CHAB mediterranean center for human health advanced biotechnologies

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The contribution of electron paramagnetic resonance (EPR) spectroscopy in the dosimetry of mixed field used for NCT

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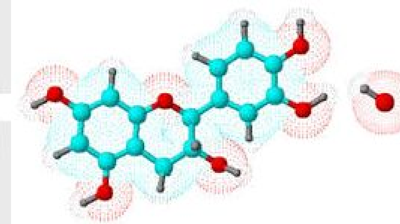
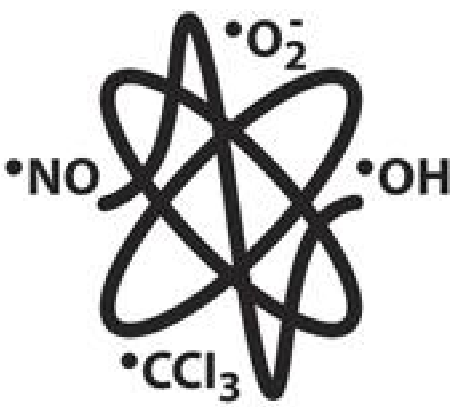
Workshop
Terapia por Captura Neutrónica en Boro (BNCT): Neutrones para la Salud
JORNADAS DEL CUIA EN ARGENTINA 9ª Edición

Principle of application of ESR for dosimetry

Ionizing radiations release energy in matter → Production of paramagnetic centers (*i.e.* free radicals, point defects, etc)

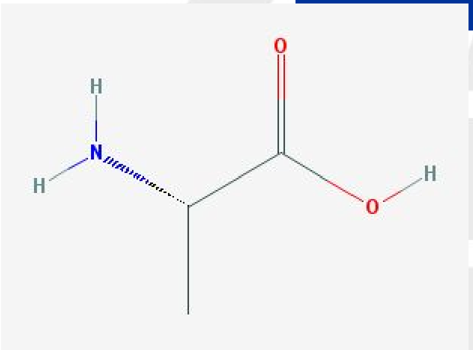


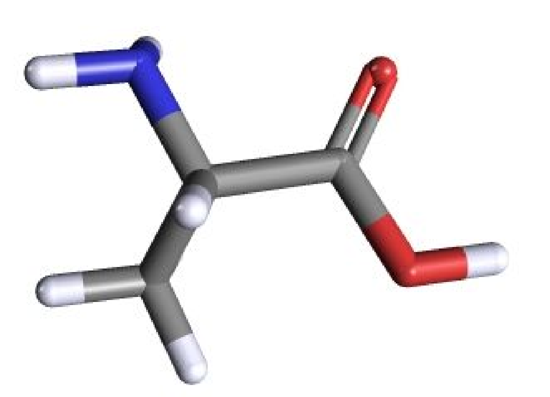
→ Electron Spin resonance (ESR) can detect paramagnetic species



Since the readout does not affect the ESR signal, it is possible to exploit additive dose response and repeated readings can be performed

ESR dosimetry – Alanine ($C_3H_7NO_2$) dosimetry

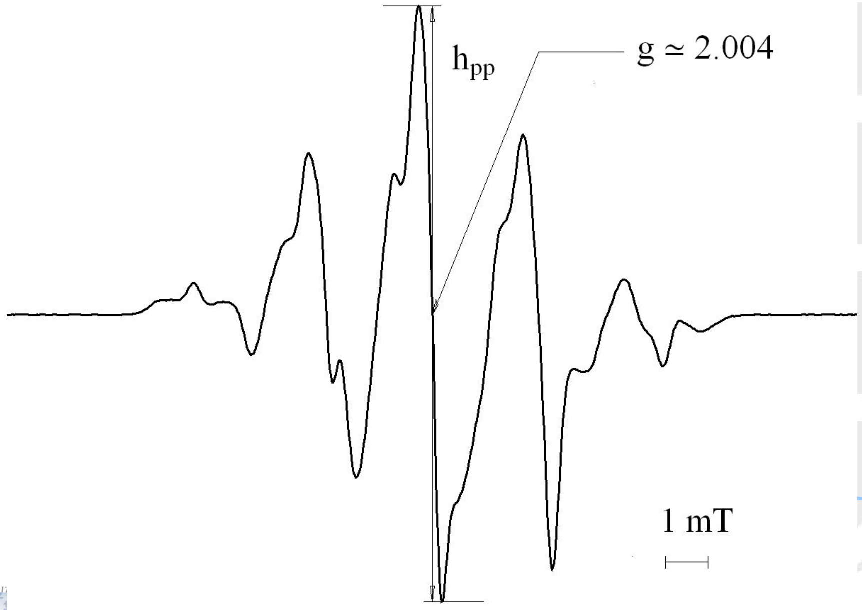




The alanine at present it is formally accepted by

- IAEA (International Atomic Energy Agency, Vienna, Austria)
- NIST (National Institute for Standards and Technology, USA) and
- NPL (National Physical Laboratory, UK)

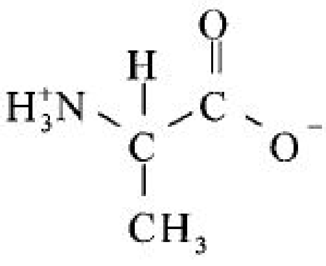
as a secondary reference and transfer dosimeter for high dose irradiation.



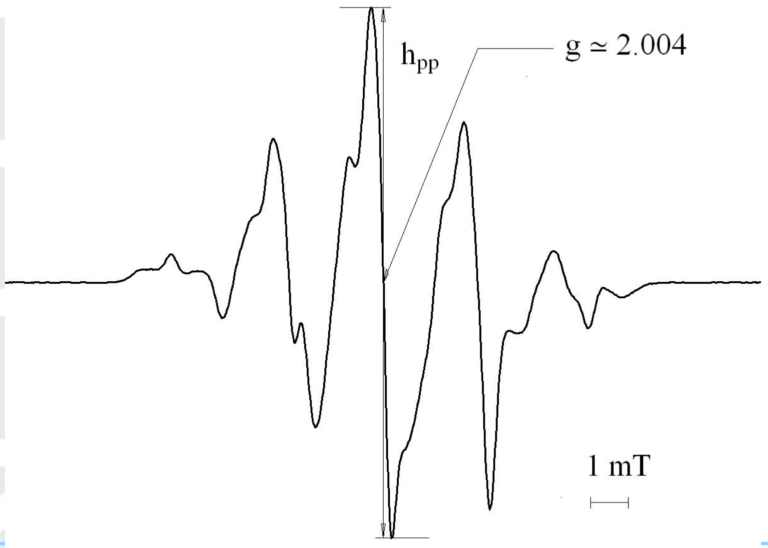
ESR/alanine dosimetry

Features of the amino acid alanine:

- The linearity of the EPR response in a wide range of doses from 10 up to 5×10^4 Gy.
- near tissue equivalence
- high radiation chemical yield
- near invariant response to
  - variations in photon energy
  - minor temperature variations
  - other variations in ambient conditions
- high stability of radiation products

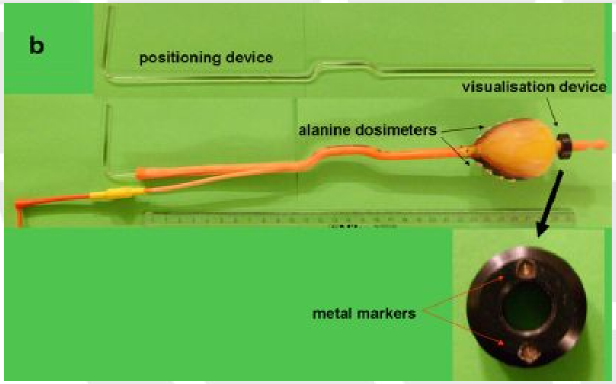


L-α-Alanine



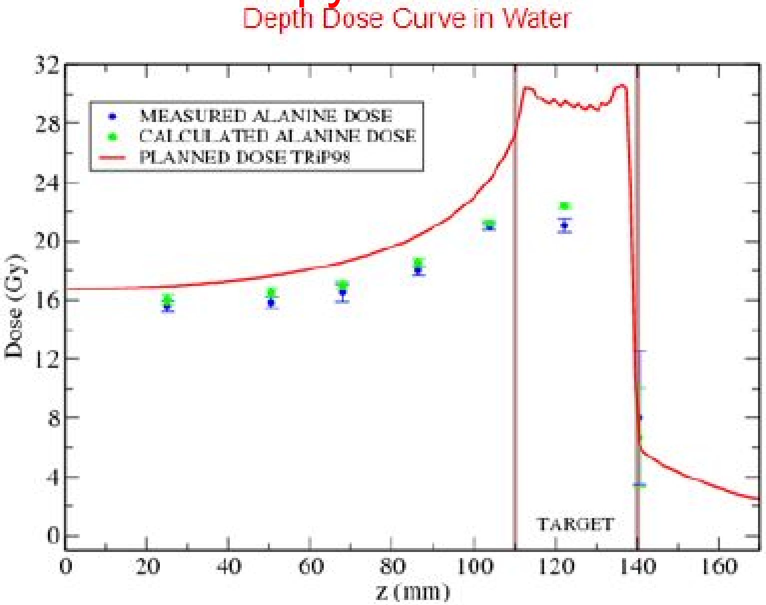
Applications in radiotherapeutic field

Applications for radiation therapy:
Brachitherapy for prostate cancer
Brachitherapy for uterus cancer
Therapy for breast cancer
…



D. Wagner et al. Radiotherapy and Oncology 88 (2008) 140–147

Hadrontherapy with Carbon ions



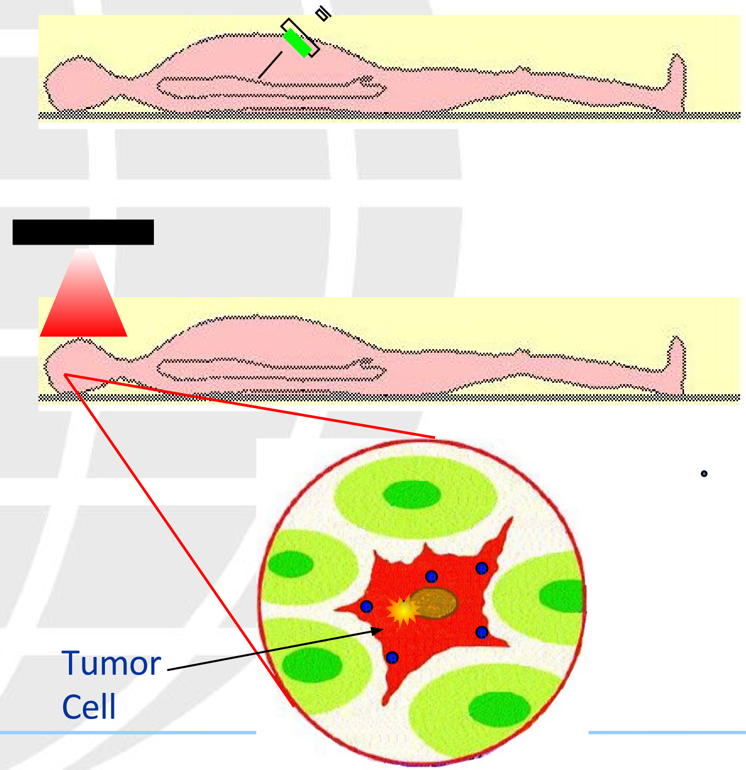
La Tessa C. et al *^{12}C ion beam dose distribution in presence of medium inhomogeneities: comparison between different measurements and simulations with treatment planning system for particles TRiP98.* ERRS2012 abstract

How does EPR dosimetry can contribute to Neutron Capture Therapy?

Drugs containing ^{10}B o ^{157}Gd Administration

Neutrons irradiation

Nuclear reaction in tumor cells



Need for determination of the neutron and photon components in the mixed (n,γ) field

COMBINED USE OF TWO EPR DOSIMETERS WITH DIFFERENT SENSITIVITIES FOR NEUTRON AND PHOTON COMPONENTS IN THE MIXED

DEVELOPMENT OF EXPERIMENTAL PROCEDURE TO ISOLATE THE NEUTRON AND THE GAMMA COMPONENTS (EXPERIMENTAL DATA AIDED BY MONTE CARLO SIMULATIONS)

COMBINED USE OF TWO EPR DOSIMETERS

Two detectors are needed

$$\begin{cases} R_A^{n+\gamma} = f_A^n \Phi + f_A^\gamma D_\gamma \\ R_B^{n+\gamma} = f_B^n \Phi + f_B^\gamma D_\gamma \end{cases}$$

The knowledge of f_A^γ f_A^n f_B^γ f_B^n is needed.

$$\begin{cases} D_\gamma = \dfrac{f_B^n R_A^{n+\gamma} - f_A^n R_B^{n+\gamma}}{f_A^\gamma f_B^n - f_B^\gamma f_A^n} \\ \Phi = \dfrac{f_A^\gamma R_B^{n+\gamma} - f_B^\gamma R_A^{n+\gamma}}{f_A^\gamma f_B^n - f_B^\gamma f_A^n} \end{cases}$$

Study of the response to gamma photons and neutrons

Neutron Dosimetry for Biology and Medicine: ICRU Report 26

COMBINED USE OF TWO EPR DOSIMETERS

- **DEVELOPMENT OF NEW MATERIALS WITH LARGER NEUTRON SENSITIVITY IN ORDER TO BE USED IN NCT DOSIMETRY**

- **STUDY OF THE EFFECTS OF ADDITIVES ON THE SAMPLE SENSITIVITIES**

ORGANIC BLENDS USED

- ALANINE (A)
- ALANINE WITH GADOLINIUM (AG)
- ALANINE WITH BORIC ACID

- AMMONIUM TARTRATE (T)
- AMMONIUM TARTRATE WITH GADOLINIUM (TG)

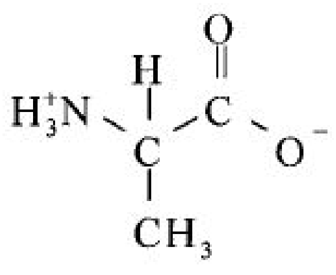
- IRGANOX PHENOL (P)
- IRGANOX PHENOL WITH GADOLINIUM (PG)

IRRADIATIONS:

- ^{60}Co gamma photons: UniPA
- Thermal neutrons: LENA Reactor UNIVERSITY OF PAVIA, PAVIA

