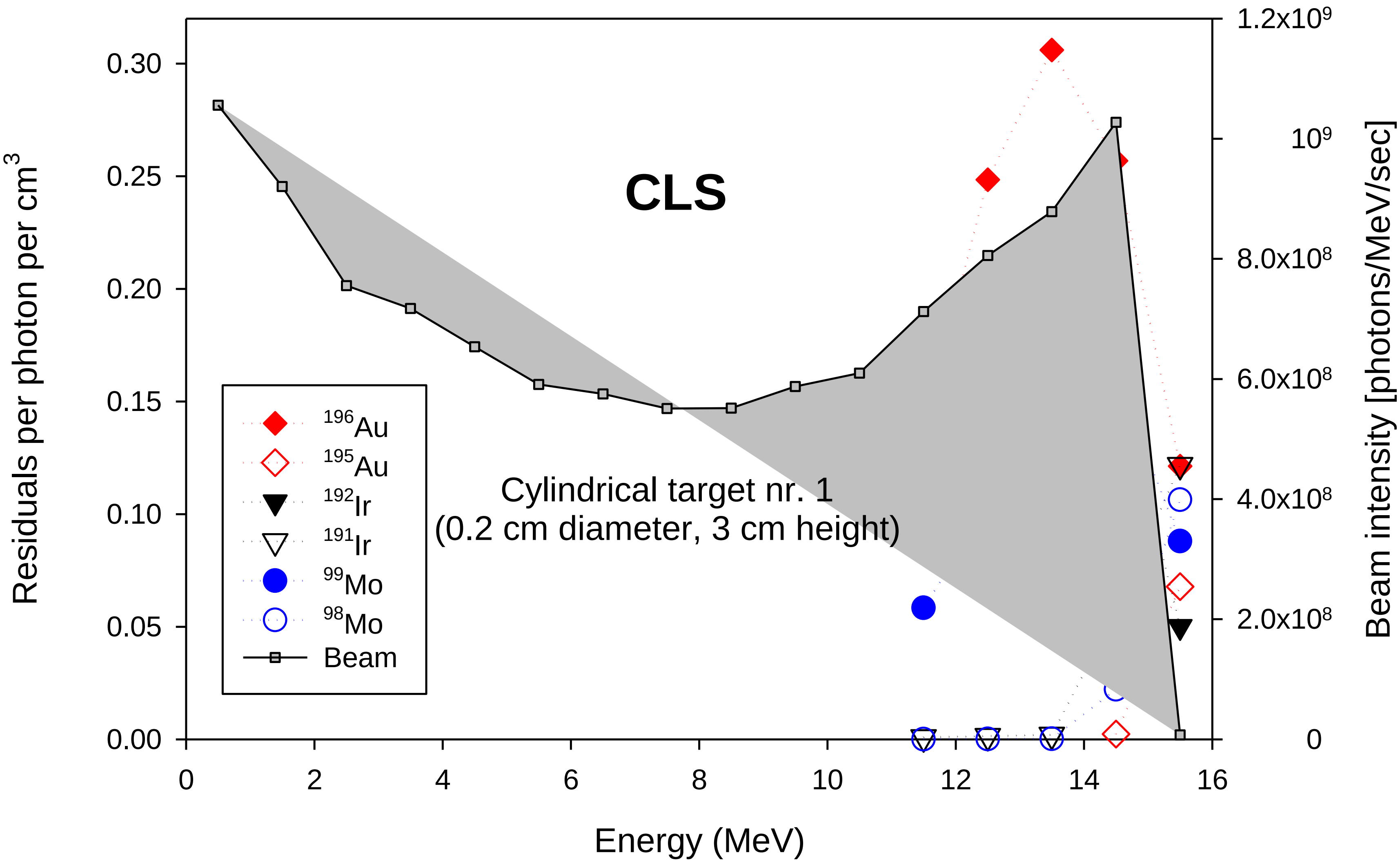
Simulated by S. Daté Spring 8, Japan, photon intensity for the CO_2 laser back scatter systems at the CLS



