Microdosimetric modeling of the relative efficiency of luminescent detectors exposed to heavy charged particles

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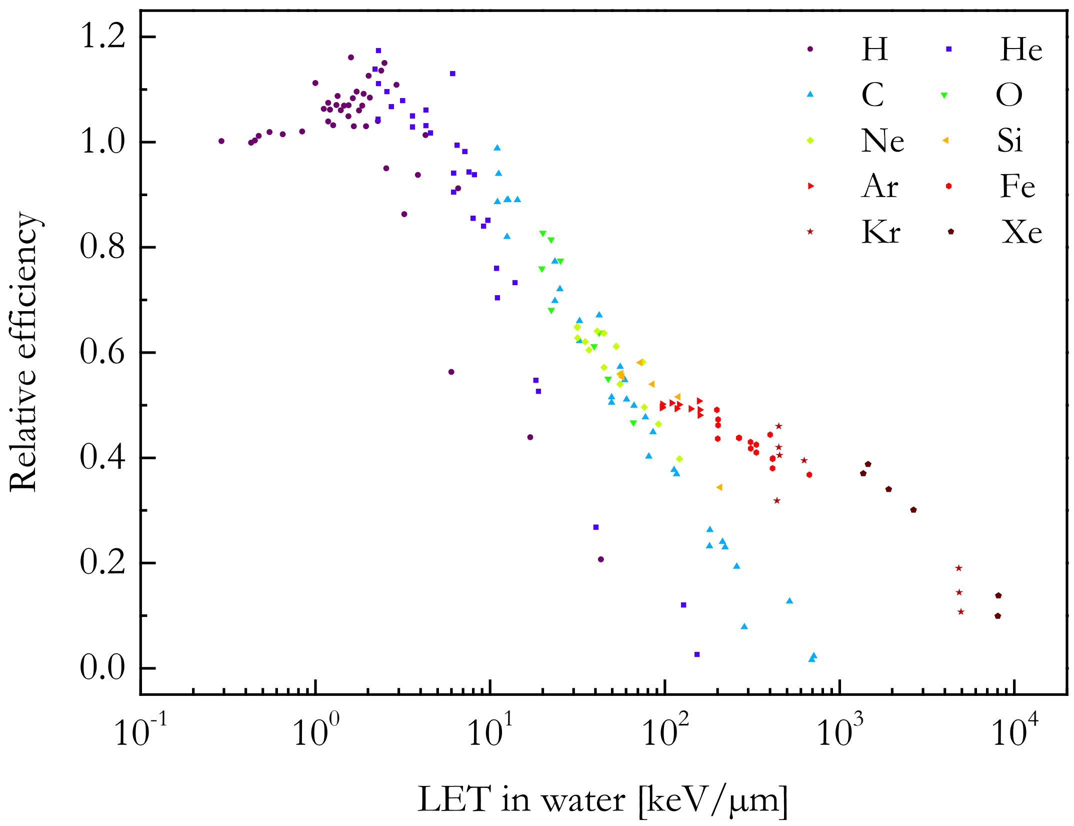
RADIATION PROTECTION DOSIMETRY AND CALIBRATION EXPERT GROUP

Introduction

- Luminescent detectors have been used in space since decades
- The space radiation environment is characterized by an extreme variety of particles (H – Fe ions, e, μ, π…) and energies
- A lot of effort has been spent on the experimental determination of the relative efficiency of these detectors through irradiations in calibrated heavy ion accelerators
- This process is time consuming and expensive

Experimental relative efficiency of LiF:Mg,Ti for various HCPs

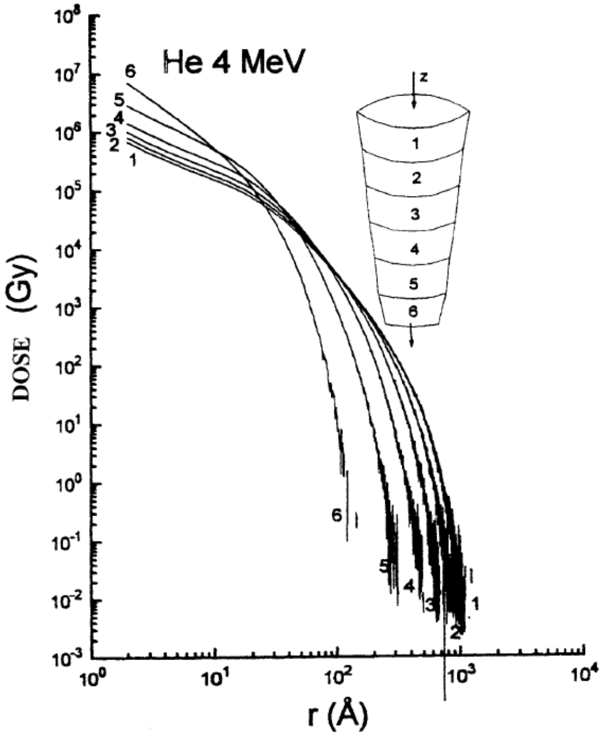


Data from Massillon-JL et al. 2007, Berger and Hajek 2008, Bilski and Puchalska 2010, Sądel et al. 2015

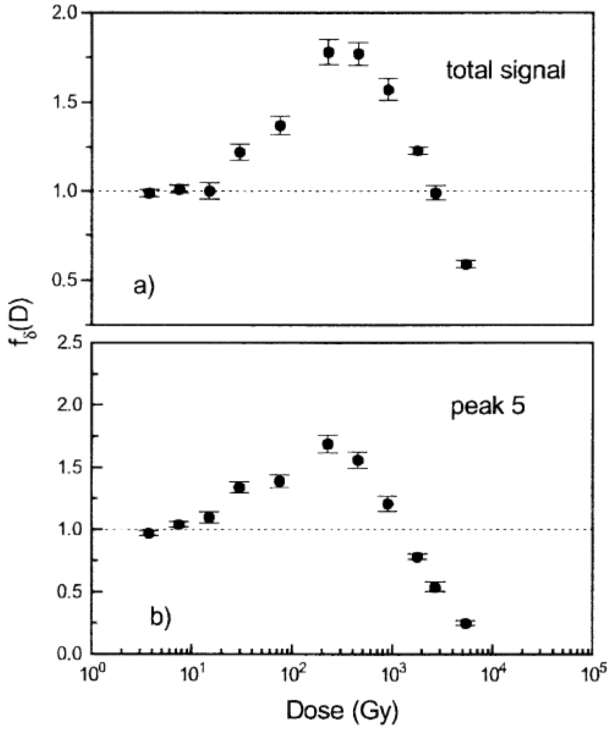
State of the art: modified track structure theory for thermoluminescent detectors

- Radial dose distribution *D(r)*
  - Analytical or Monte Carlo
- Dose response function *R(D)*
  - Gammas, X-rays, betas
- Slowing down considered
- Efficiency evaluated folding *R(D)* into *D(r)*

Radial dose distribution



Dose response LiF:Mg,Ti



$$\eta_{HCP,\gamma} = \eta_{\delta,\gamma} \frac{\bar{W}_\gamma \int_0^{R_{max}} \int_0^{r_{max}} f\delta(D) D(r,l,E) 2\pi \, dr \, dl}{\bar{W}_{HCP} \int_0^{R_{max}} \int_0^{r_{max}} D(r,l,E) 2\pi \, dr \, dl}$$