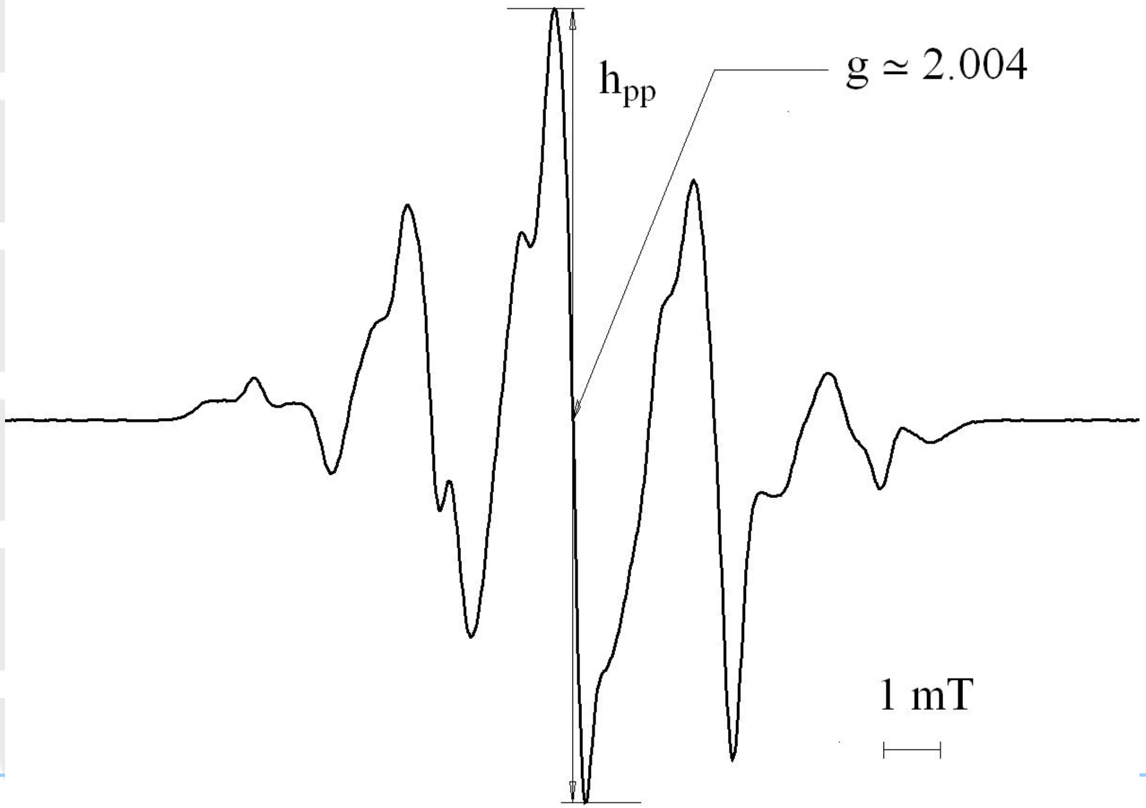
ORGANIC COMPOUND USED
ALANINE

STRUCTURE FORMULA



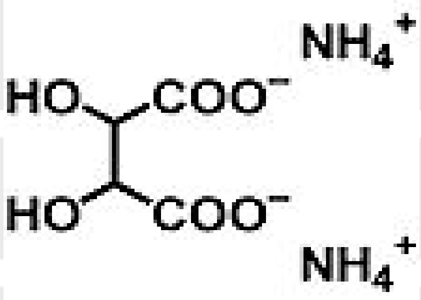
ℓ-α-Alanine

ESR SPECTRUM

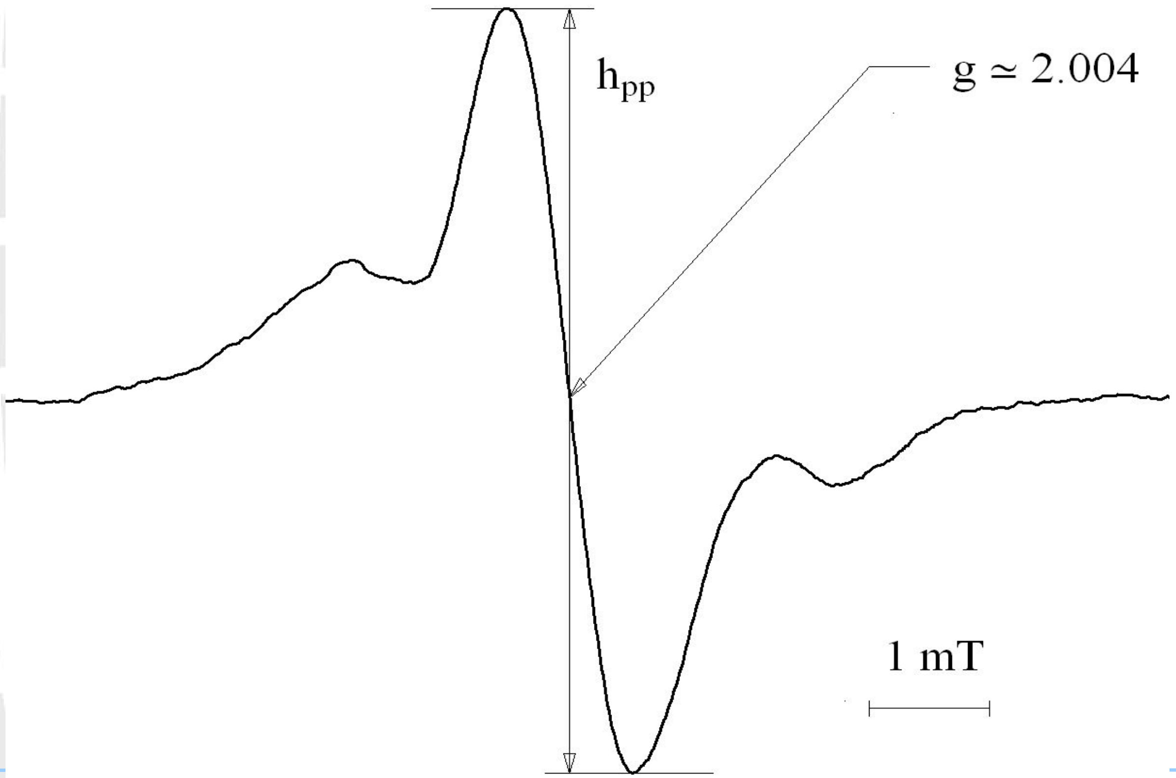


OTHER ORGANIC COMPOUND USED
AMMONIUM TARTRATE

STRUCTURE FORMULA

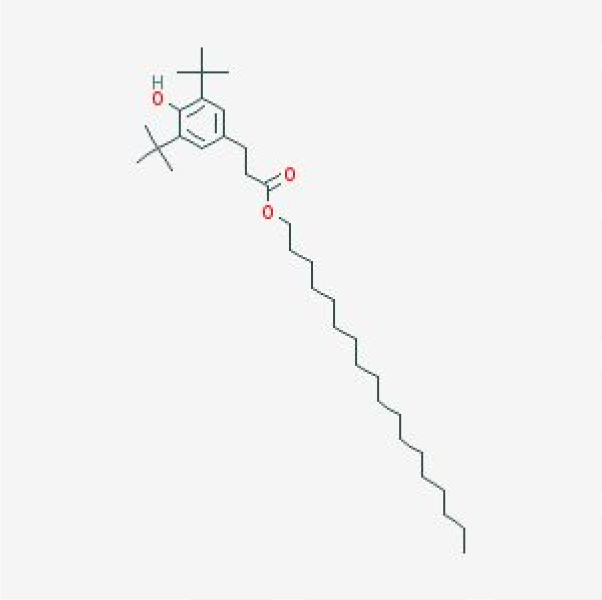


ESR SPECTRUM

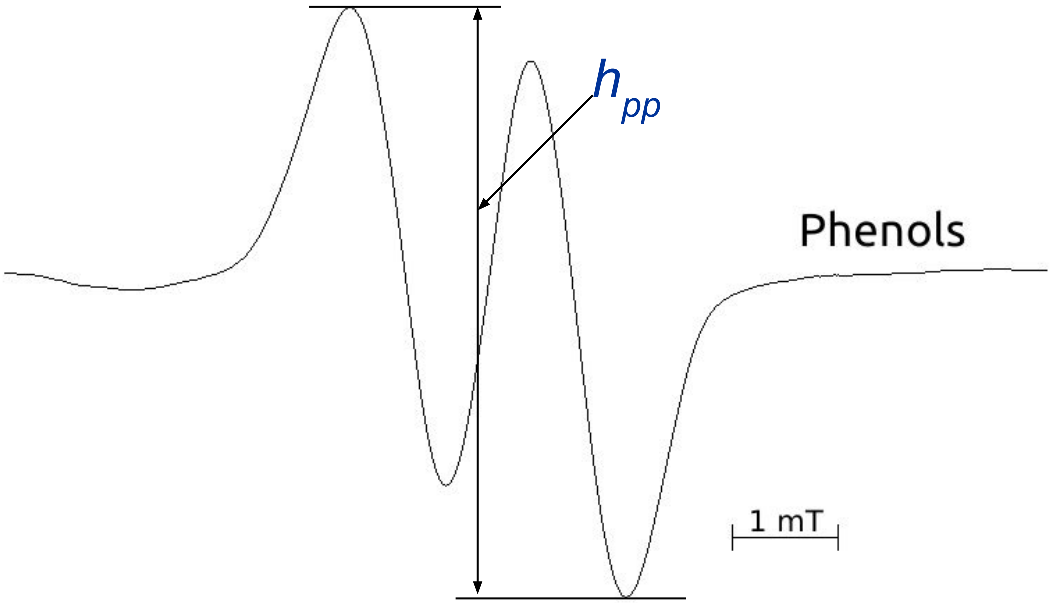


OTHER ORGANIC COMPOUND USED
IRGANOX 1076 - PHENOLIC COMPOUND

STRUCTURE FORMULA



ESR SPECTRUM

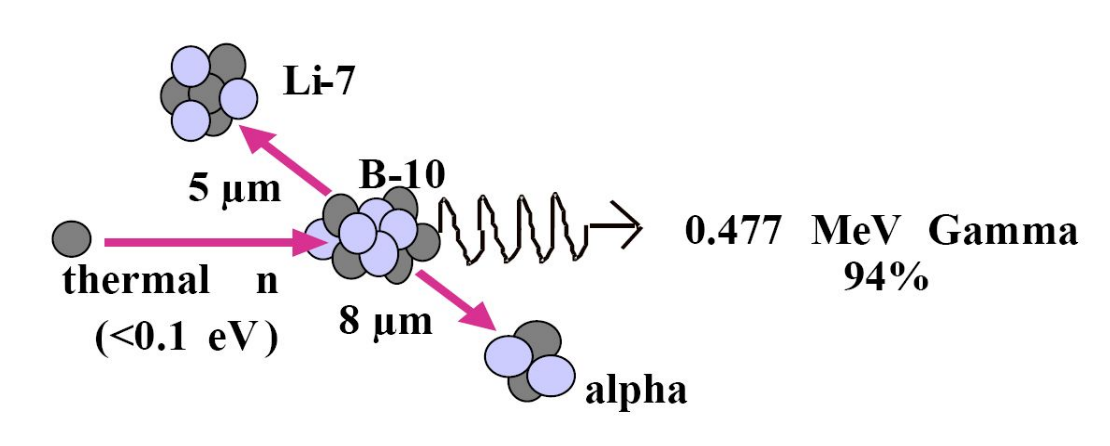


Cross sections and nuclear reactions with thermal neutrons

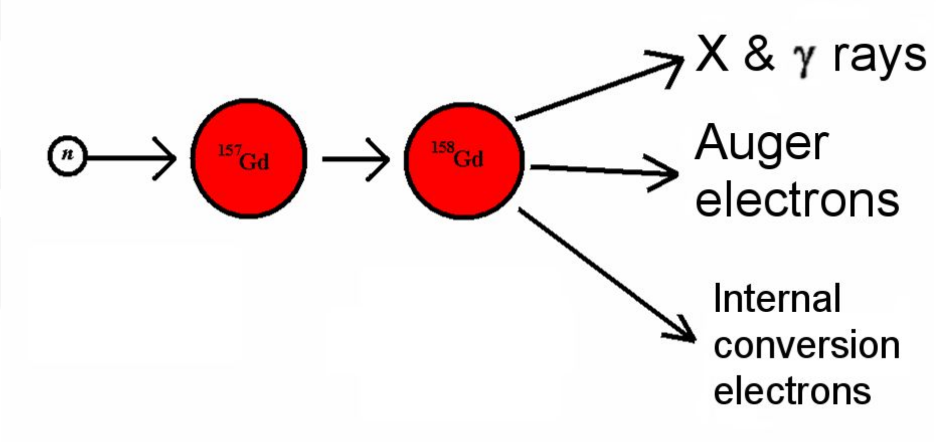
Nuclide	σ_{th} (barn)	Reaction
^{1}H	$3.33*10^{-1}$	(n,γ)
^{6}Li	$9.41*10^{2}$	(n,α)
^{10}B	$3.84*10^{3}$	(n,α)
^{12}C	$3.50*10^{-3}$	(n,γ)
^{14}N	1.83	(n,p); (n,γ)
^{16}O	$1.90*10^{-4}$	(n,γ)
^{23}Na	$4.30*10^{-1}$	(n,γ)
^{24}Mg	$5.30*10^{-3}$	(n,γ)
^{35}Cl	$3.27*10^{1}$	(n,γ)
^{113}Cd	$2.06*10^{4}$	(n,γ)
$^{135}Xe^{*}$	$2.72*10^{6}$	(n,γ)
^{157}Gd	$2.55*10^{5}$	(n,γ)
^{155}Gd	$7.50*10^{4}$	(n,γ)
$^{235}U^{*}$	$6.81*10^{2}$	(n,f)
$^{241}Pu^{*}$	$1.38*10^{3}$	(n,f)
$^{242}Am^{*}$	$8.00*10^{3}$	(n,f)

Interaction of ^{10}B and ^{157}Gd with thermal neutrons

σ_{th} (barn)

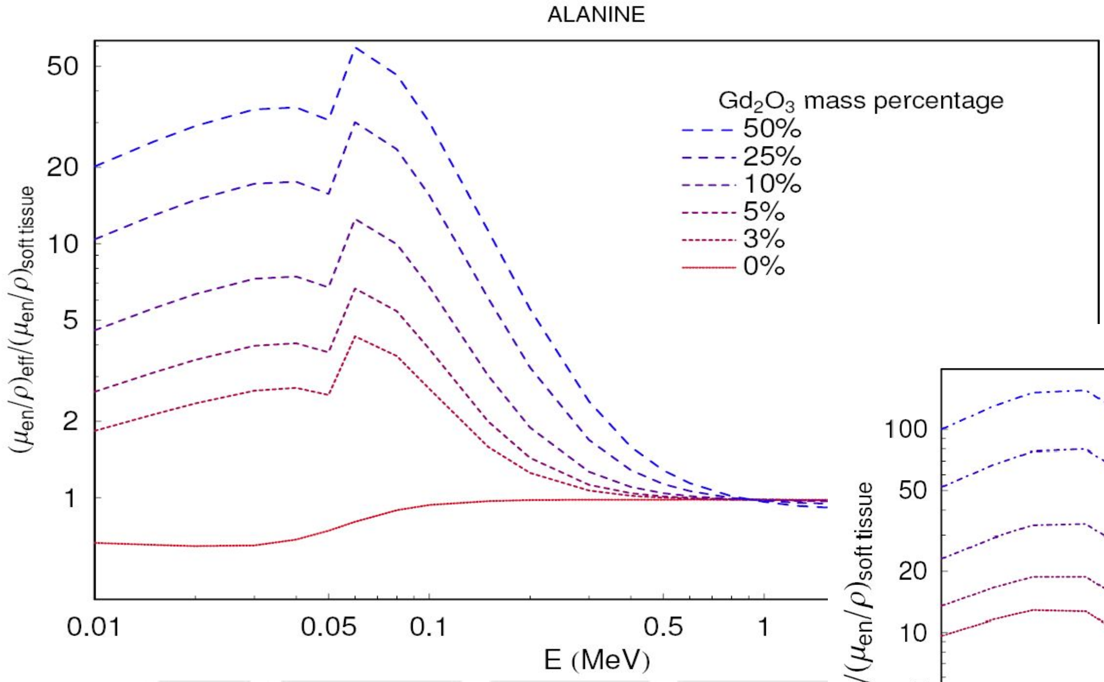


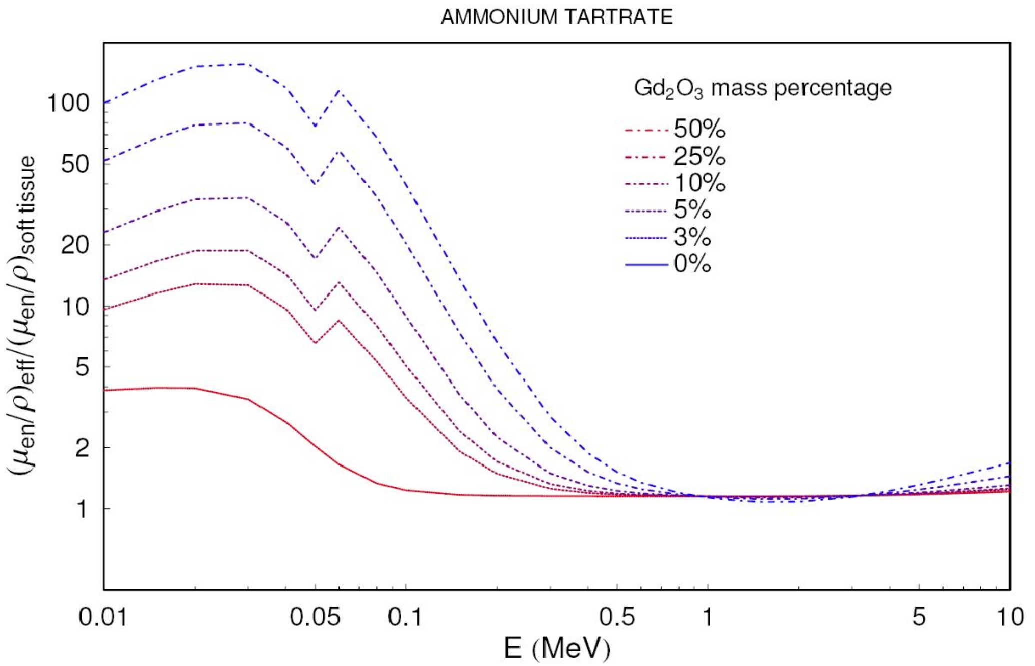
3838



255000

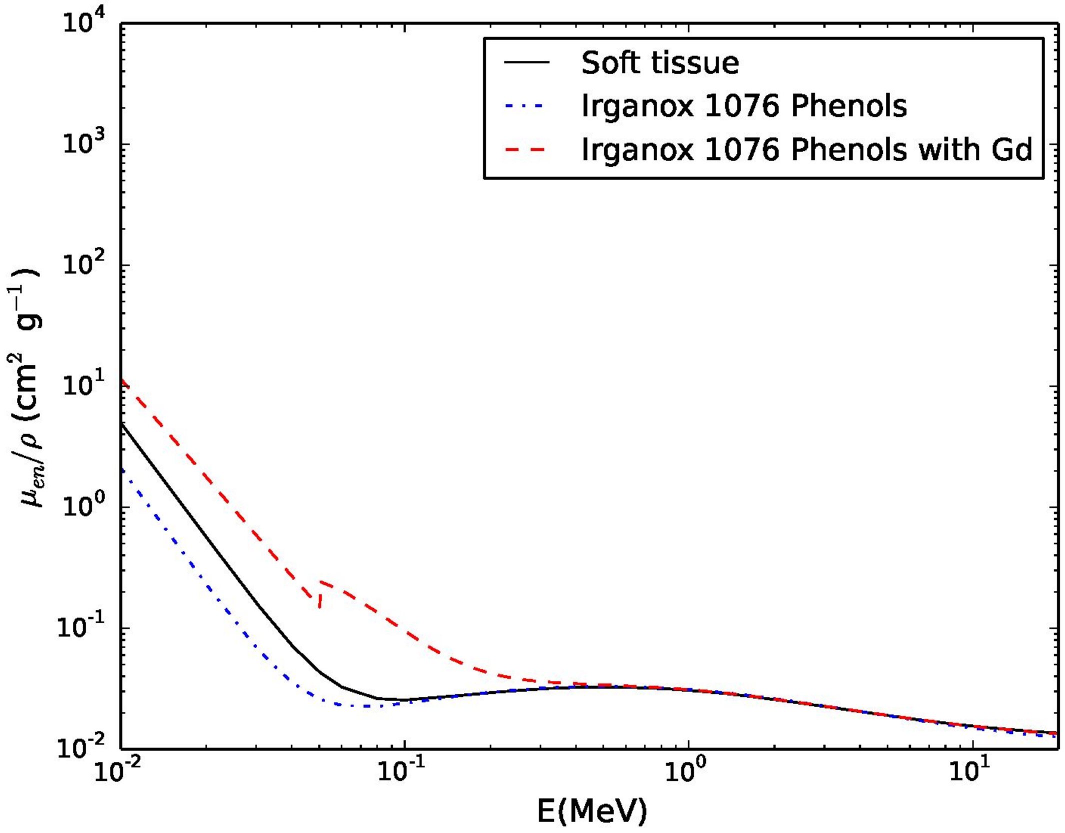
Mass energy absorption coefficient for photon beams