Residuals of target nr. 1 per cm^3 per 1 MeV photon



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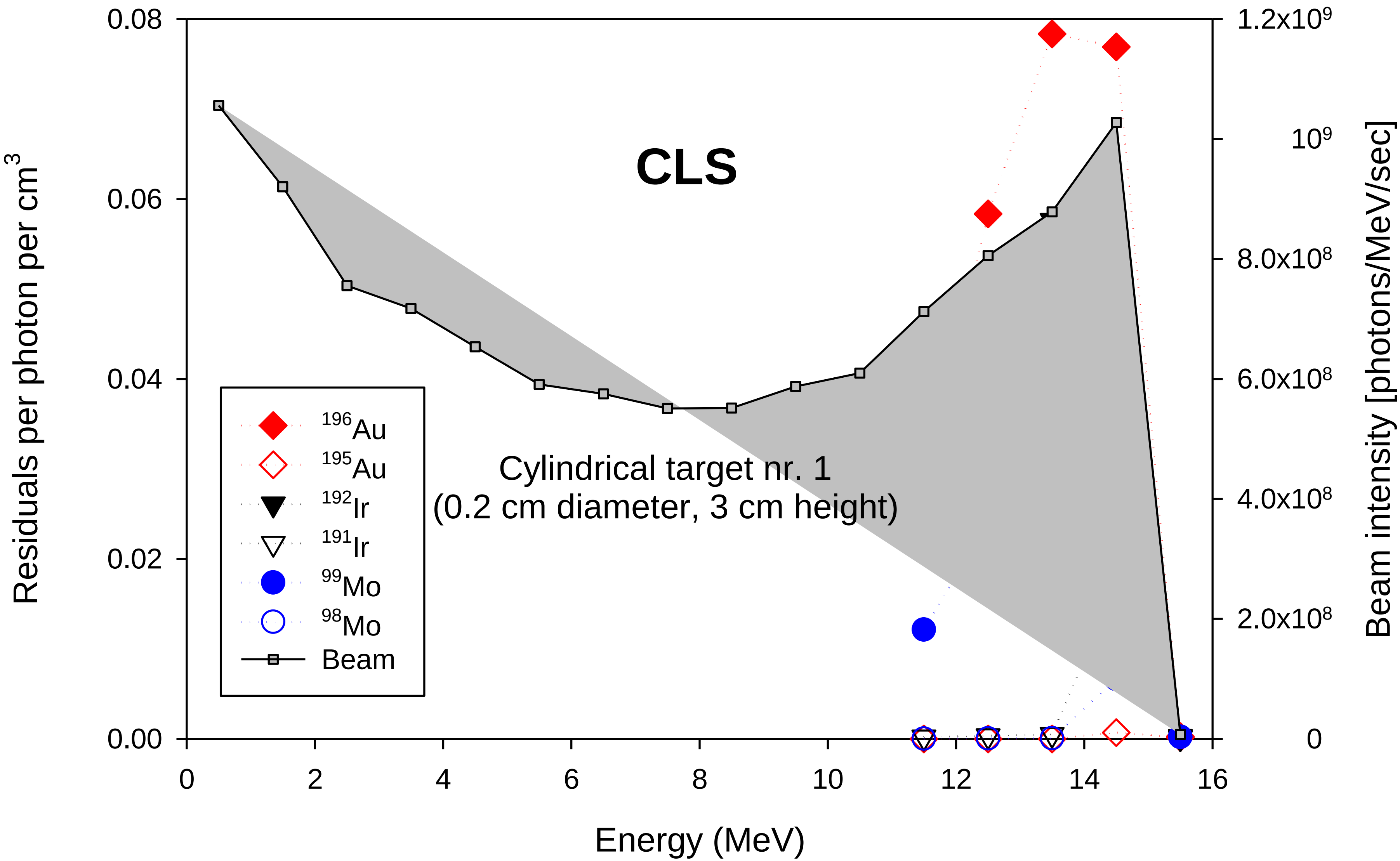
Residuals of target nr. 1 per cm^3 per 1 MeV photon times intensity weight