Figures from Horowitz et al. 2001

State of the art: Olko's microdosimetric model

	Model by Olko 2002	This work – Microdosimetric d(z) model
Particles	Z = 1-8	Z = 1-54
Max energy	20 MeV/u	1000 MeV/u
Target	H_2O, infinitesimal	LiF, thickness = 0.9 mm
Slowing down	Not considered	Considered

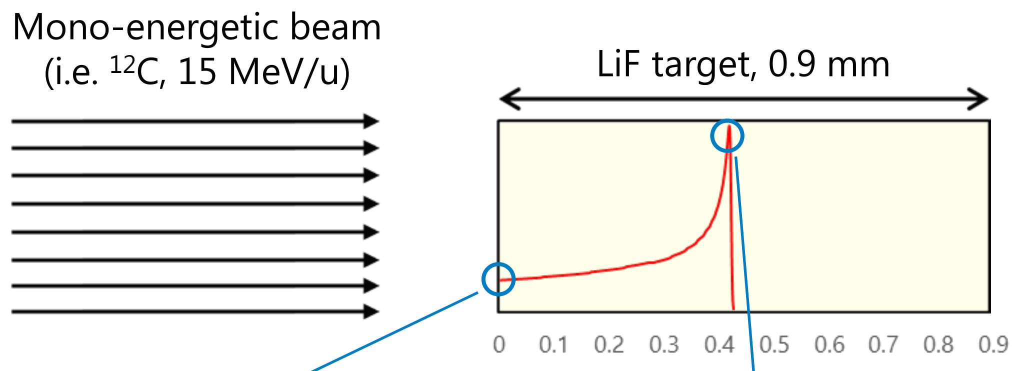
$$D(r) \rightarrow f(z) \qquad R(D) \rightarrow r(z)$$

$$z = microdosimetric\ specific\ energy$$

$$\eta_{HCP} = \frac{\left[\frac{1}{\overline{\overline{z}}_f}\int_0^{+\infty} f(z)\, r(z)\, dz\right]_{HCP}}{\left[\frac{1}{\overline{\overline{z}}_f}\int_0^{+\infty} f(z)\, r(z)\, dz\right]_{^{137}Cs}}$$

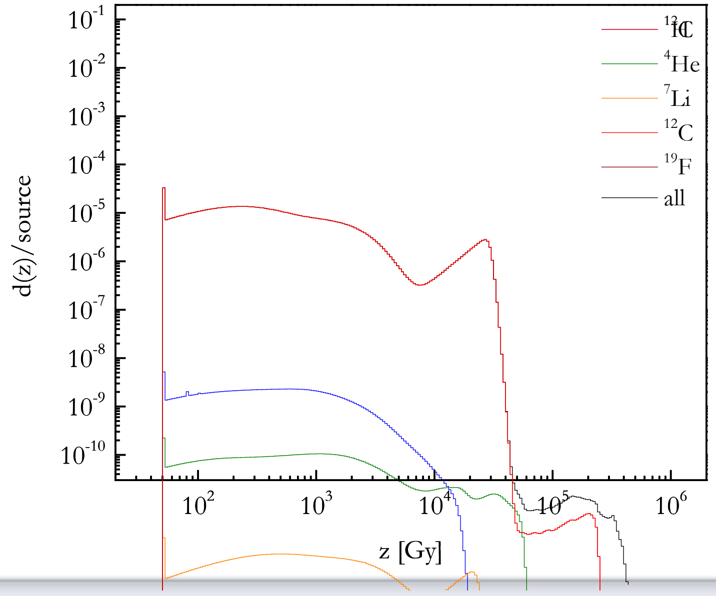
$$\eta_{HCP} = \frac{\left[\int_0^{+\infty} d(z)\, r(z)\, dz\right]_{HCP}}{\left[\int_0^{+\infty} d(z)\, r(z)\, dz\right]_{^{60}Co}}$$

Microdosimetric d(z) model – assessment of d(z) with PHITS



$$\int_0^{+\infty} d(z)\,dz = 1$$

Example for d = 40 nm



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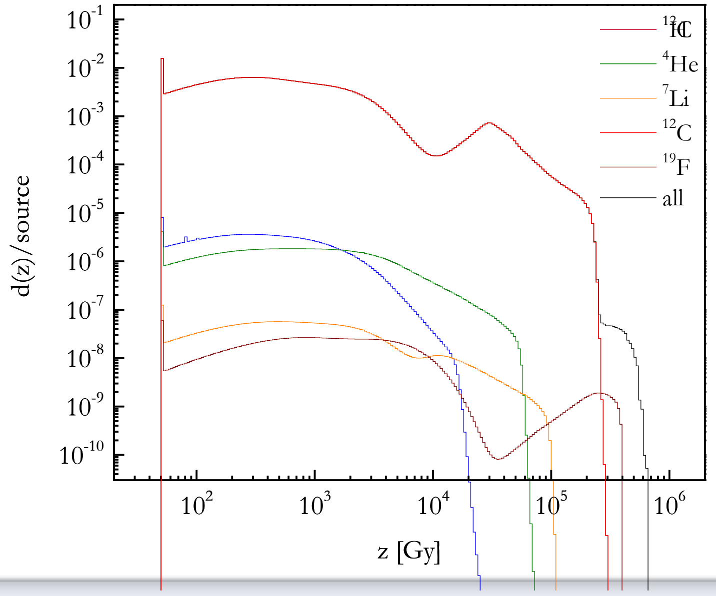