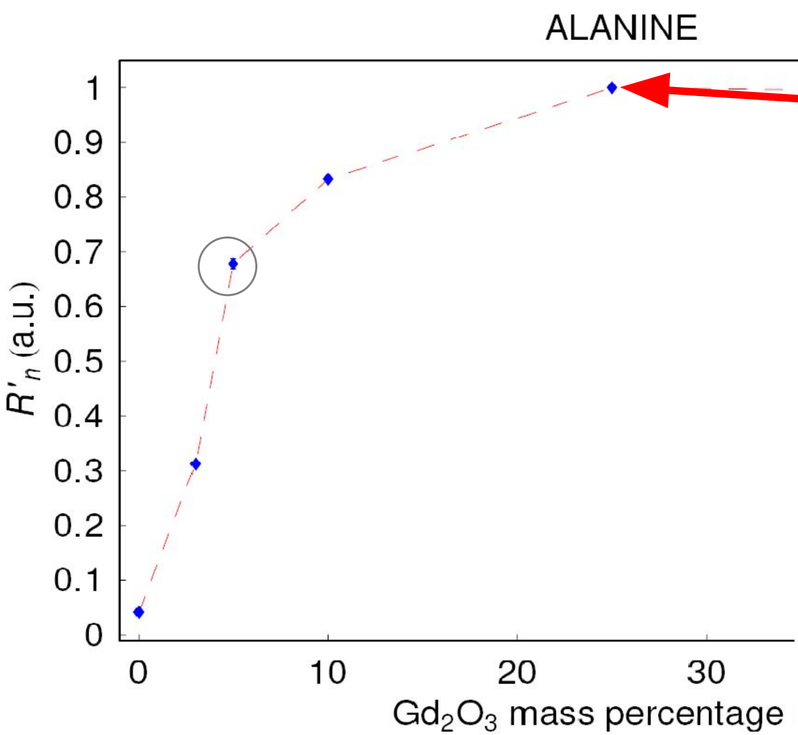
M. MARRALE et al.
Radiat. Res. 169
232-239 (2008)

Mass energy absorption coefficient for photon beams

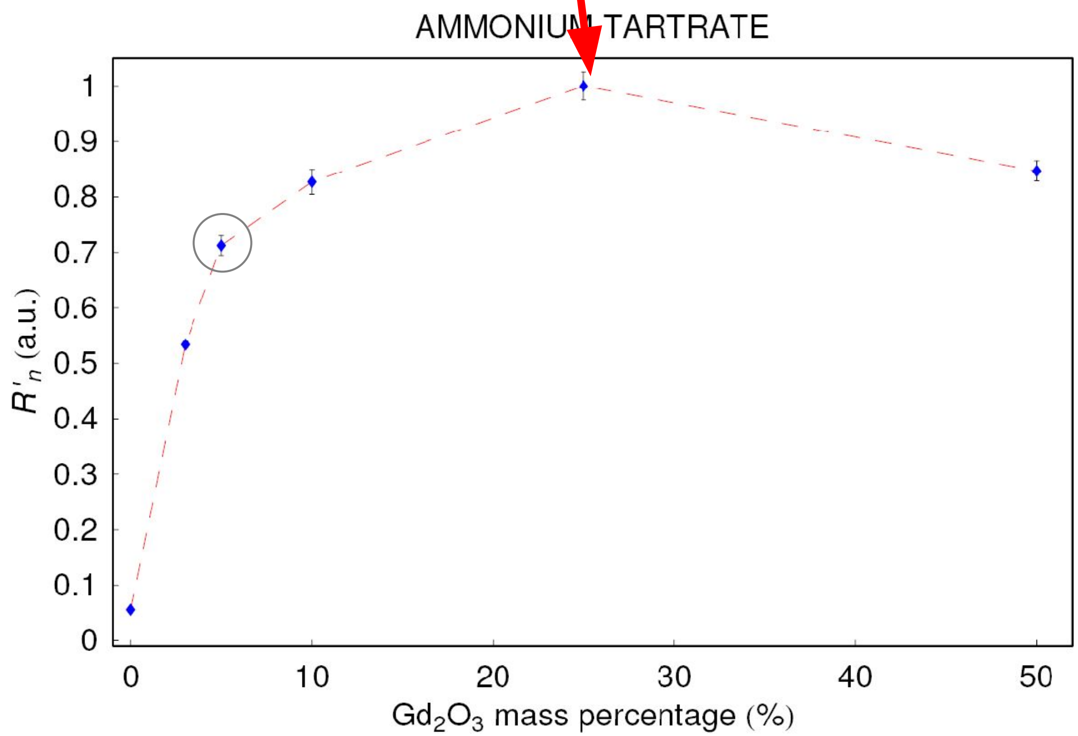


M MARRALE et al. *Radiat. Meas.* 75, 15-20 (2015)

Analysis as function of Gd concentration



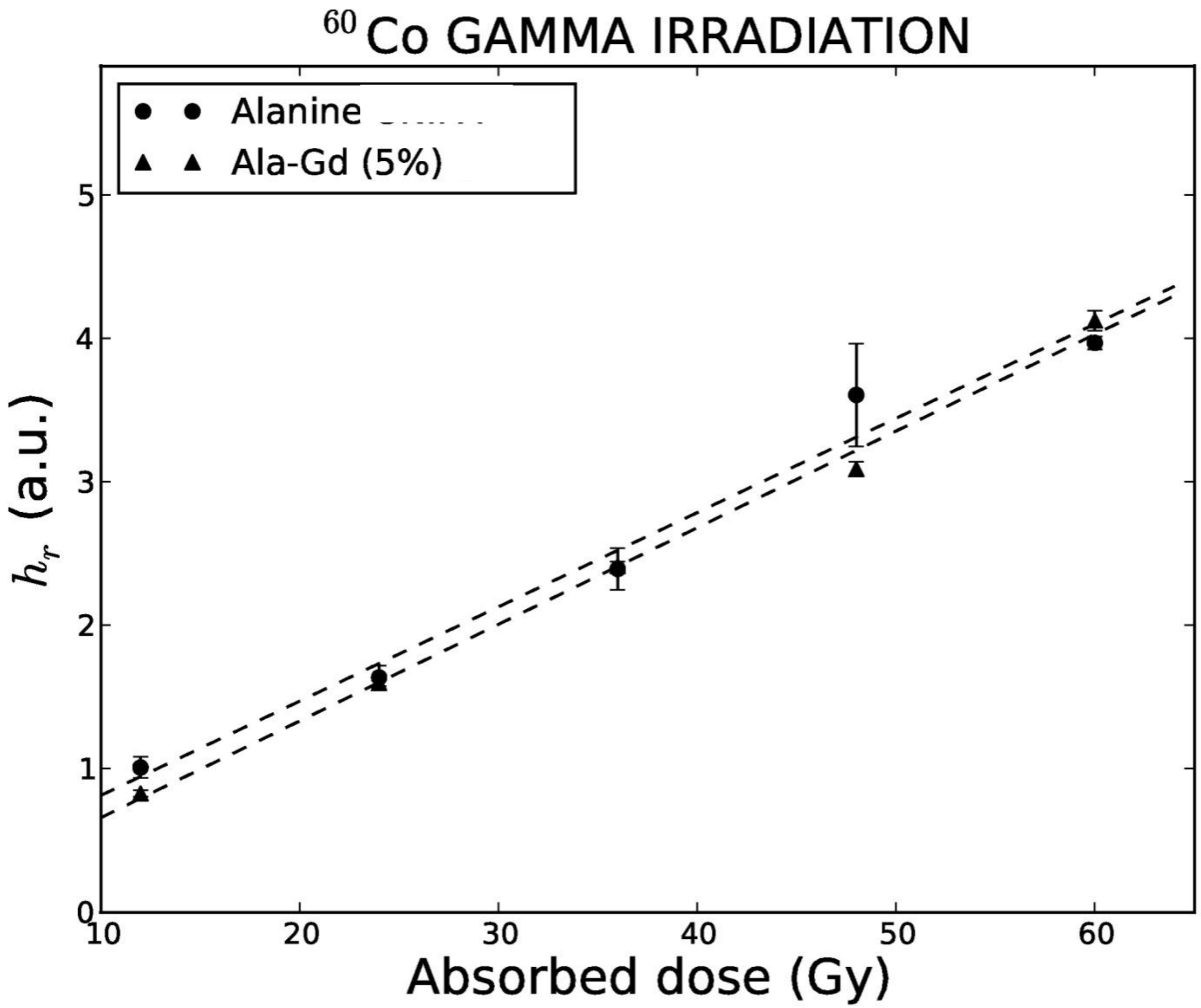
Sensitivity improvement more than 20 times