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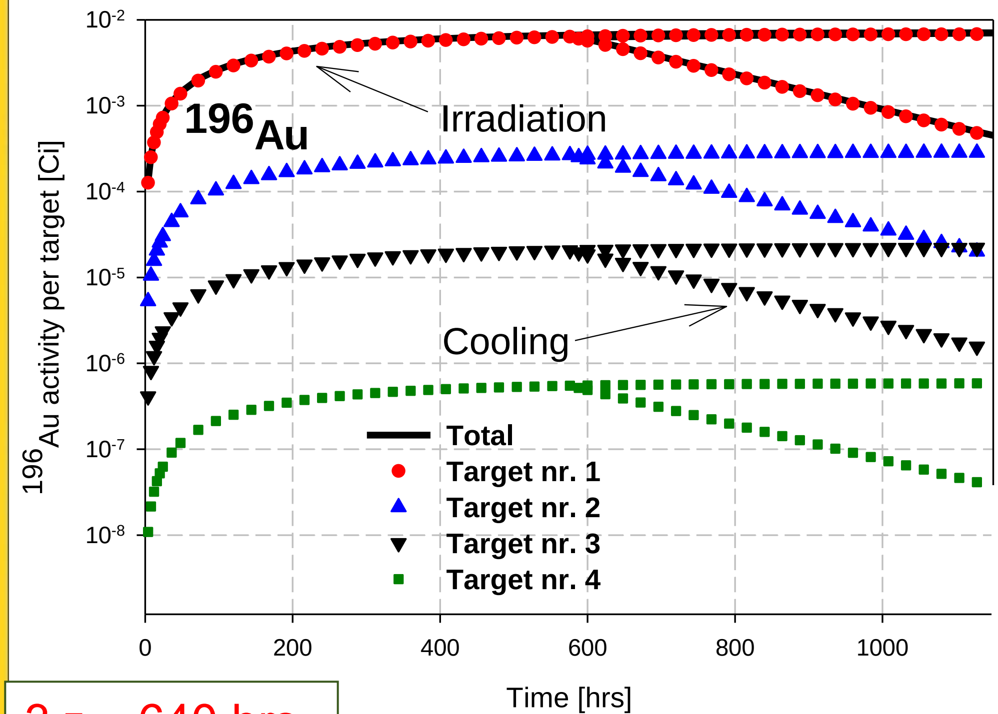
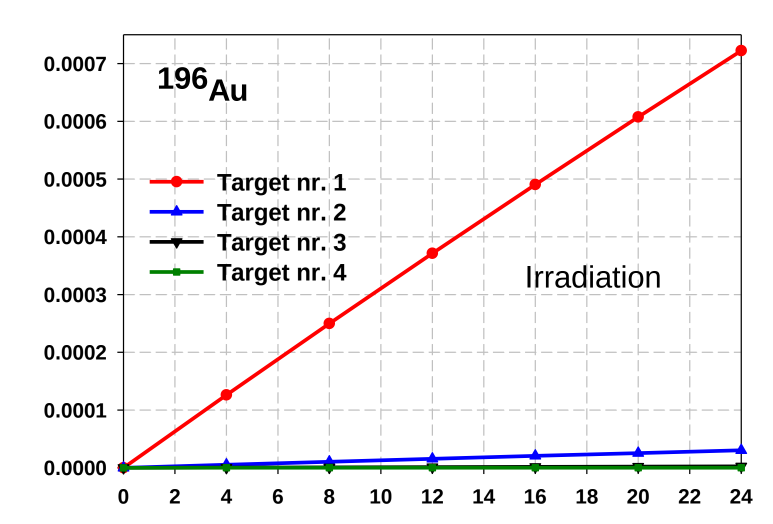
FLUKA hybrid simulations of induced activity of ^{196}Au (^{197}Au (γ,n)^{196}Au)
(Effective flux (4 MeV window) produced by 200 mA electrons (CLS)
and 1 kW laser; 3.43×10^{9} photons/s)





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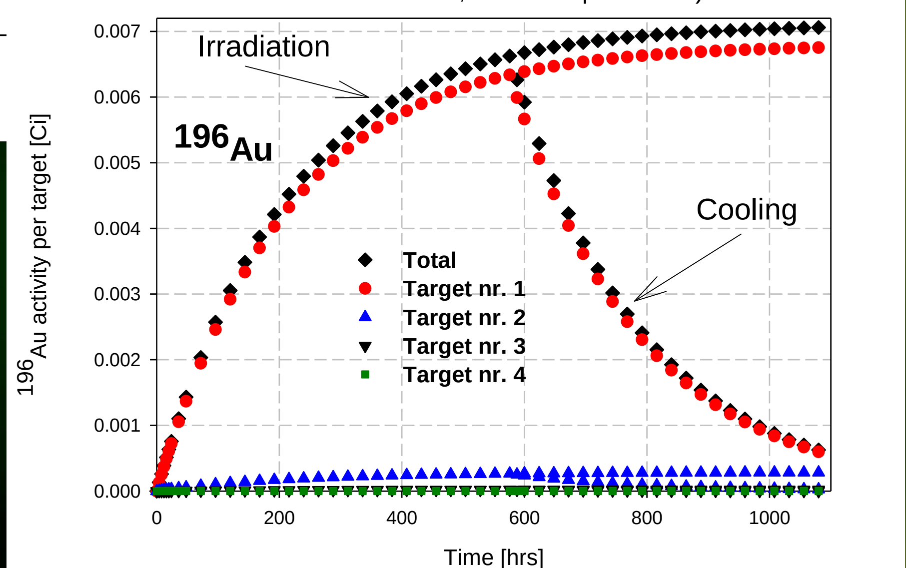