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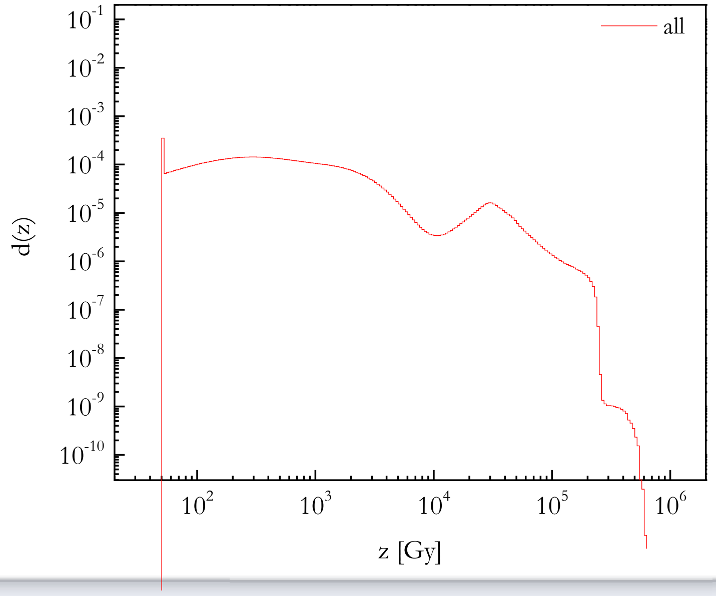
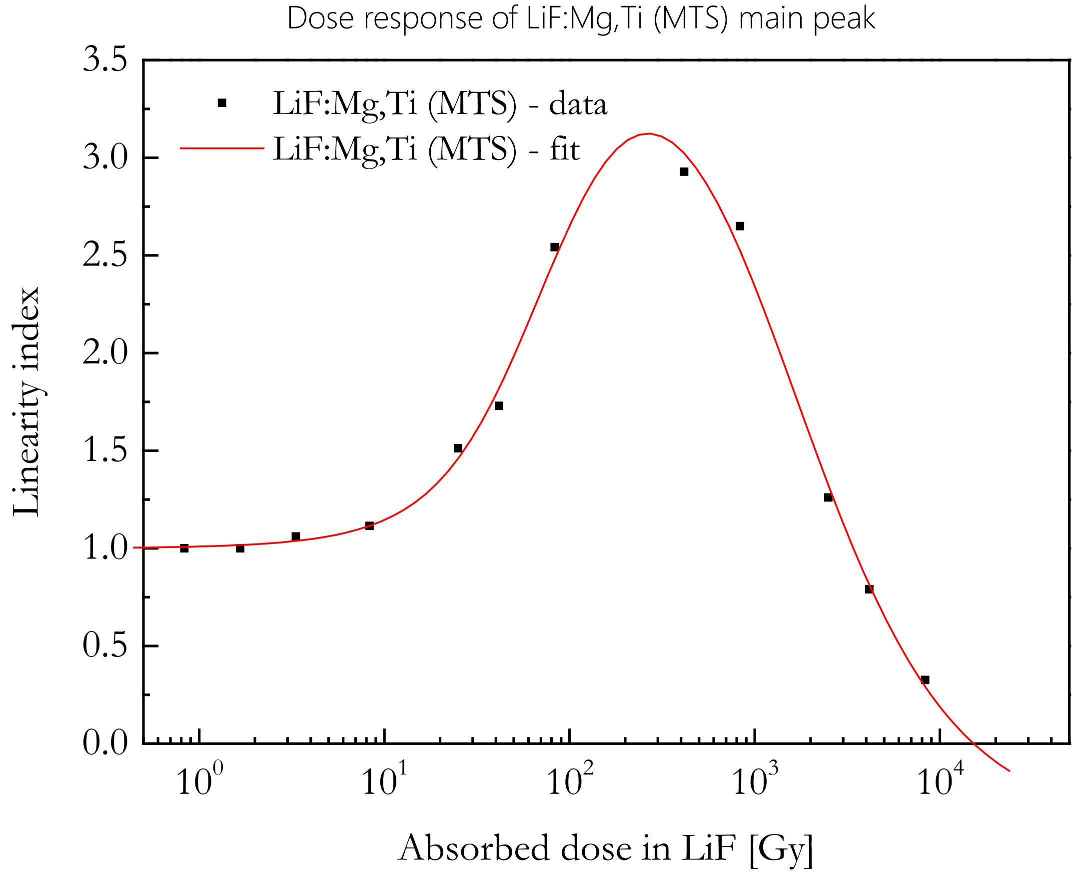


Microdosimetric d(z) model – assessment of r(z)



Data from Bilski et al. 2007

- Linearity index

$$linearity\ index = \frac{\left(\frac{light\ intensity}{dose}\right)_{dose}}{\left(\frac{light\ intensity}{dose}\right)_{reference}}$$

- Dose in water converted in dose in LiF
- As in Olko 2002, it has been assumed that the macroscopic dose response function *R(D)* can be applied as microdosimetric specific energy response function *r(z)*
- Differences with Olko 2002
  - Use of linearity index
  - Data relative to ^{60}Co gammas instead of ^{137}Cs

Microdosimetric d(z) model – assessment of the relative efficiency

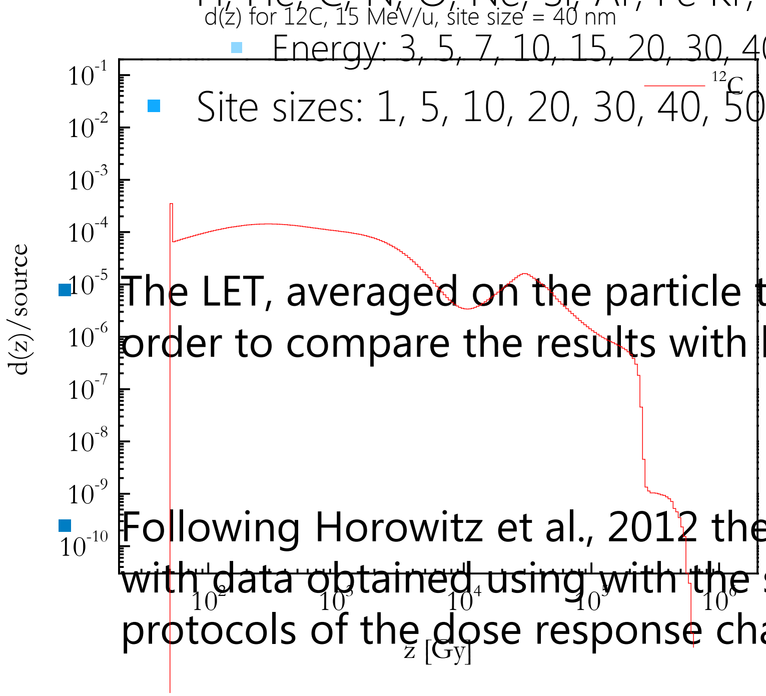
- Having determined d(z) and r(z), the relative efficiency can be evaluated as:

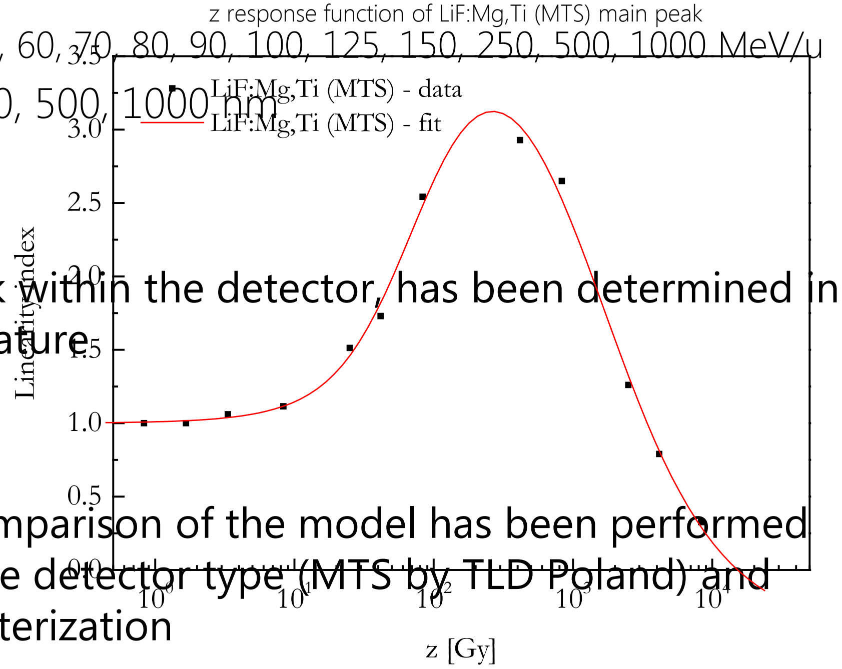
$$\eta_{HCP} = \frac{\left[\int_0^{+\infty} d(z)\, r(z)\, dz\right]_{HCP}}{\left[\int_0^{+\infty} d(z)\, r(z)\, dz\right]_{^{60}Co}}$$