M. MARRALE et al.
*Radiat. Res.*169
232-239 (2008)

Neutron fluence: ~$2*10^{13}$ cm^{-2}

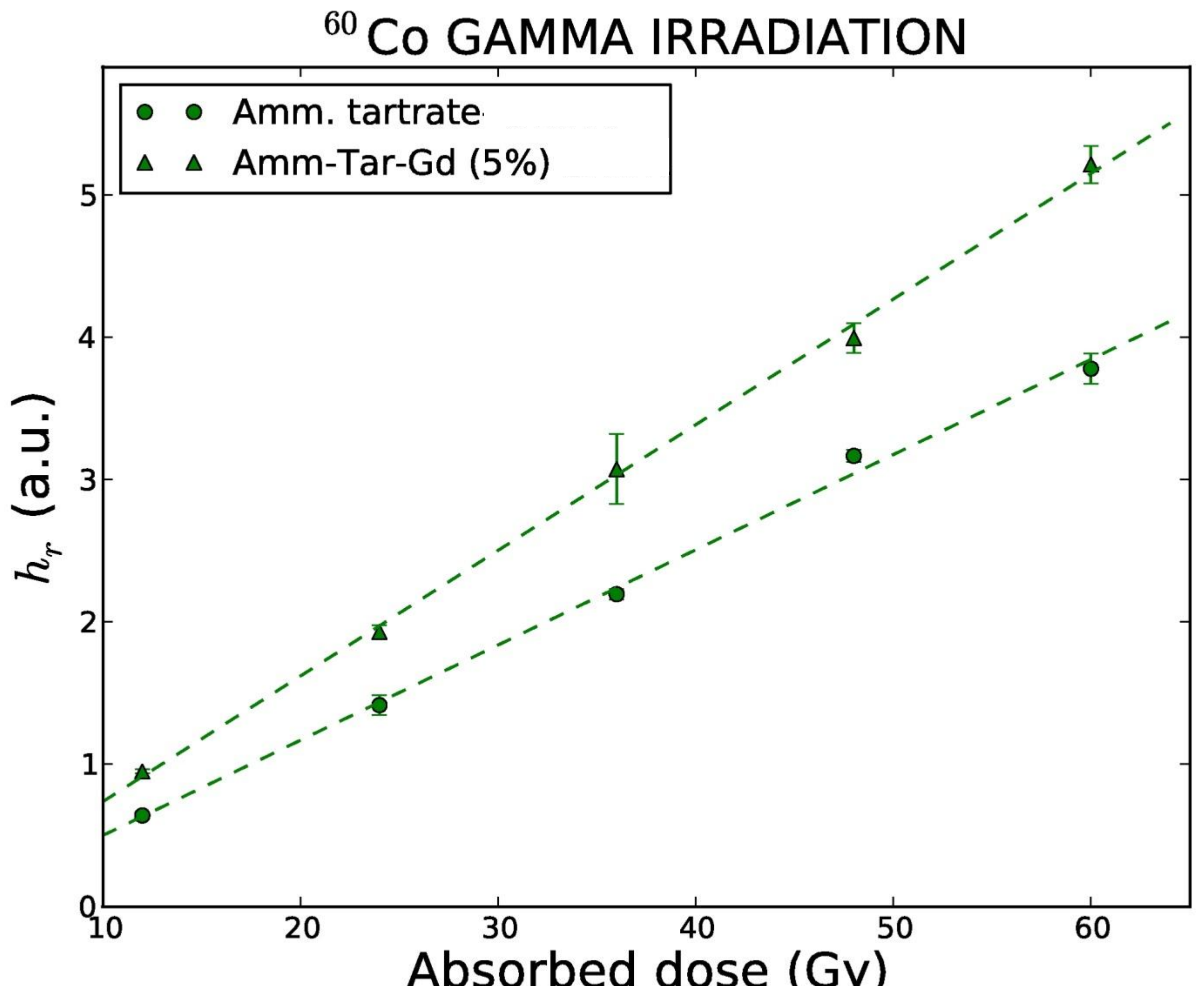
Gd-Alanine - Gamma irradiation



Linear response up to 60 Gy

Gadolinium addition does not increase photon sensitivity

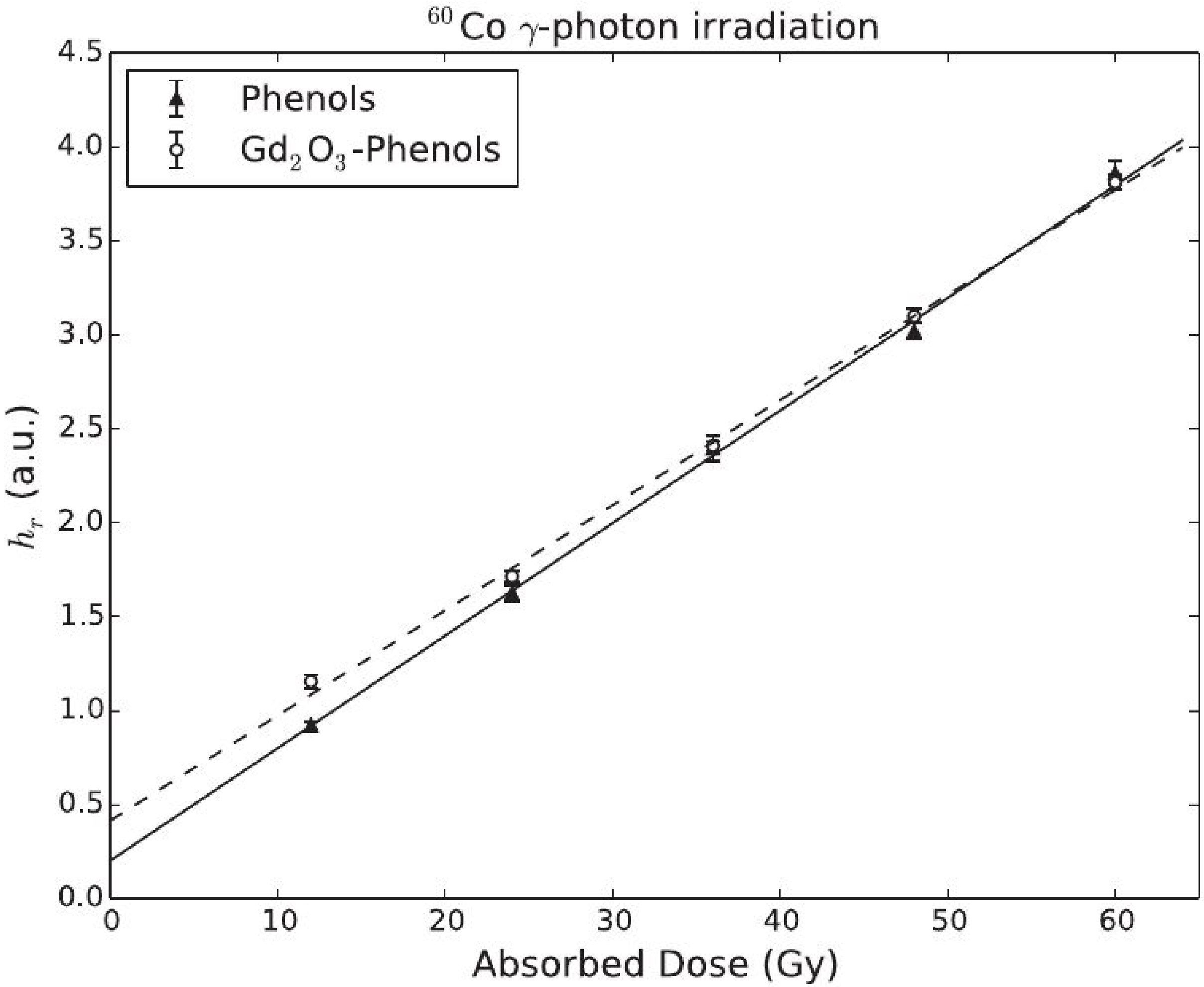
Gd-Ammonium Tar. - Gamma irradiation



Linear response up to 60 Gy

Gadolinium addition slightly increases photon sensitivity

Gd-Phenols - Gamma irradiation

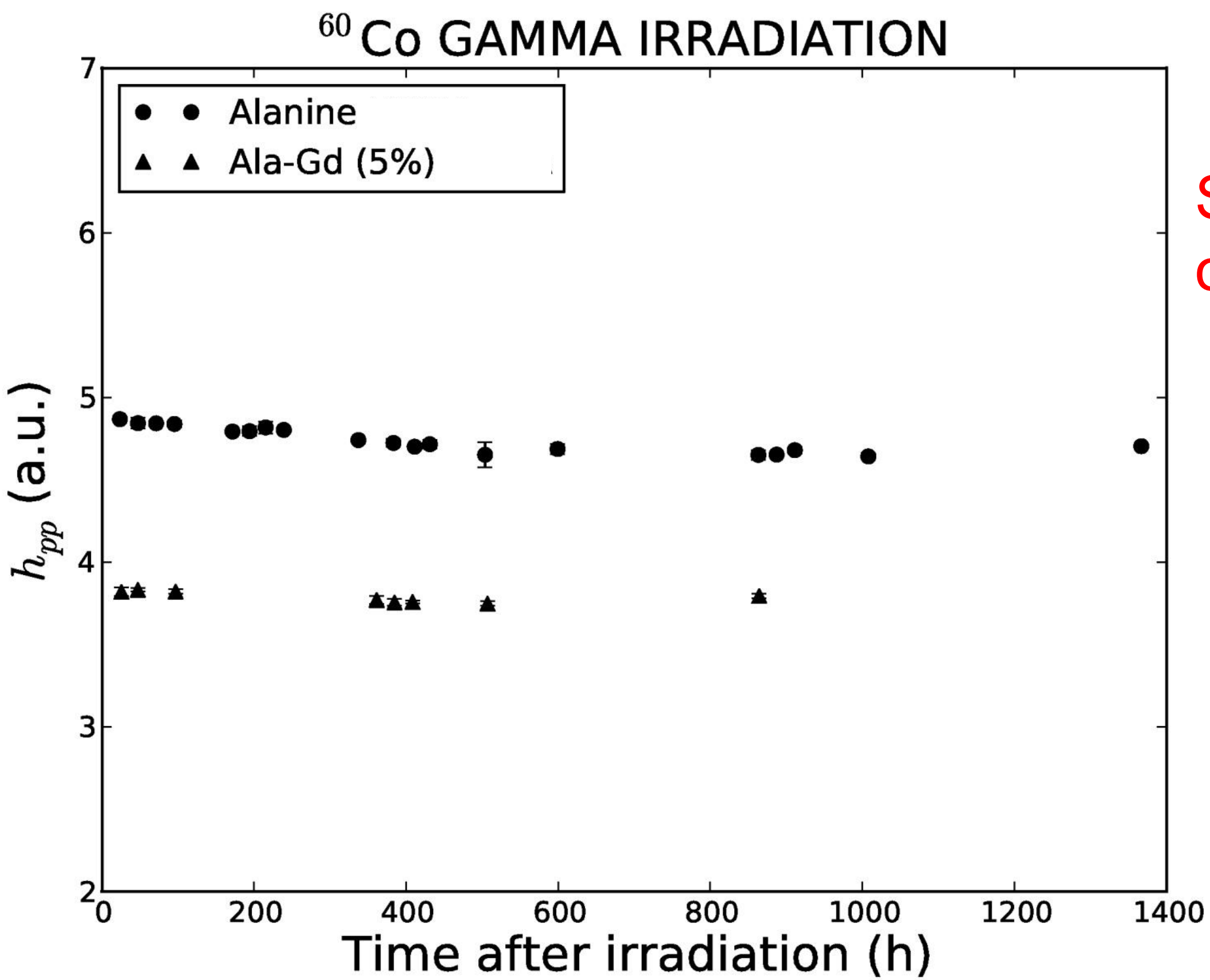


Linear response up to 60 Gy

Gadolinium addition does not increase photon sensitivity

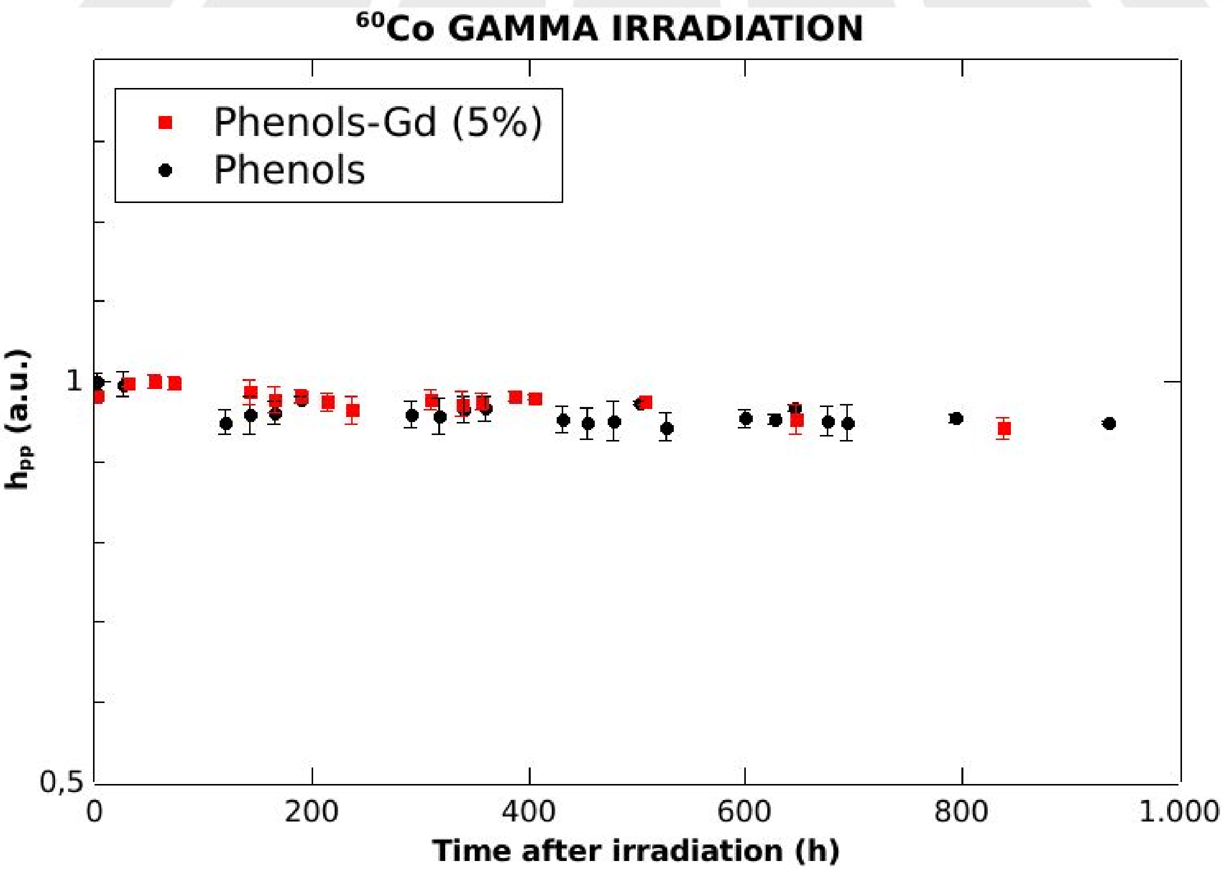
M MARRALE et al. *Radiat. Meas.* 75, 15-20 (2015)

Fading analysis - Alanine – Gamma Irradiation



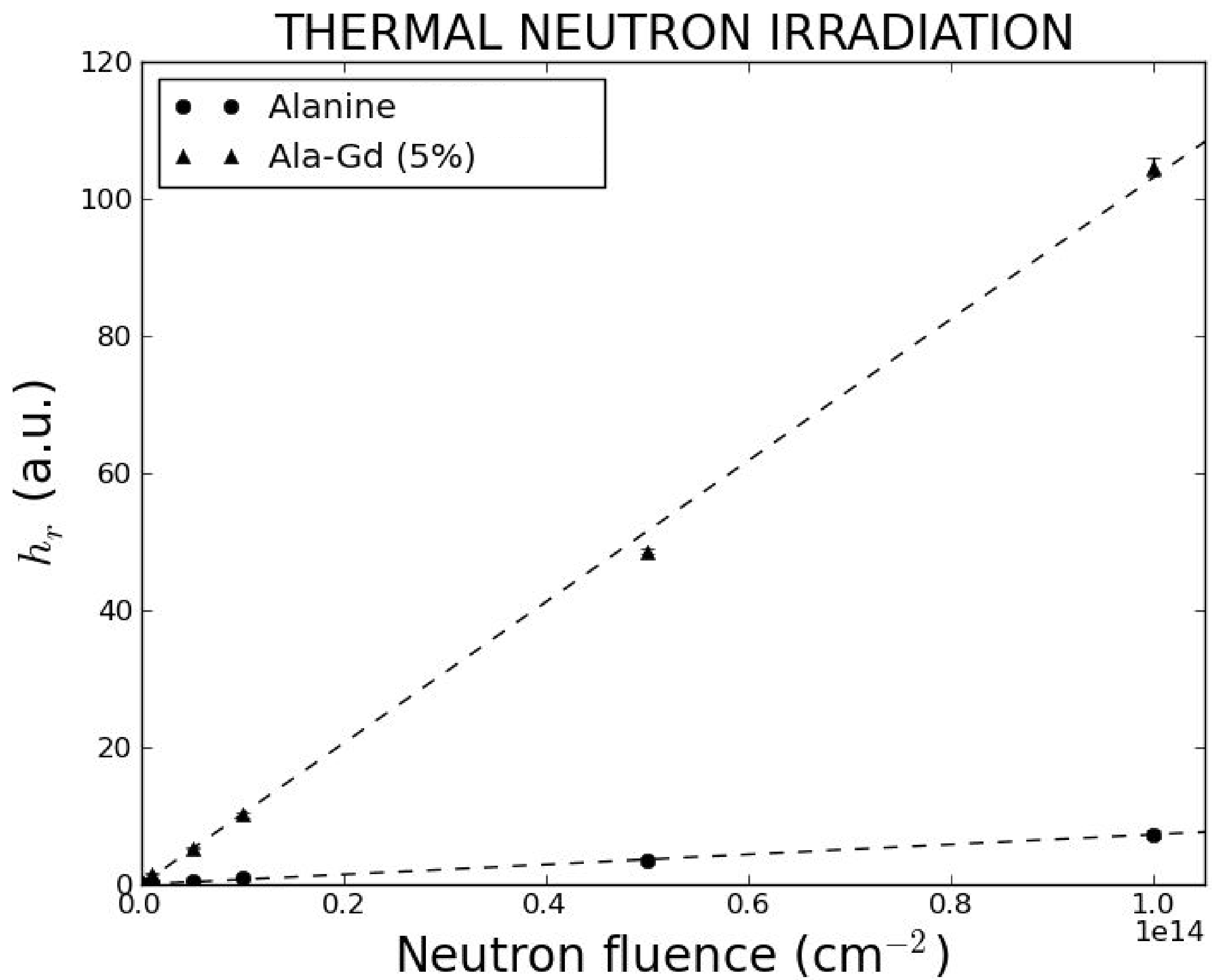
Signal decrease of 2-3% in 1000h

Fading analysis - Phenols – Gamma Irradiation



Signal decrease of 2-3% in 1000h

Gd-Alanine – Neutron irradiation

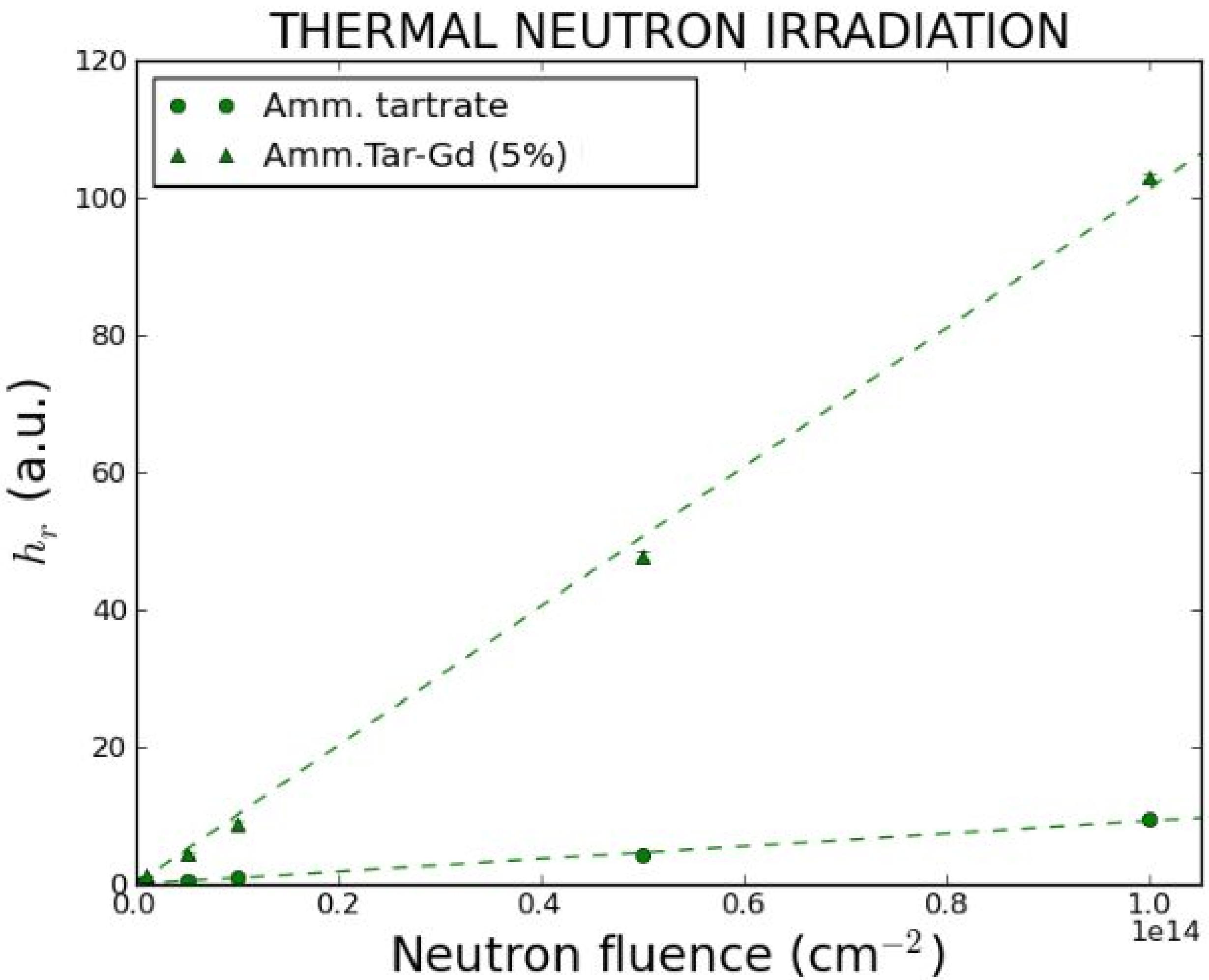


Linear response up to 10^{14} cm^{-2}

Sensitivity improvement of more than 10 times

M MARRALE et al. *Radiat. Prot. Dos.* (2014) 161 (1-4): 383-386.