$3\ \tau = 640$ hrs

Estimated from FLUKA activity of ^{196}Au isomers not included

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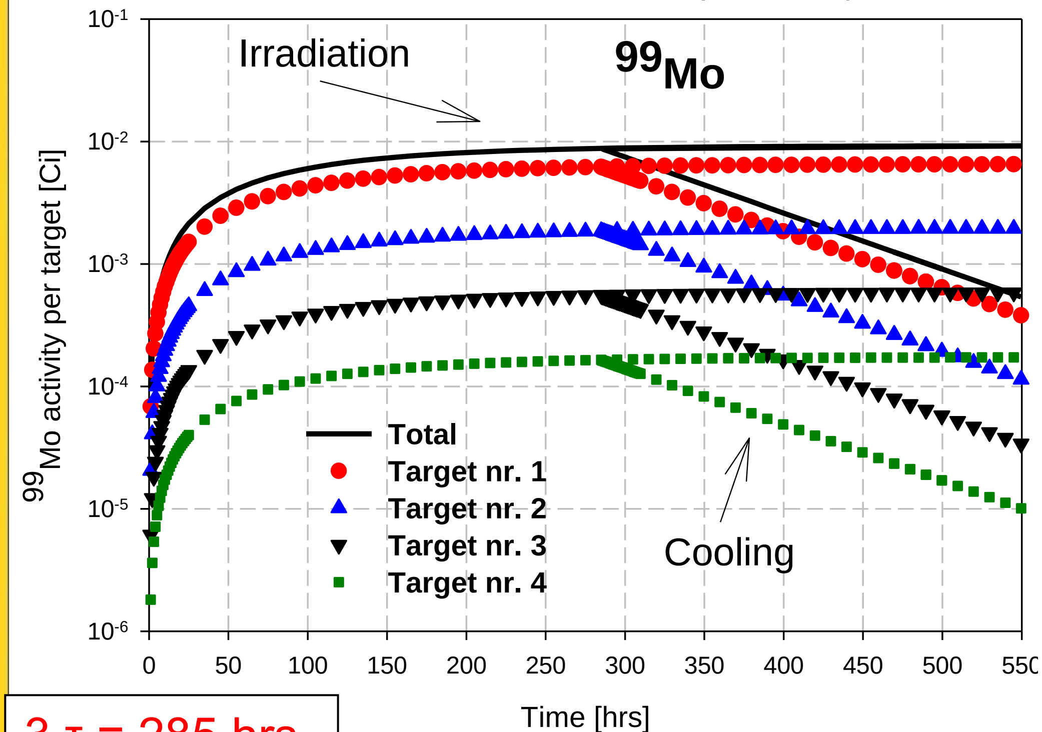
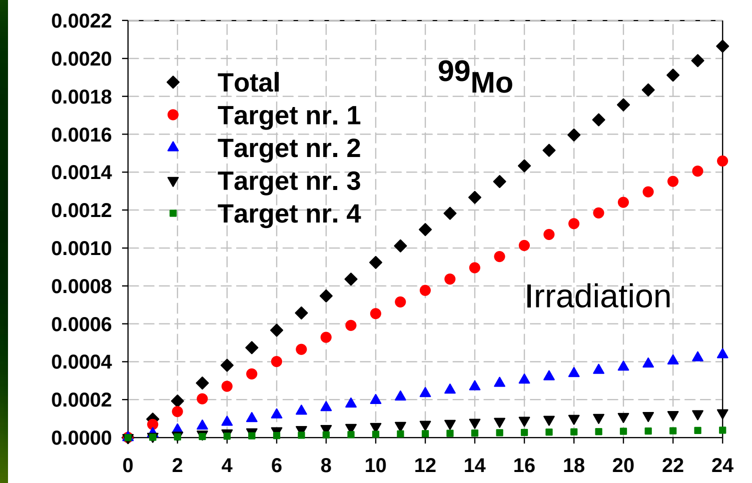
FLUKA hybrid simulations of induced activity of ^{99}Mo ($^{100}Mo(\gamma,n)^{99}Mo$)
(Effective flux (4 MeV window) produced by 200 mA electrons (CLS)
and 1 kW laser; 3.43×10^{9} photons/s)