- The procedure has been repeated for:
  - H, He, C, N, O, Ne, Si, Ar, Fe Kr, Xe
    - Energy: 3, 5, 7, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 100, 125, 150, 250, 500, 1000 MeV/u
  - Site sizes: 1, 5, 10, 20, 30, 40, 50, 100, 500, 1000 nm

- The LET, averaged on the particle track within the detector, has been determined in order to compare the results with literature

- Following Horowitz et al., 2012 the comparison of the model has been performed with data obtained using with the same detector type (MTS by TLD Poland) and protocols of the dose response characterization





↓

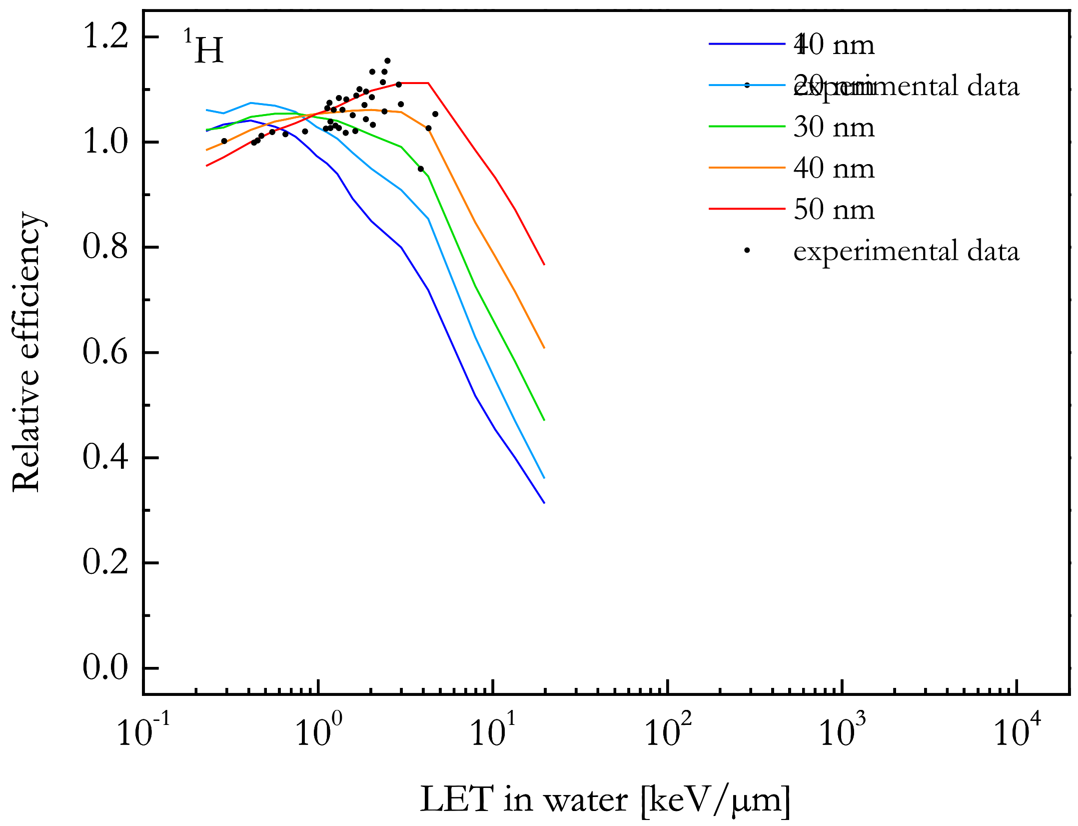
0.291

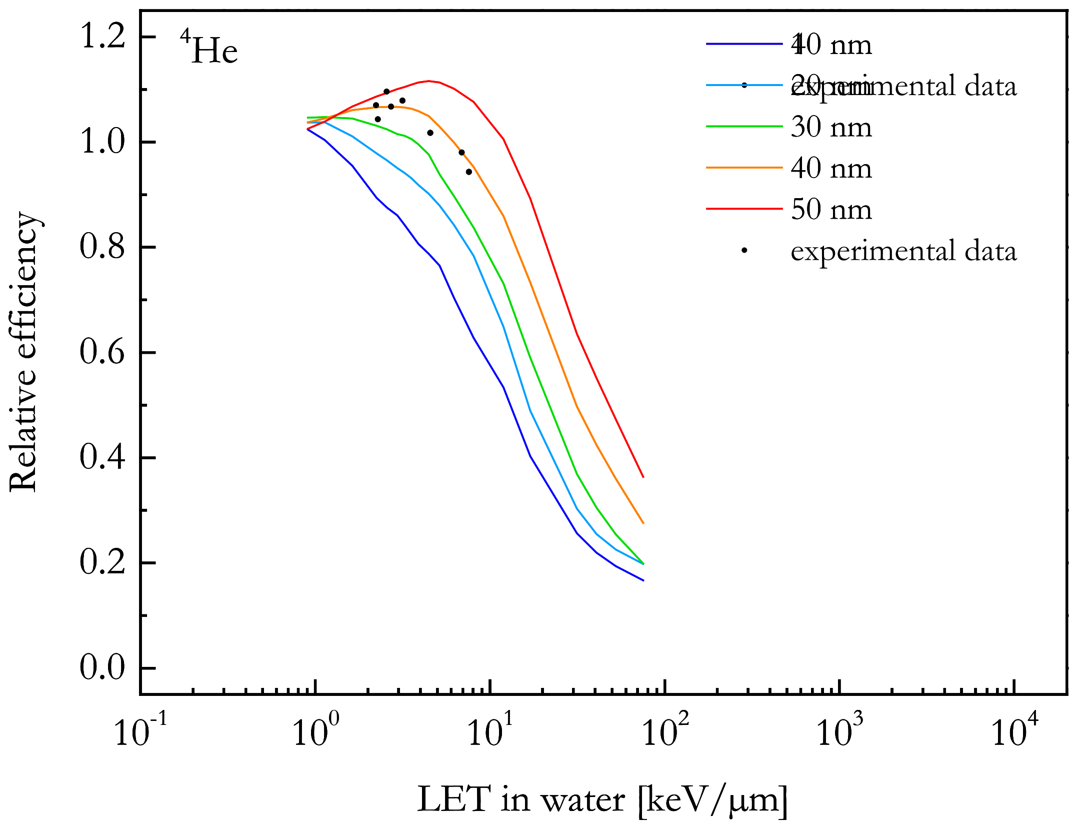
Relative efficiency for

^{12}C, $E = 15$ MeV/u

Site size = 40 nm

Microdosimetric d(z) model – LiF:Mg,Ti (MTS)