Gd-Ammonium Tar. – Neutron irradiation

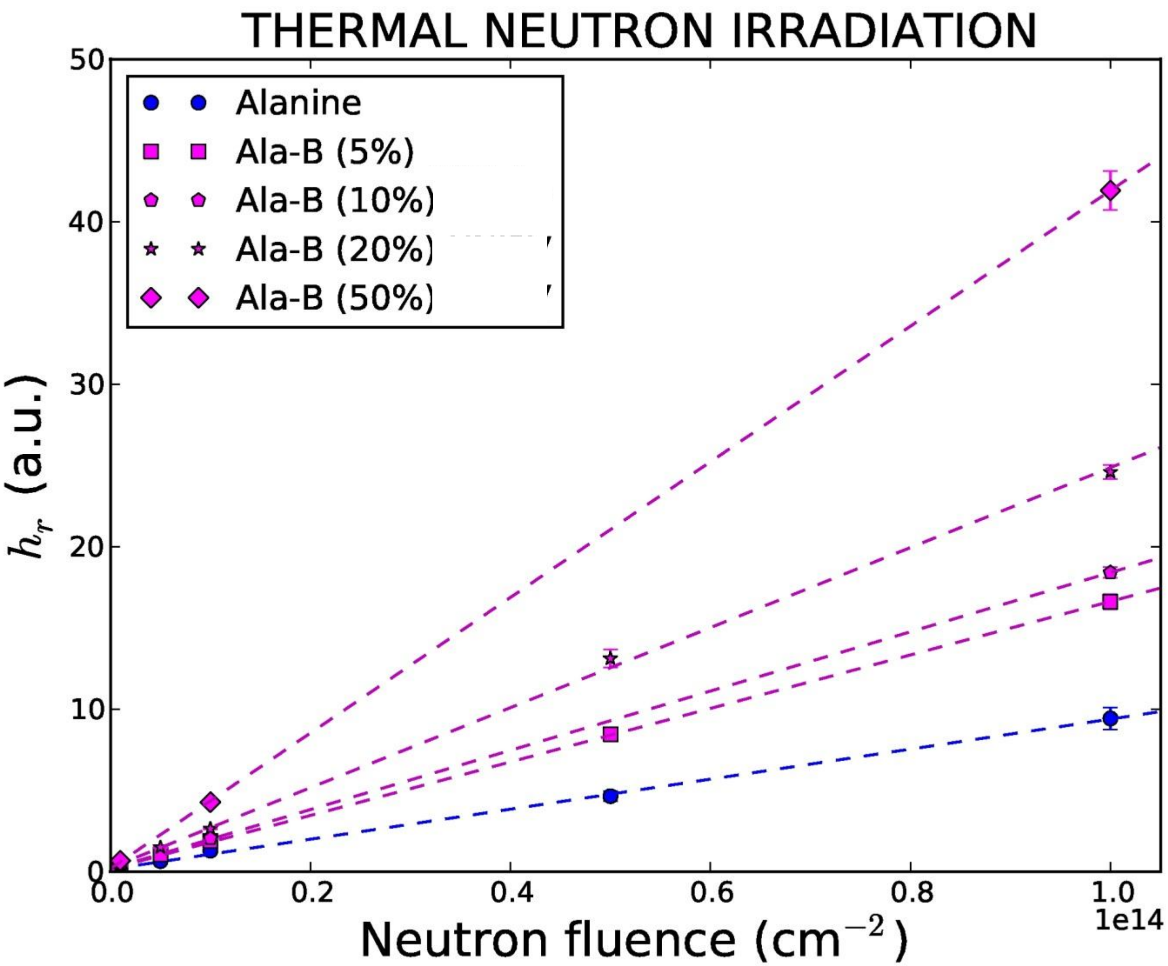


Linear response up to 10^{14} cm^{-2}

Sensitivity improvement of more than 10 times

M MARRALE et al. *Radiat. Prot. Dos.* (2014) 159 (1-4), 233-236

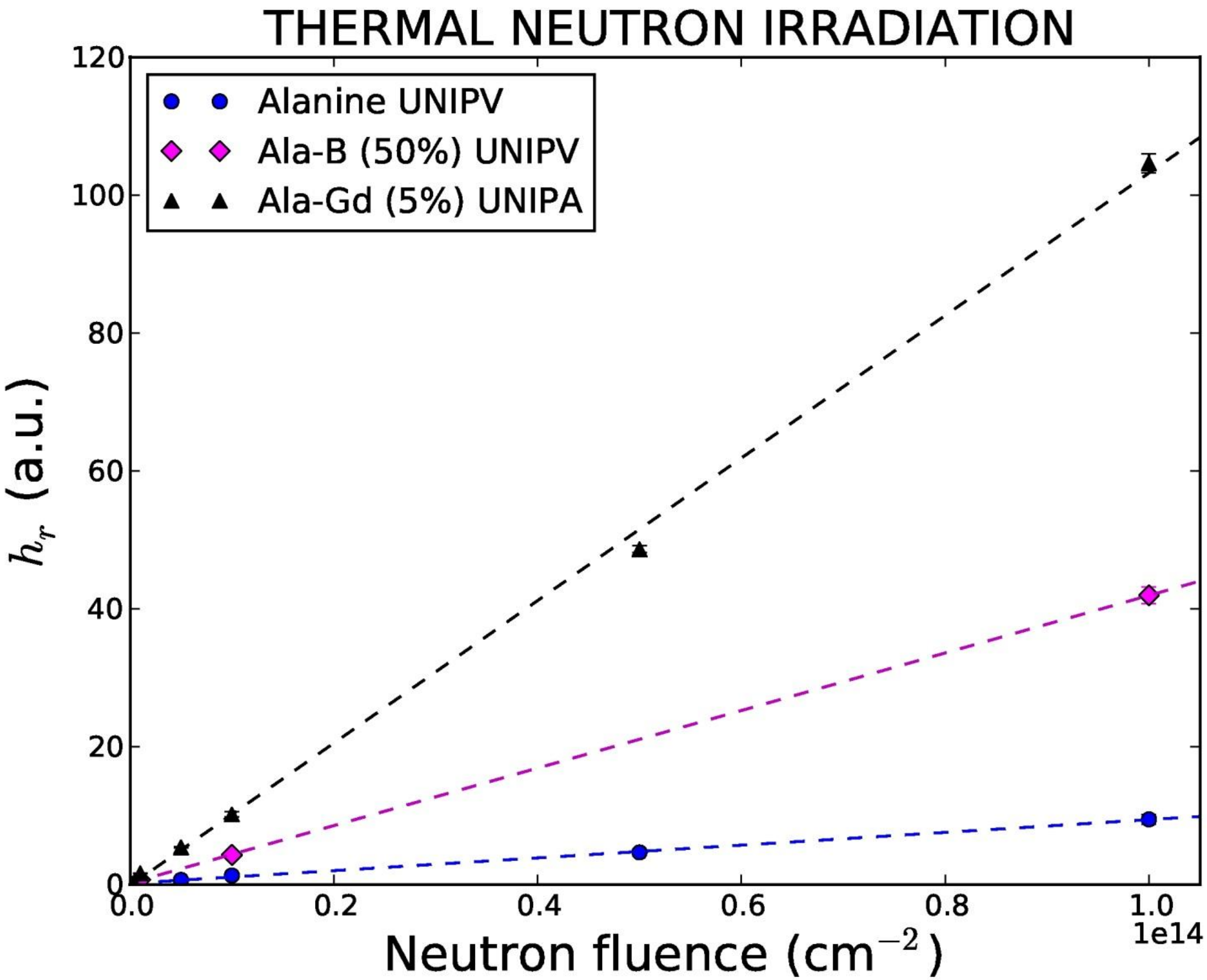
B-Alanine – Neutron irradiation



Linear response up to 10^{14} cm^{-2}

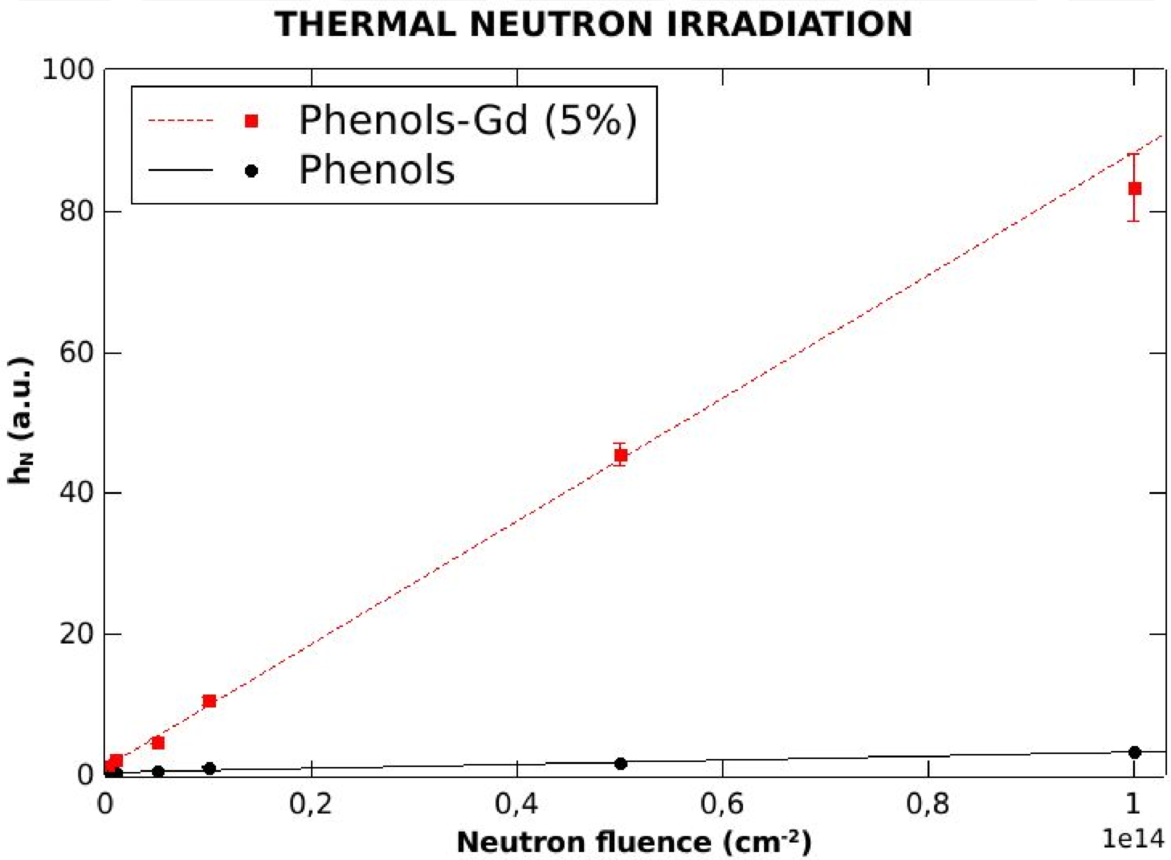
Maximum sensitivity improvement of about 5 times

Neutron irradiation - Comparison



Gadolinium addition (5%) increases neutron sensitivity than Boron addition (50%)

Gd-Phenols – Neutron irradiation

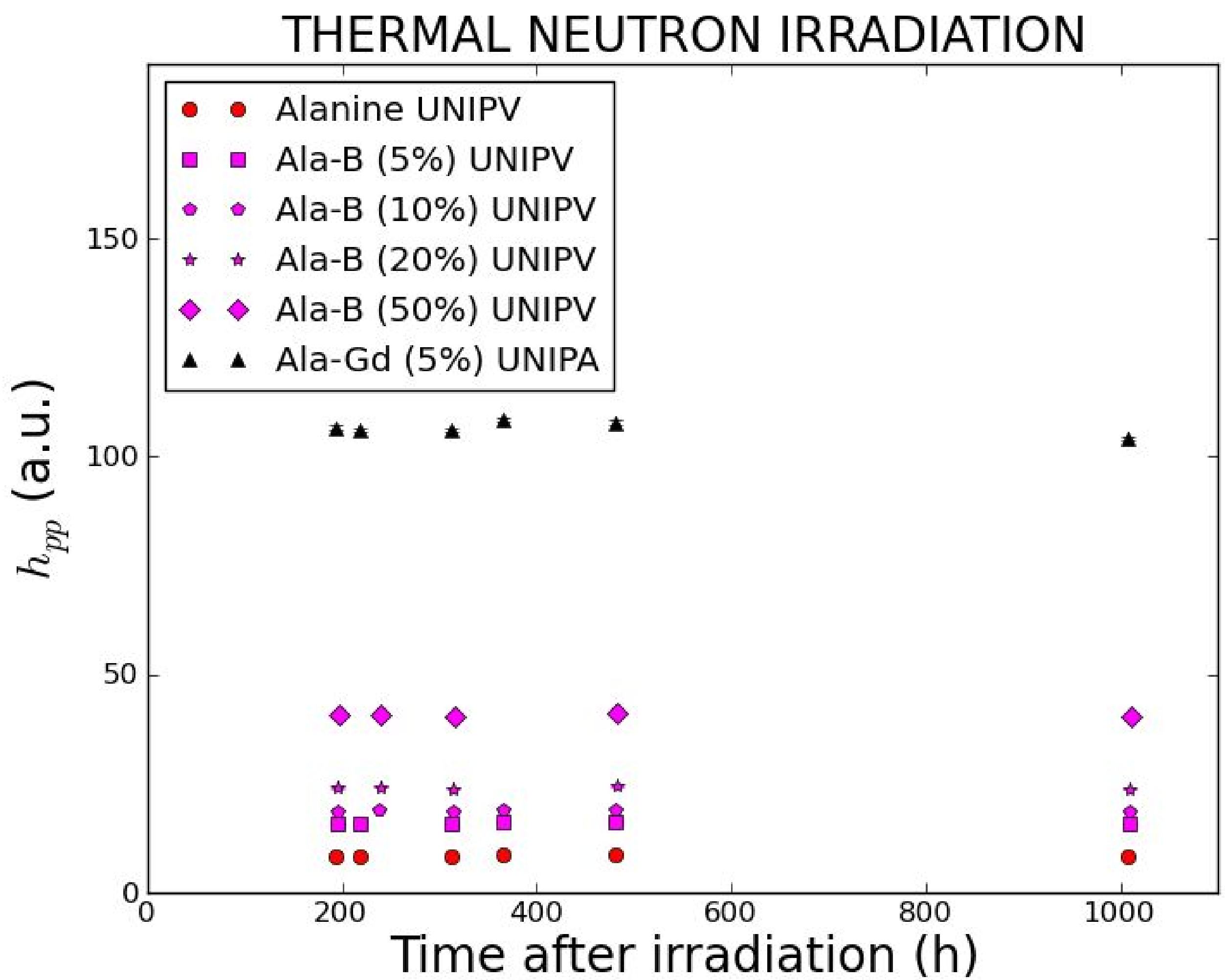


Linear response up to 10^{14} cm^{-2}

Sensitivity improvement of more than 10 times

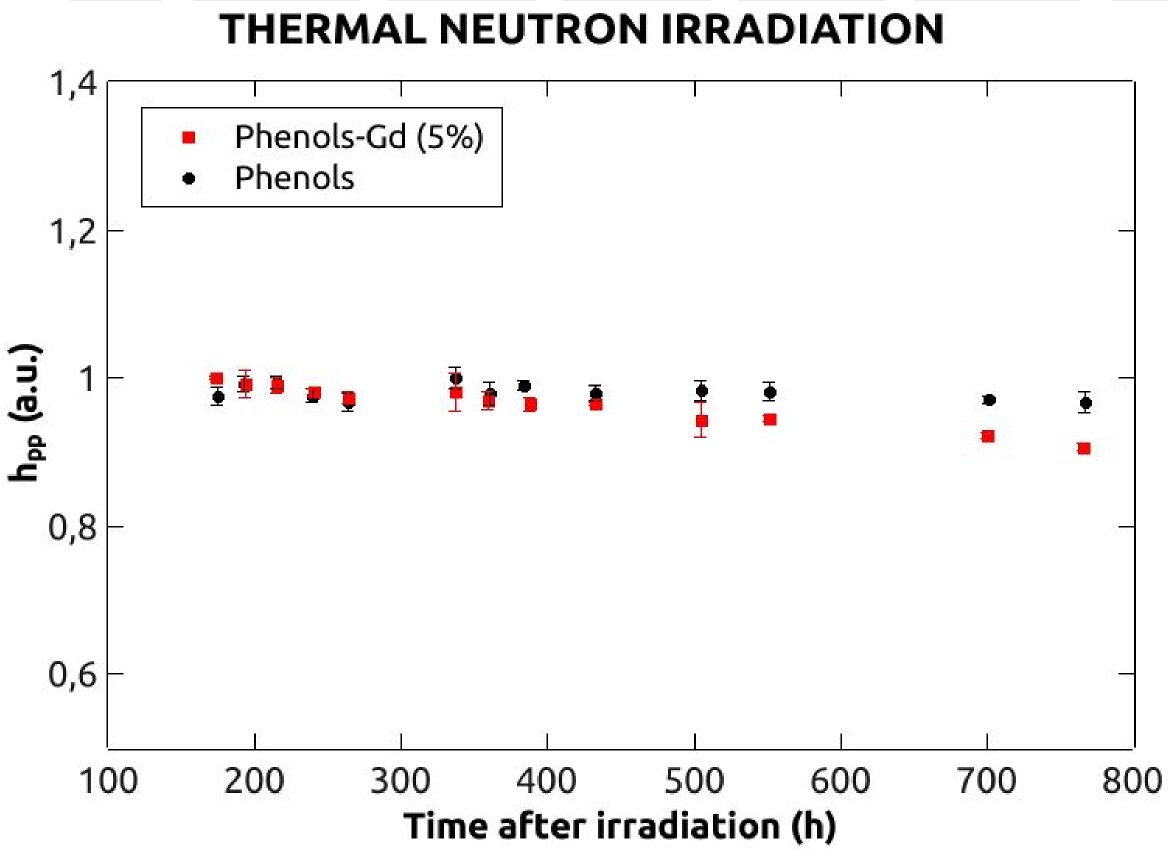
M MARRALE et al. *Radiat. Meas.* 75, 15-20 (2015)