3 τ = 285 hrs



FLUKA hybrid simulations of induced activity of ^{99}Mo ($^{100}Mo(\gamma,n)^{99}Mo$)
(Effective flux (4 MeV window) produced by 200 mA electrons (CLS)
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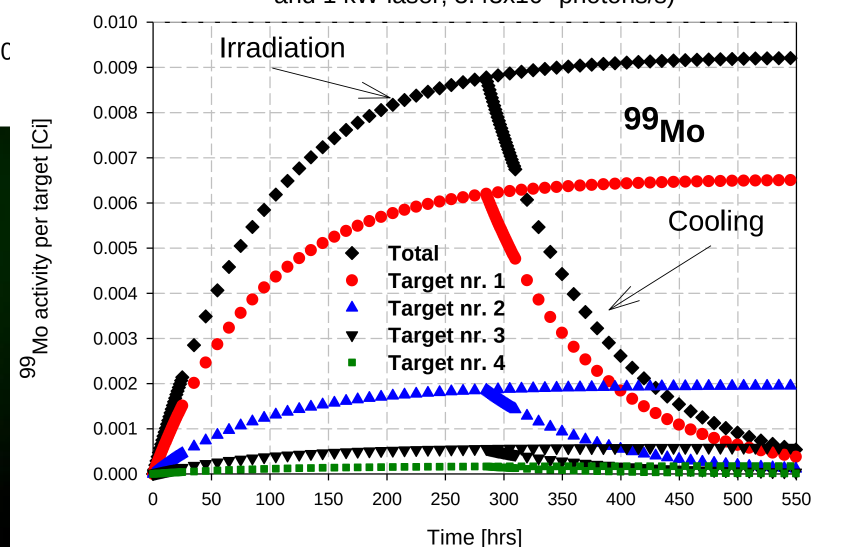

Photofission versus GDR transmutation

Szpunar B., Rangacharyulu C., Date' S. and Ejiri H., 33rd Annual Conference of the Canadian Nuclear Society, Saskatoon, Canada, 3A/138, June 10-13 (2012)

Photons (16 MeV)	Fission yield per one photon [Nuclei/cm^3] (May be heavily underestimated by the FLUKA currently! (?))							β^- yield
Target	**^{99}Mo(42)**	^{99}Kr(36)	^{99}Rb(37)	^{99}Sr (38)	^{99}Y(39)	^{99}Zr(40)	^{99}Nb(41)	**^{99}Mo(42)**
^{238}U	**1.17×10^{-7}**	8.32×10^{-8}	3.94×10^{-6}	1.83×10^{-5}	6.47×10^{-5}	3.46×10^{-5}	6.15×10^{-6}	**1.28×10^{-4}**
Errors (%)	**20.2**	20.5	2.1	1.1	0.9	0.7	2.3	

14.8 MeV

Produced Isotope (reaction)	Yield [per one photon/cm^3]	Error [%]
(n,γ) ^{101}Mo#	3.65×10^{-06}	1.2
(γ,e$^+$e$^-$)$_{atomic}$ ^{100}Mo	7.85×10^{-05}	0.4
(γ,n) ^{99} Mo	**1.31×10^{-02}**	**0.03**
(γ,2n) ^{98}Mo	6.06×10^{-03}	0.1

#Secondary neutron capture

Summary and conclusion

- FLUKA simulations show that the production of the desired isotopes via GDR (photon) are orders of magnitude higher than the other isotopes, indicating this technique to be promising method for artificial transmutations
- Applications
  - Production of medical and industrial isotopes
  - Induced transmutation & photofission as a source of neutrons

Acknowledgement

- Access to FLUKA code
- FLUKA developers and support group (especially Francesco Cerutti)
- V. Vlachoudis for FLAIR graphic interface with FLUKA
- C. Cederstrand for technical support
- Science and Engineering division for start up funding and support

Thank you for your attention!

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