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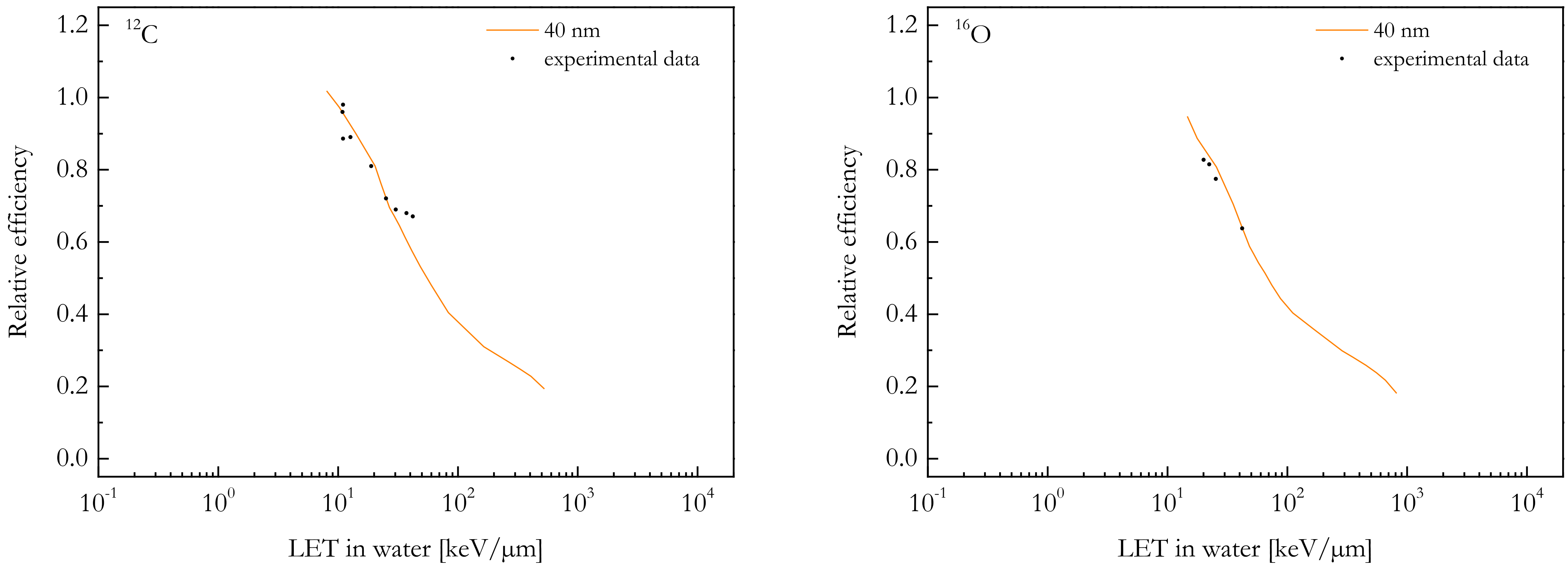

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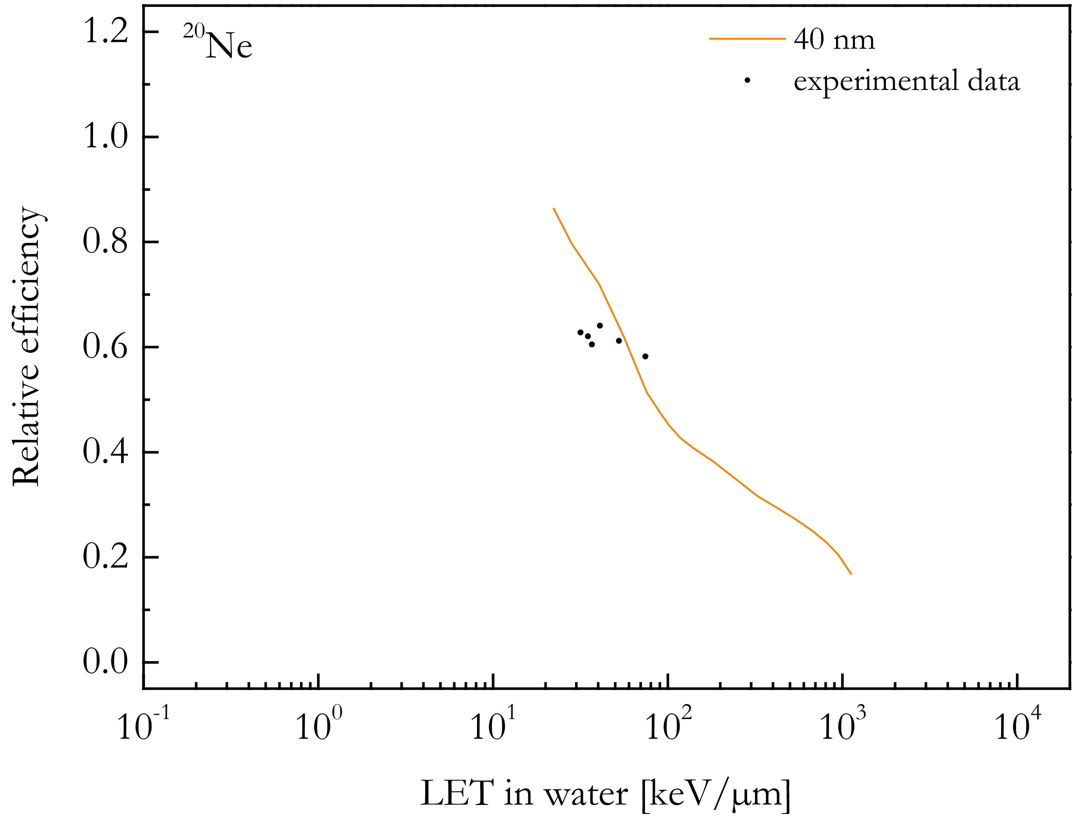