Fading analysis - Alanine - Neutron Irradiation



Signal decrease of 2-3%

Fading analysis - Phenols - Neutron Irradiation



Signal is stable for 2 weeks after irradiation

Signal decrease of Gd-phenols of ~5% in about 1 month

EXAMPLE OF COMBINED USE OF TWO EPR DOSIMETERS: BLIND TEST

Blind values

$\Phi = (4.80 \pm 0.14) \times 10^{12}\ cm^{-2}$

$D_\gamma = (0.410 \pm 0.012)\ Gy$

Dosimeter A	$f_A = f_A^n / f_A^\gamma$	Dosimeter B	$f_B = f_B^n / f_B^\gamma$	$\Phi\ (10^{12}\ cm^{-2})$	D_γ (Gy)
A	1.15	AG	22.1	4.81 ± 0.14	1.2 ± 0.4
A	1.15	ATG	26.5	4.7 ± 0.5	1.3 ± 0.7
AT	1.71	AG	22.1	4.76 ± 0.15	2.2 ± 1.2
AT	1.71	ATG	26.5	4.6 ± 0.6	2.4 ± 1.5

M BRAI et al. *Phys. Med. Biol.* 52 (17), 5219 (2007)

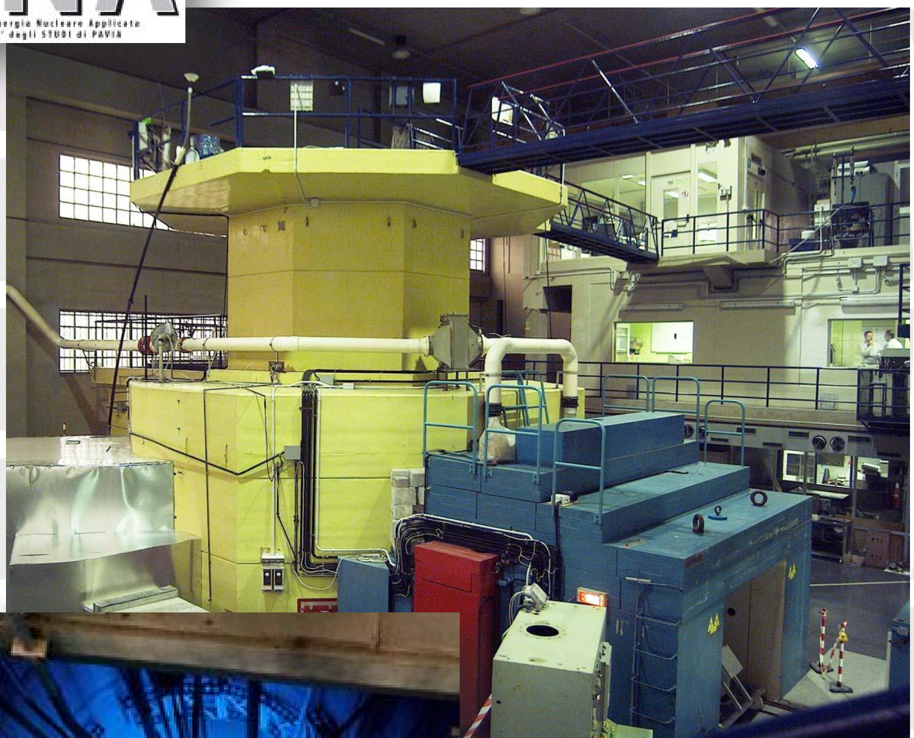
The reconstructed values of gamma dose is wrong because its blind value is smaller than lowest detectable dose (≃1 Gy)

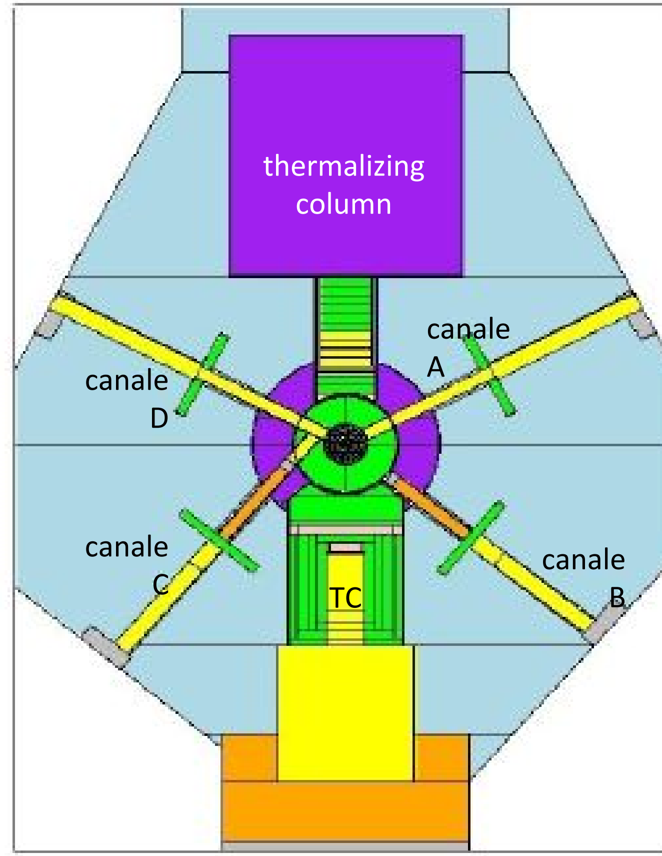
Conclusions (1)

- The addition of Gd_2O_3 at 5% mass percentage slightly increases the ammonium tartrate sensitivity to gamma photons.
- The addition of Gd_2O_3 at 5% mass percentage hugely (more than 10 times) increases, both alanine and ammonium tartrate dosimeters sensitivity to thermal neutrons.
- Sensitivity to thermal neutrons of H_3BO_3 doped alanine dosimeters increases with the increasing of doping compound percentage. However, the 50%-H_3BO_3-alanine dosimeter shows less sensitivity to thermal neutrons than 5% Gd_2O_3 alanine or tartrate ones
- Tradeoff between increased sensitivity and reduction of tissue equivalence has been reached by using only the 5% of Gd_2O_3.
- The gamma dose values are correctly reconstructed if they are sufficiently higher than lower detectable doses (about 1 Gy)

Other procedure to discriminate neutron and gamma components

Other procedure to discriminate neutron and gamma components

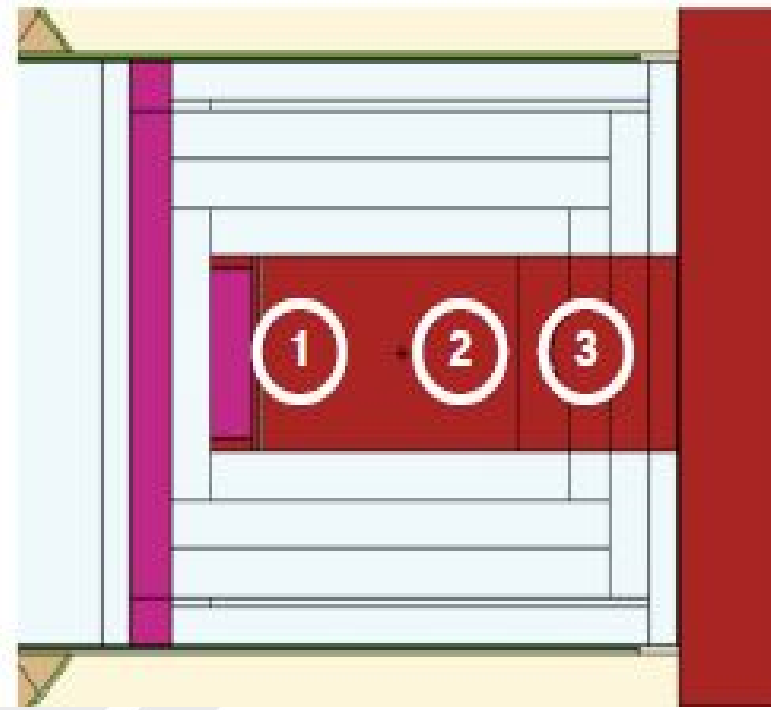




Nuclear reactor TRIGA Mark II of Pavia

Other procedure to discriminate neutron and gamma components

- ✓ Monte Carlo simulation of the reactor, in particular of the thermal neutron column and calculation of the γ spectrum into three irradiation positions: POS 1, POS 2, POS 3;
- ✓ Determination through Monte Carlo simulations of the supports employed in measurements to ensure the equilibrium conditions of the secondary charged particles (CPE) and to separate the photon and neutron components in the mixed field;
- ✓ optimization of the irradiation setup for the calibration of the detectors;
- ✓ irradiation of the uncovered and covered detectors to separate the dose contributions due to the thermal neutron and photon components.



BORTOLUSSI S. et al.
Manuscript to be submitted

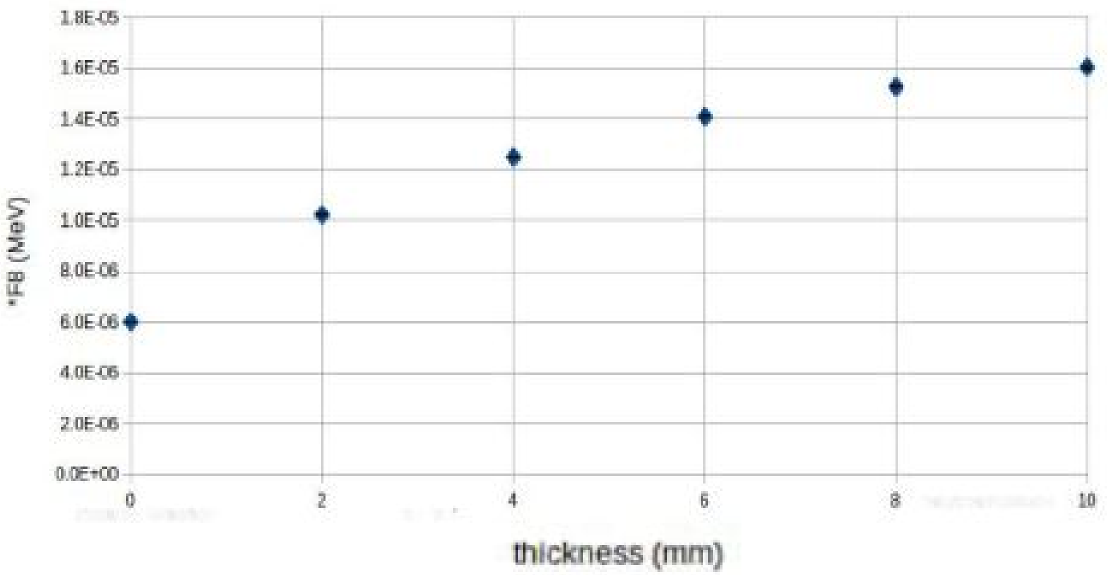
Irradiation setup of alanine dosimeters: Charged Particles Equilibrium

In order to ensure the conditions of CPE during irradiation of the detectors and in the calibration procedures we made use of suitable graphite containers designed by means of Monte Carlo simulations.

GRAPHITE HOLDER

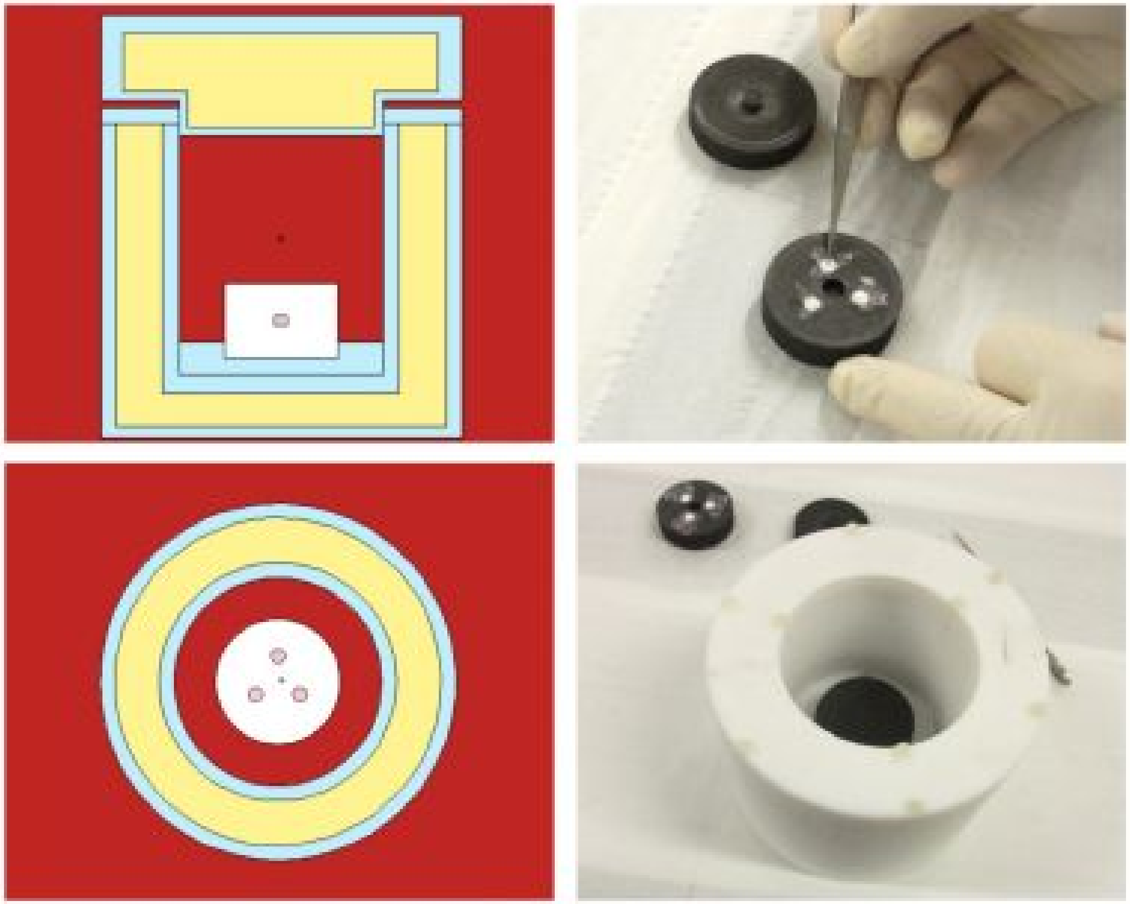
Choice of the dimension

- CPE



BORTOLUSSI S. et al. *Manuscript to be submitted*

Irradiation setup to eliminate thermal neutron component

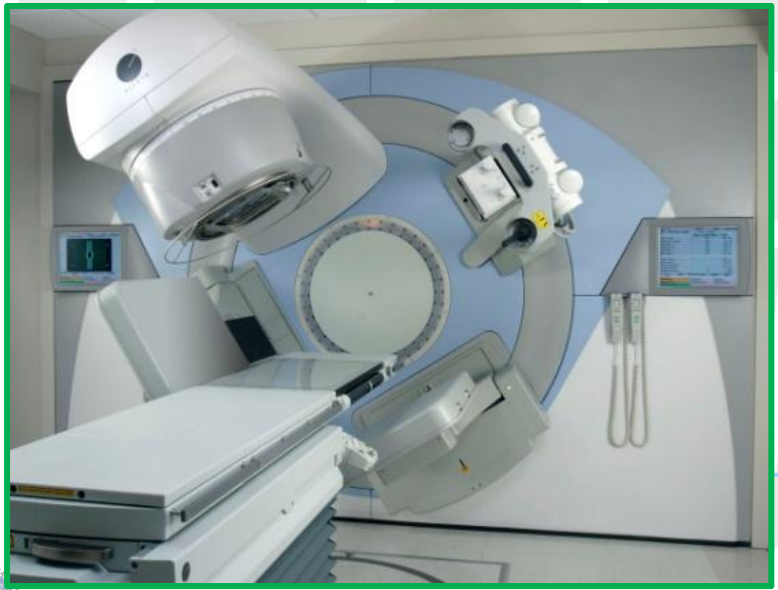


Shield for thermal neutrons composed of lithium carbonate enriched to 95% with ^{6}Li