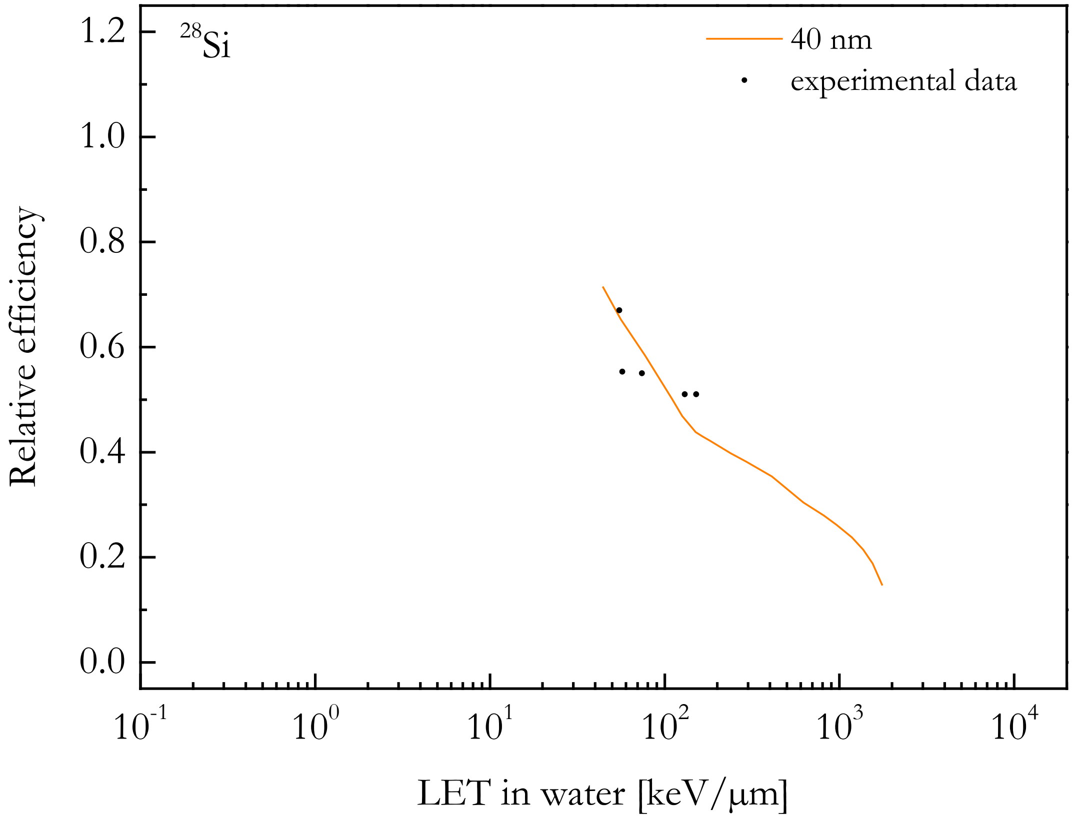

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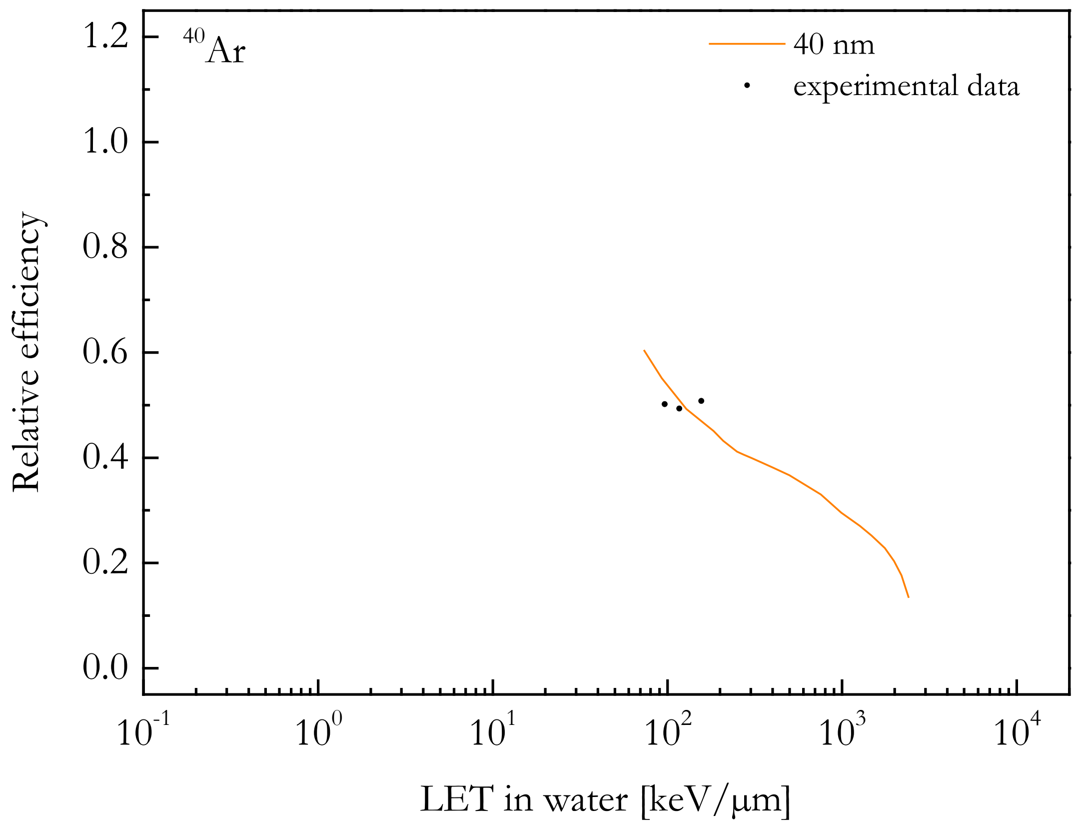