Attenuation factor of the thermic component ~ 10^{-3}

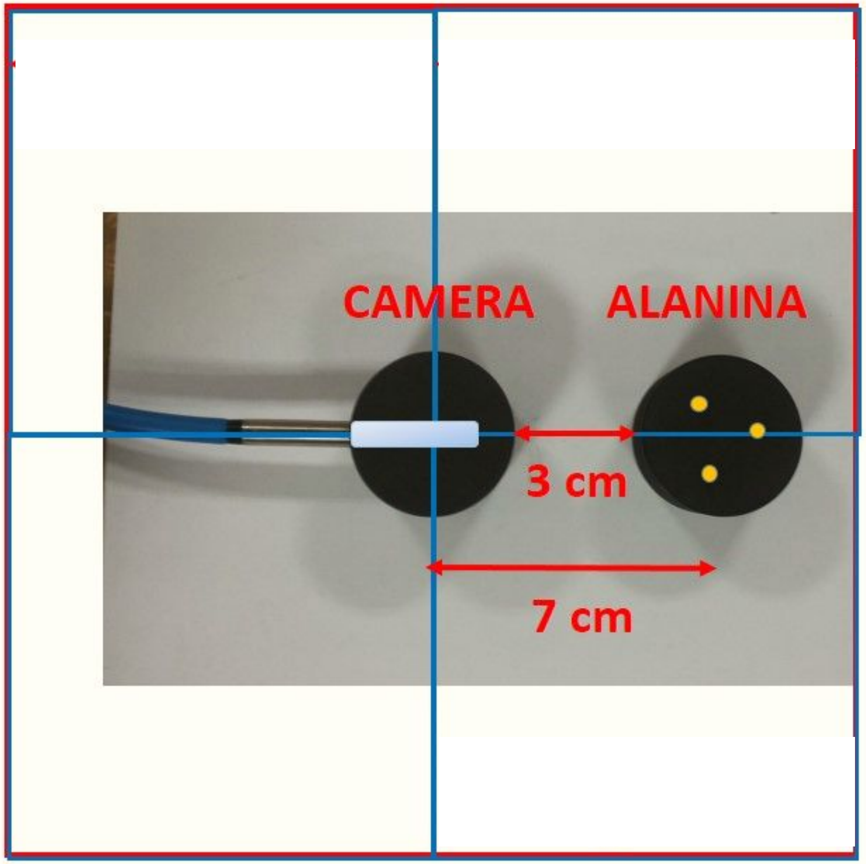
Irradiation setup to calibrate alanine detectors to gamma photons

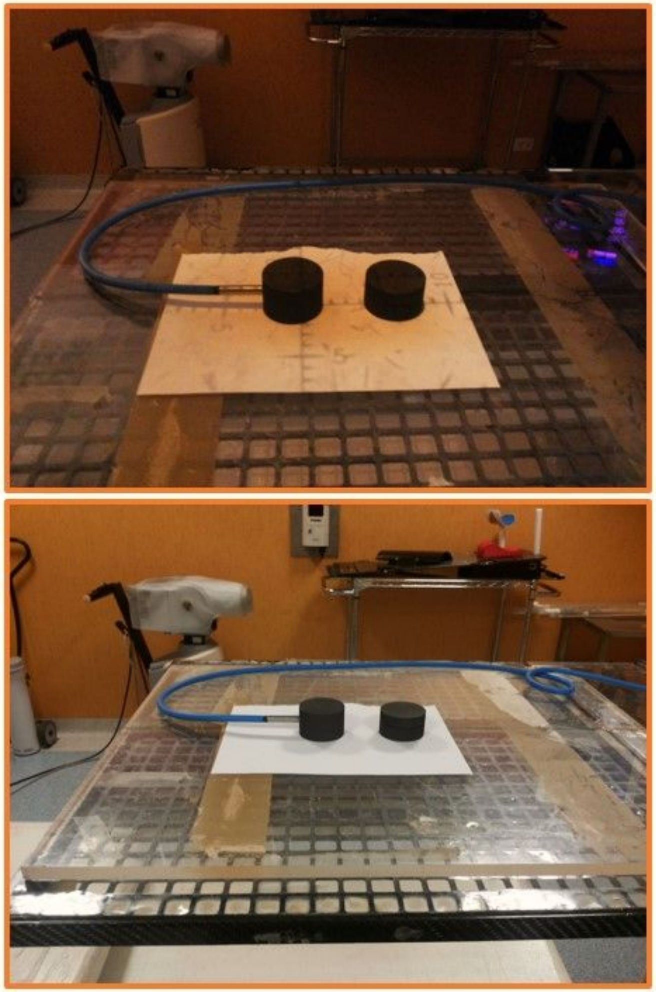
Clinical photons from linear accelerator at 6 MV at the Oncological Hospital in Palermo



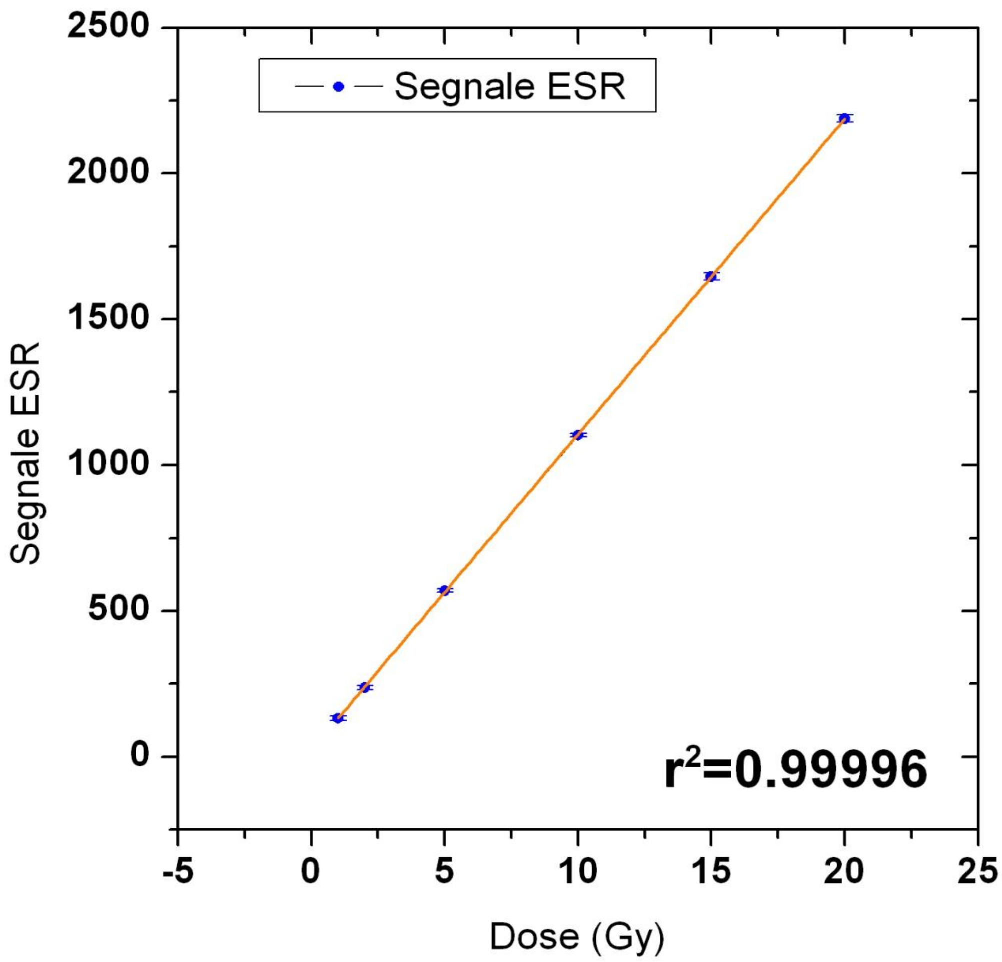
Dose rate: ≃ 1 Gy/min
Dose range: 0-20 Gy
Field size: 37×37 cm^2
SSD: 100 cm

Irradiation setup to calibrate alanine detectors to gamma photons





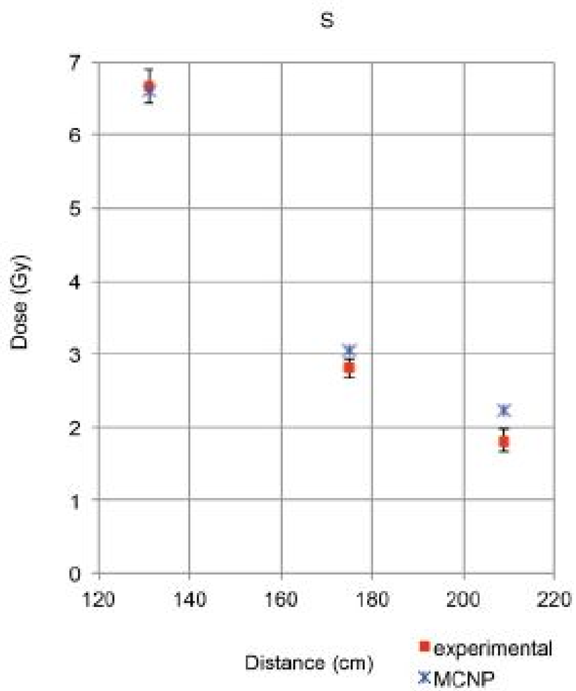
Calibration curve of alanine detectors to gamma photons

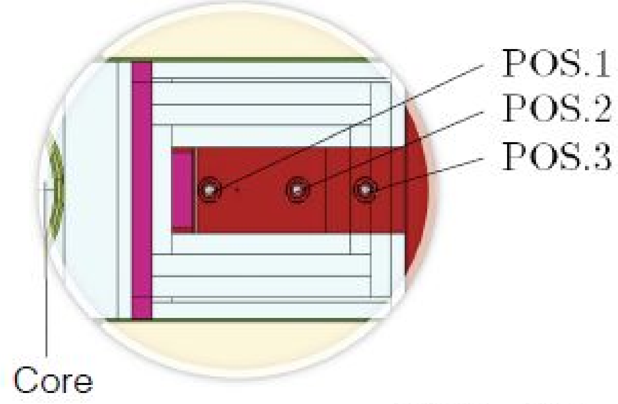


Characterization of thermal column of TRIGA reactor of Pavia: gamma dose

MEASUREMENTS

Results





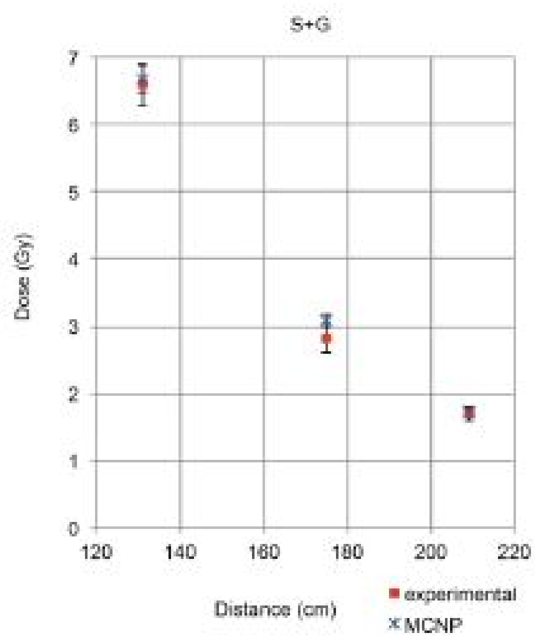
		Dose Gy	Err.
		S	
POS.1	sim.	6.60	0.03
	exp.	6.66	0.03
POS.2	sim.	3.06	0.03
	exp.	2.81	0.05
POS.3	sim.	2.24	0.03
	exp.	1.81	0.14

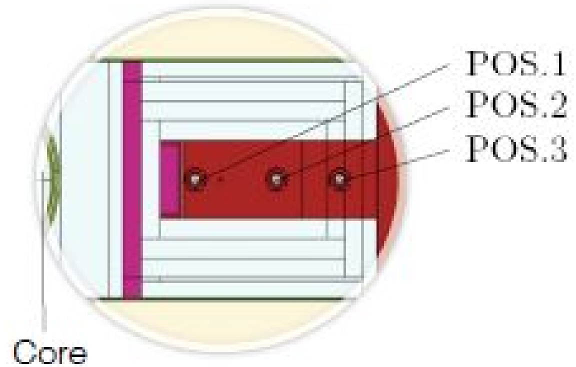
BORTOLUSSI S. et al. *Manuscript to be submitted*

Characterization of thermal column of TRIGA reactor of Pavia: gamma dose

MEASUREMENTS

Results





		Dose Gy	Err.
		S+G	
POS.1	sim.	6.68	0.03
	exp.	6.60	0.05
POS.2	sim.	3.08	0.03
	exp.	2.82	0.08
POS.3	sim.	1.72	0.03
	exp.	1.70	0.06

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Characterization of thermal column of TRIGA reactor of Pavia: total dose

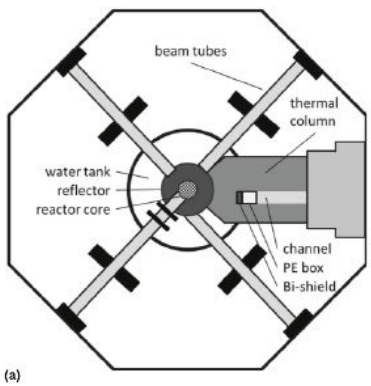
Unshielded alanine samples

$$D_{\text{total}} = D_\gamma + D_p + D_n$$

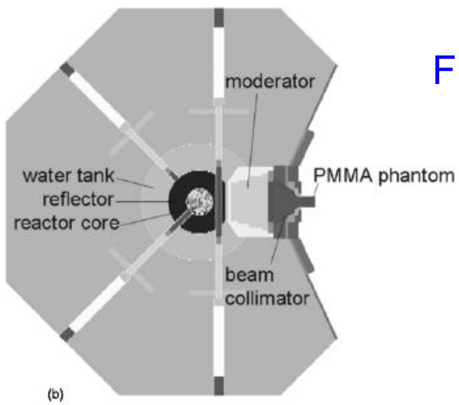
- H(n, n')H ⟶ RE = 0.6
- γ from background ⟶ RE = 1
- $^{14}N(n,p)^{14}C$ ⟶ RE = 0.4

POS 1	Sim	34.82 Gy
	Exp	36.76 Gy
POS 2	Sim	14.27 Gy
	Exp	14.13 Gy
POS 3	Sim	6.89 Gy
	Exp	6.29 Gy

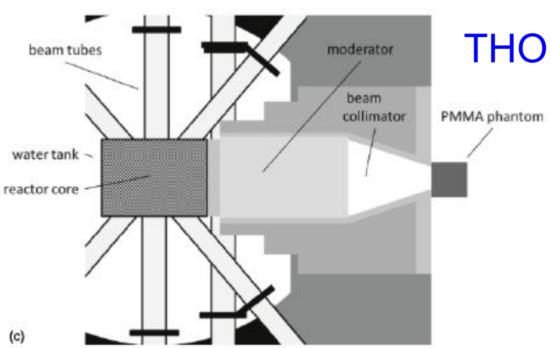
Dosimetric characterization with alanine dosimeters for other reactors