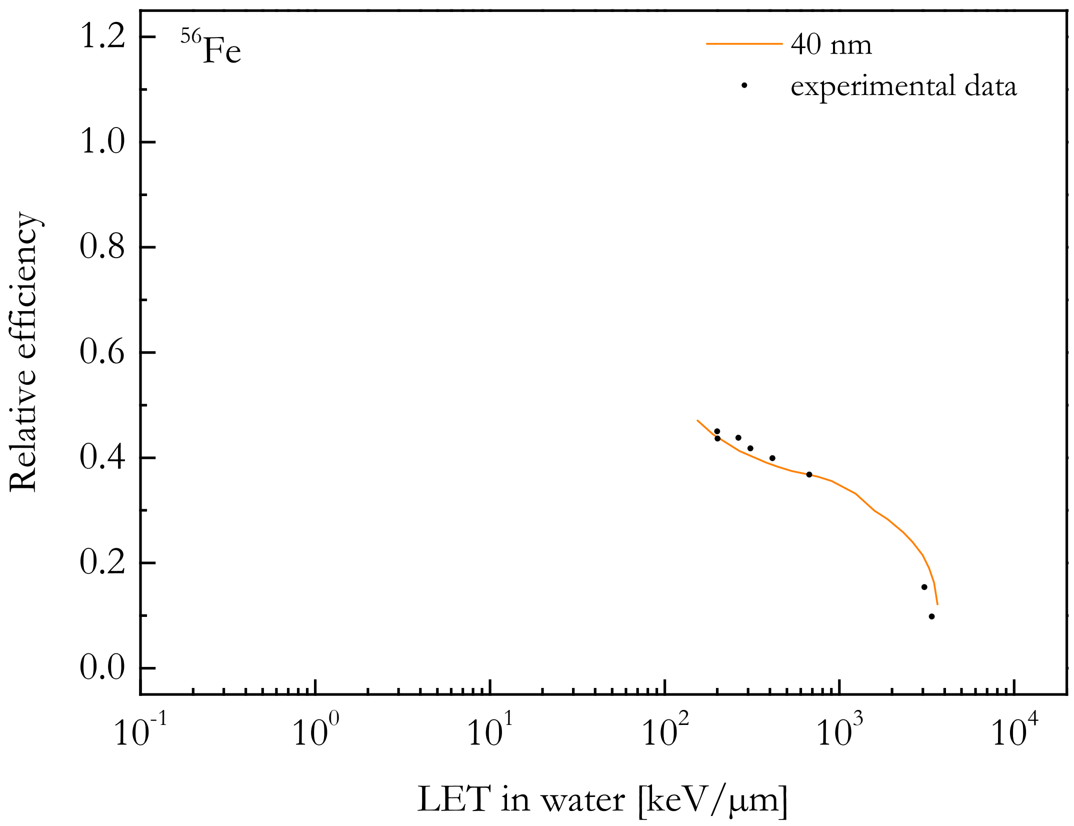

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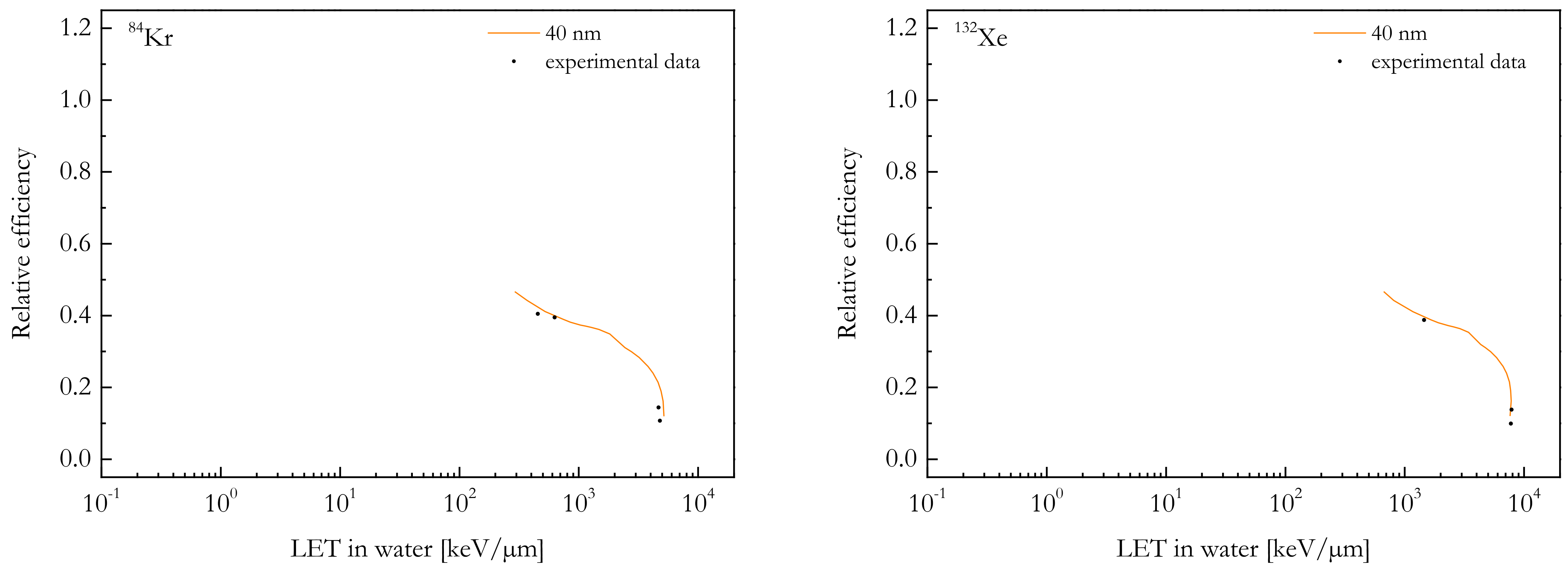

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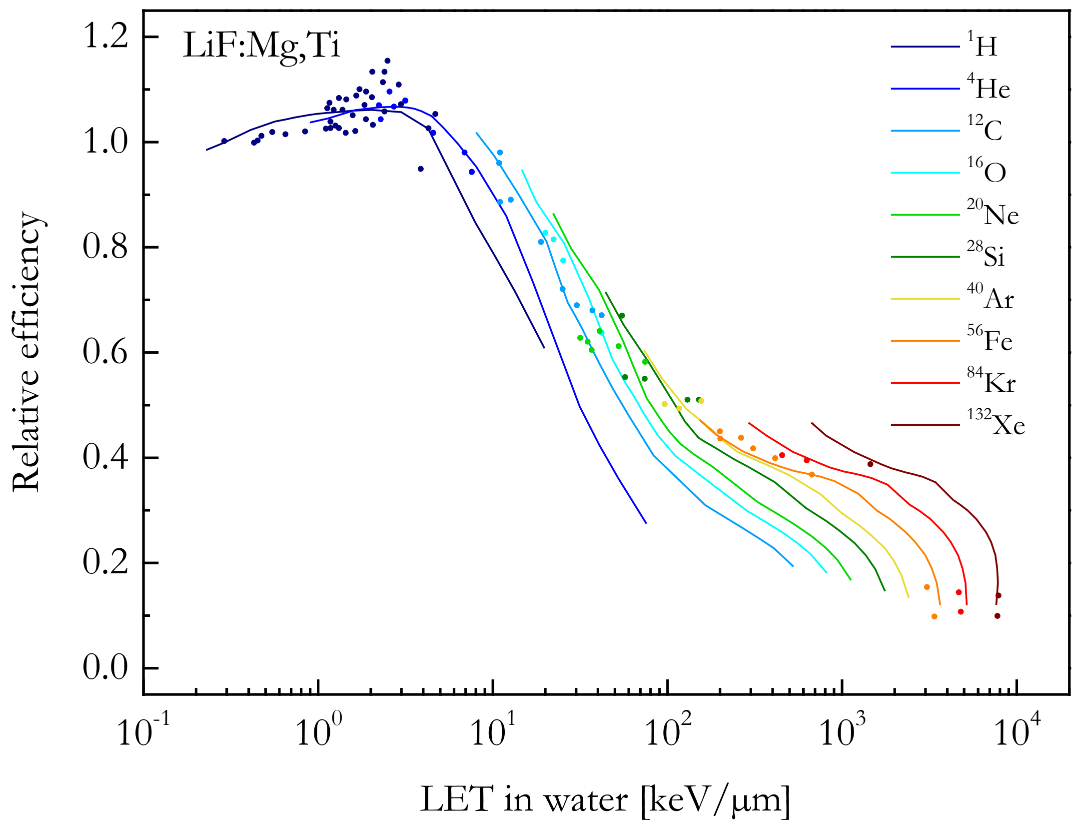


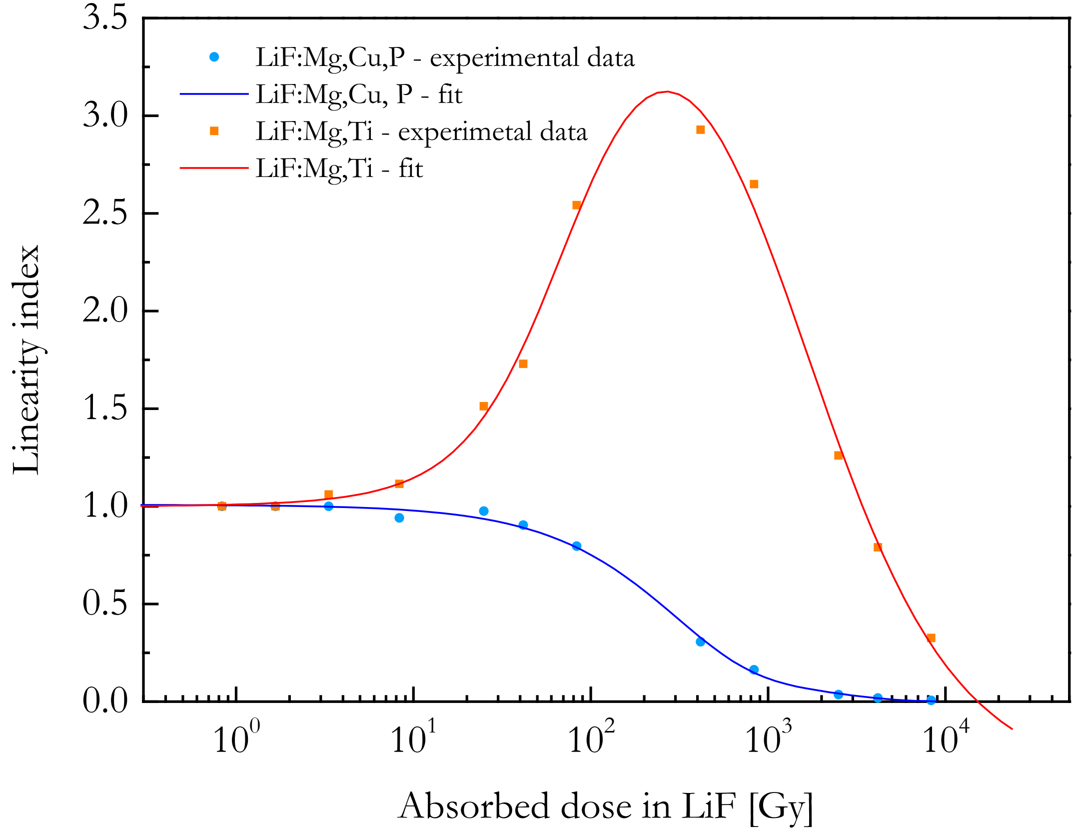
- In the case of 40 nm microdosimetric site size, the results of the model are in good agreement with the LiF:Mg,Ti (MTS) experimental data from IFJ for all particles and energies