TRIGA, Germany



FiR 1, Finland

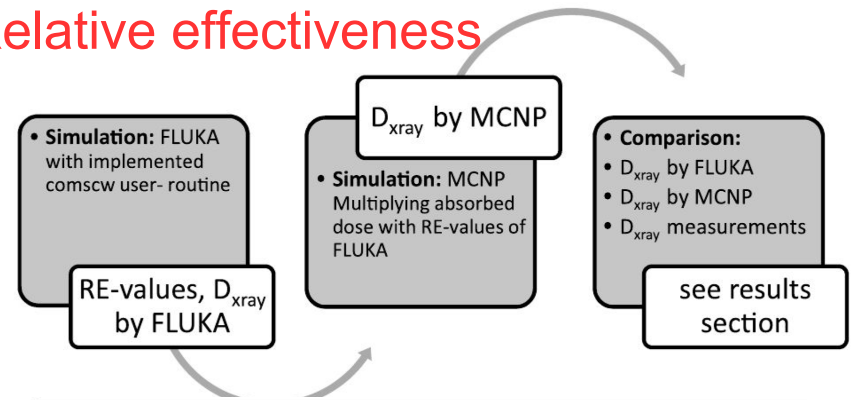


THOR, Taiwan ROC

The radiation field is composed of neutrons as well as photons

$$D_{\text{total}} = D_{\gamma} + D_{p} + D_{n}$$

Relative effectiveness



	TRIGA, Mainz (Ref. 26)	FiR 1, Helsinki (Ref. 27)	THOR, HsinChu (Ref. 28)
RE_{γ}		1.0	
RE_{p}		0.56 ± 0.01	
RE_{n}	n.d.	0.71 ± 0.03–0.58 ± 0.09	0.67 ± 0.05–0.64 ± 0.07

T. Schmitz et al . Medical Physics 42, 400 (2015)

Conclusions (2)

- The use of alanine dosimeters allows to measure the gamma dose in a mixed (thermal neutron + gamma) field.
- The determination of the gamma dose is possible by following a procedure able to eliminate thermal neutron components.
- The experimental results should be aided by Monte Carlo simulations.
- The presence of fast neutron components involves the need to correctly evaluate the relative efficacy of alanine dosimeters.
- The protocol is effective as highlighted by the good agreement between the measured doses and simulated values

Acknowledgements

University of Palermo Project titled: *Innovative materials and advanced techniques for medical and retrospective dosimetry* funded by . Project Leader: Maurizio Marrale

Italian National Institute of Nuclear Physics (INFN) Project titled: *Neutron dOsimetry and Radiation quality Measurements by ESR and TL* (NORMET). Project Leader: Maurizio Marrale

National Ministry of Research (MIUR) Project (PRIN2011): *Development and application of new materials for ionizing radiation dosimetry* . Project Leader: Francesco D'Errico

Bioquart Biologically weighted quantities in radiotherapy A Joint Research Project within the European Metrology Research Programme EMRP -JRP SIB06. Project Leader: Hans Rabus

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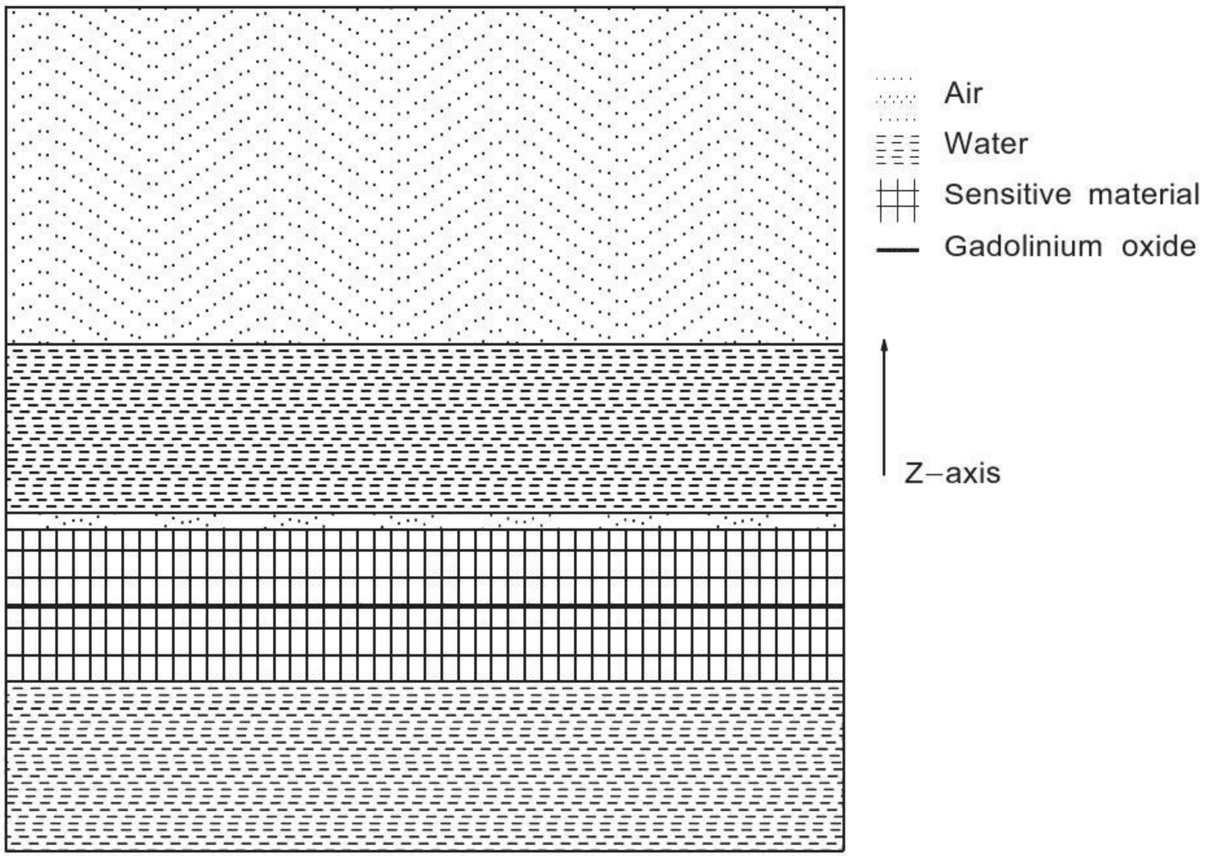
Thank you for your kind attention!

Cathedral of Palermo

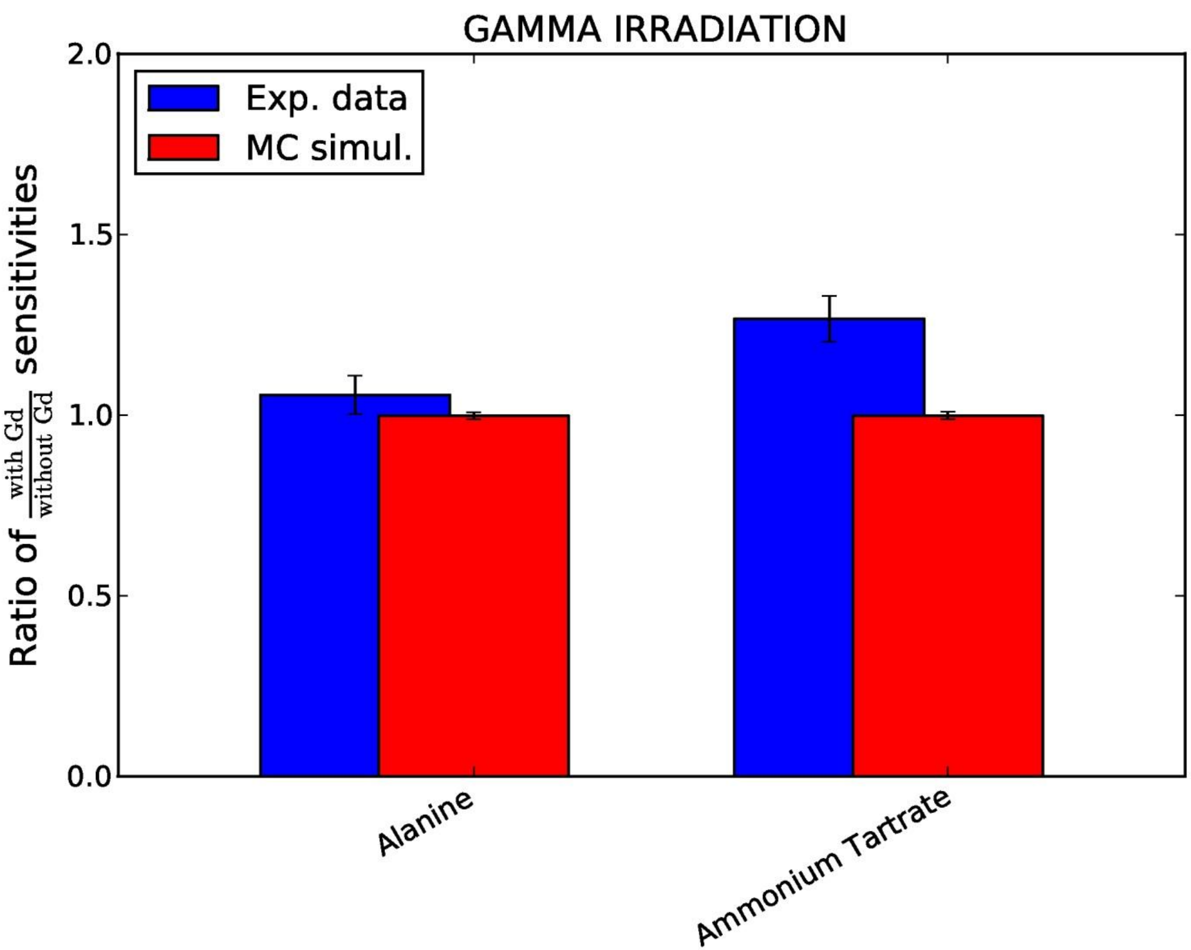
Monte Carlo simulation



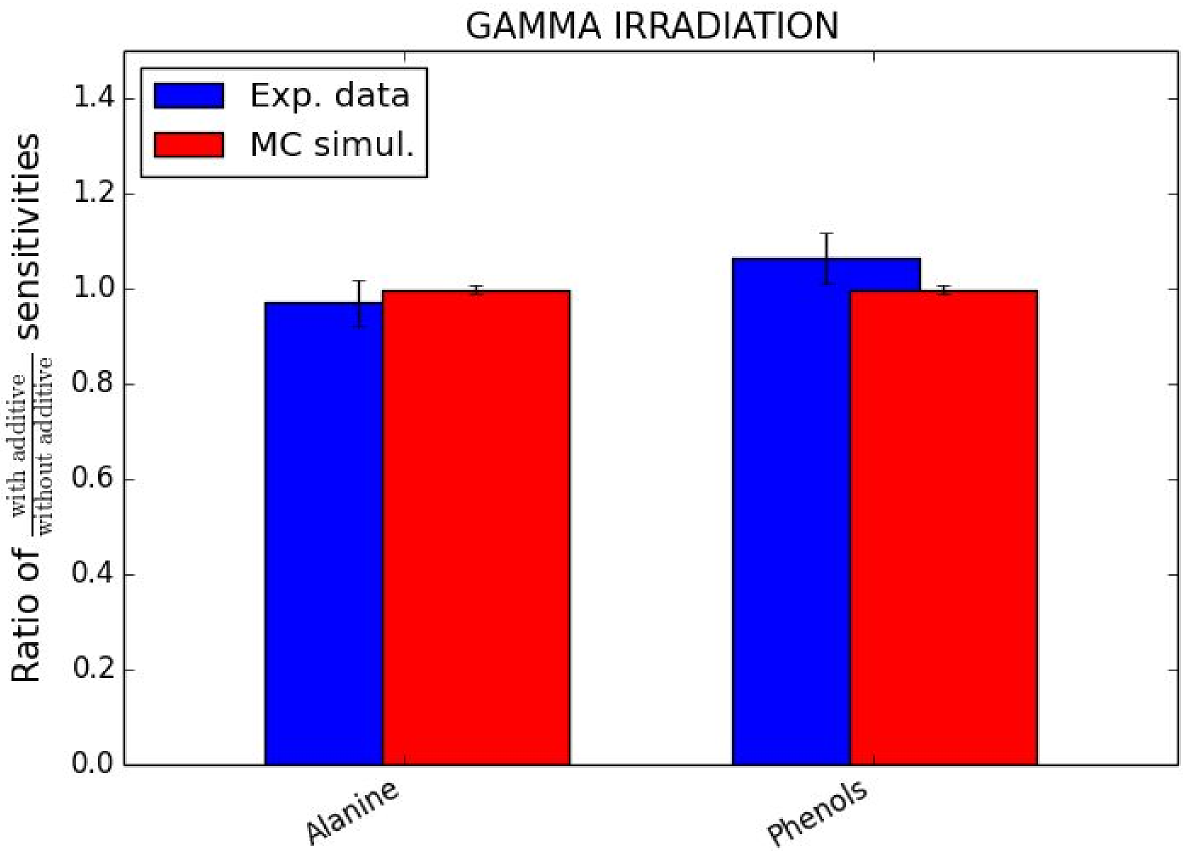
Dosimeter simulated as composed of various layers of alanine or ammonium tartrate and gadolinium

M. MARRALE et al. *Radiat. Meas.* 43, 471-475 (2008)

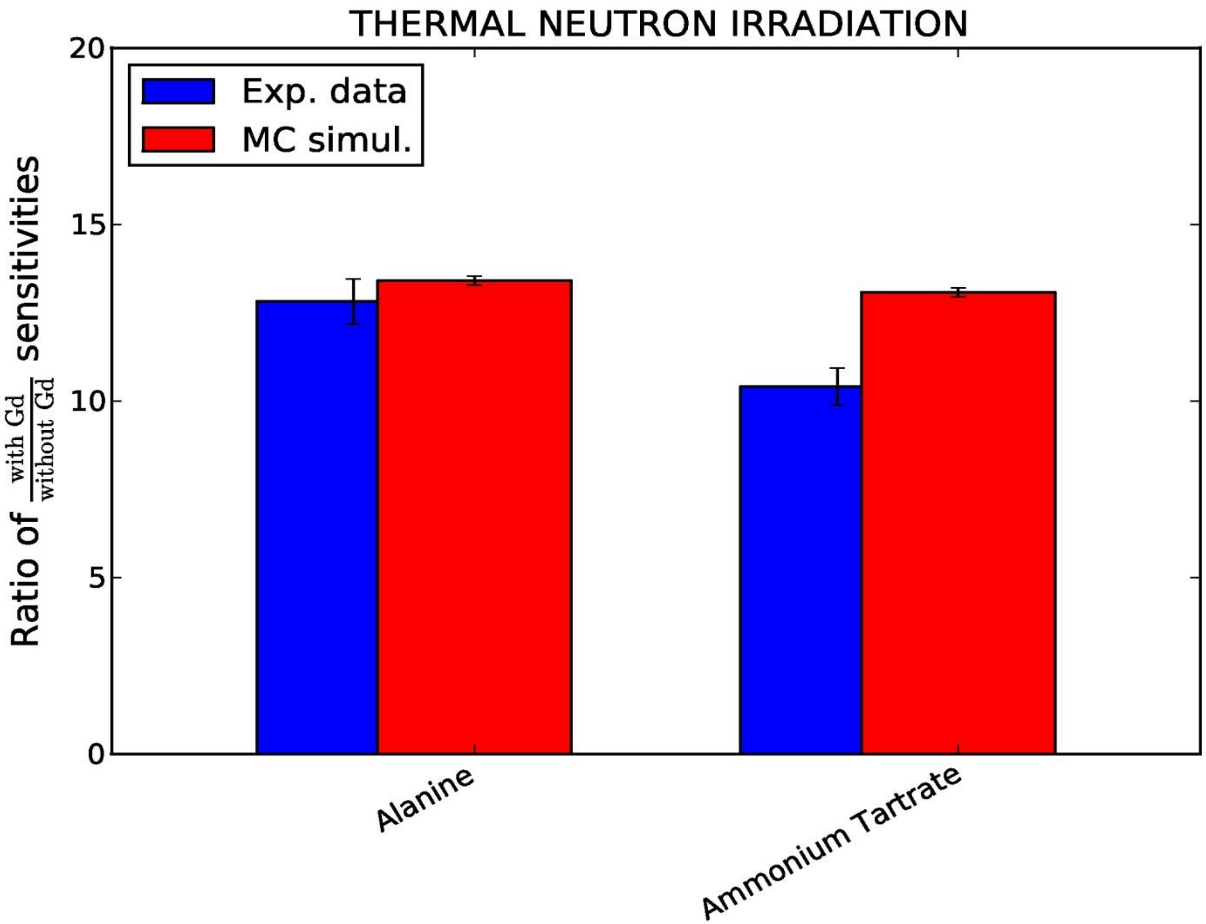
Experimental *vs* Simulation



Experimental *vs* Simulation



Experimental *vs* Simulation



Experimental *vs* Simulation