- The model well describes the not unique LET dependence of the relative efficiency

Data from Bilski and Puchalska 2010, Bilski et al., 2011, Gieszczyk et al. 2013, Sądel et al. 2015

Microdosimetric d(z) model – LiF:Mg,Cu,P (MCP)

Dose response of LiF:Mg,Ti (MTS) and LiF:Mg,Cu,P (MCP) main peak



- Linearity index

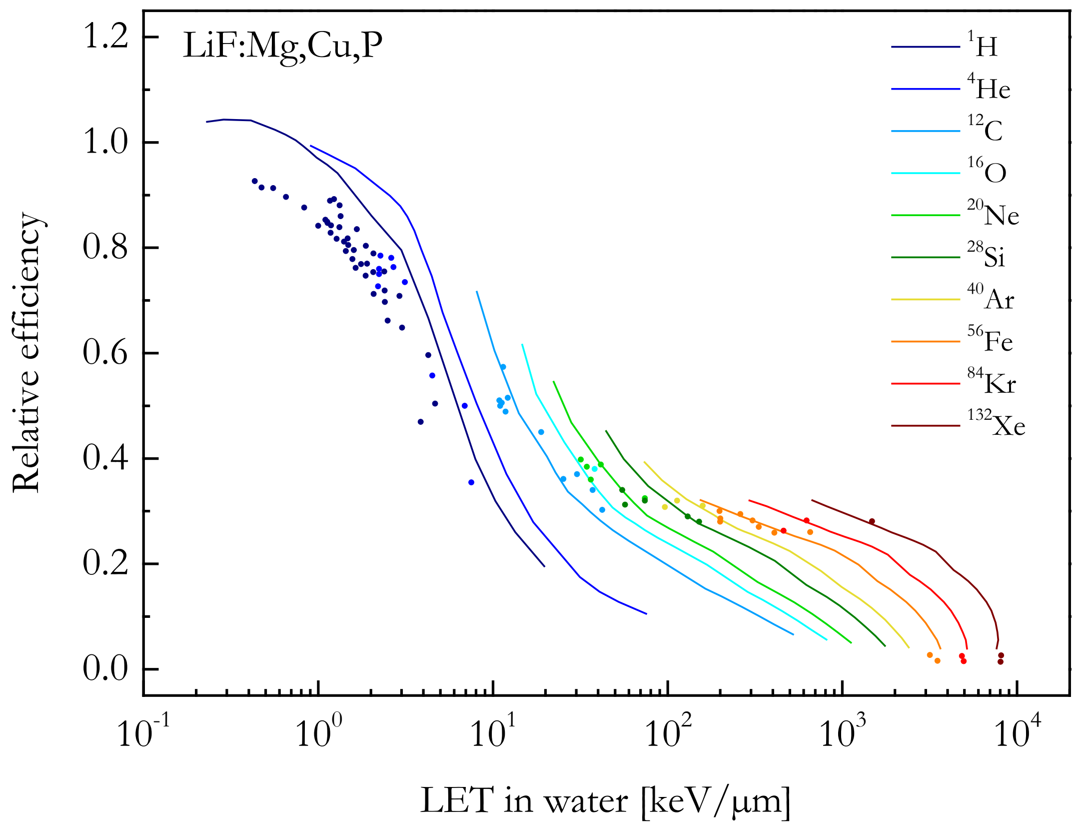
$$linearity\ index = \frac{\left(\frac{light\ intensity}{dose}\right)_{dose}}{\left(\frac{light\ intensity}{dose}\right)_{reference}}$$

- Dose in water converted in dose in LiF
- Same procedure as for LiF:Mg,Ti (MTS) detectors

Data from Bilski et al. 2007

Microdosimetric d(z) model – LiF:Mg,Cu,P (MCP)

PRELIMINARY RESULTS



- Also here very good agreement with experimental data in case of model calculations performed in a site size of 40 nm for all ions with the exceptions of ^{1}H and ^{4}He

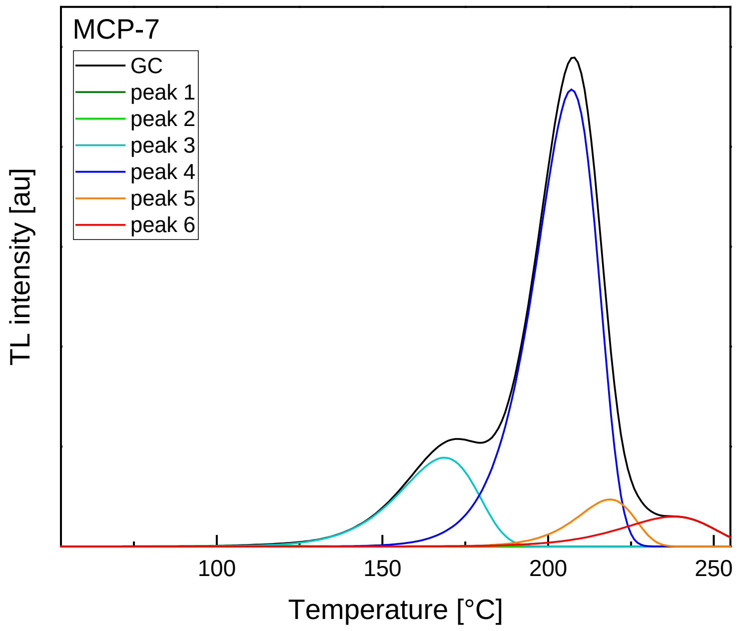
- However, for ^{1}H and ^{4}He ions an anomalous low temperature peak behavior has been reported (Parisi et al., 2017)

Data from Bilski and Puchalska 2010, Bilski et al., 2011, Gieszczyk et al. 2013, Sądel et al. 2015

LiF:Mg,Cu,P (MCP): a low temperature peak anomaly for ^{1}H and ^{4}He?

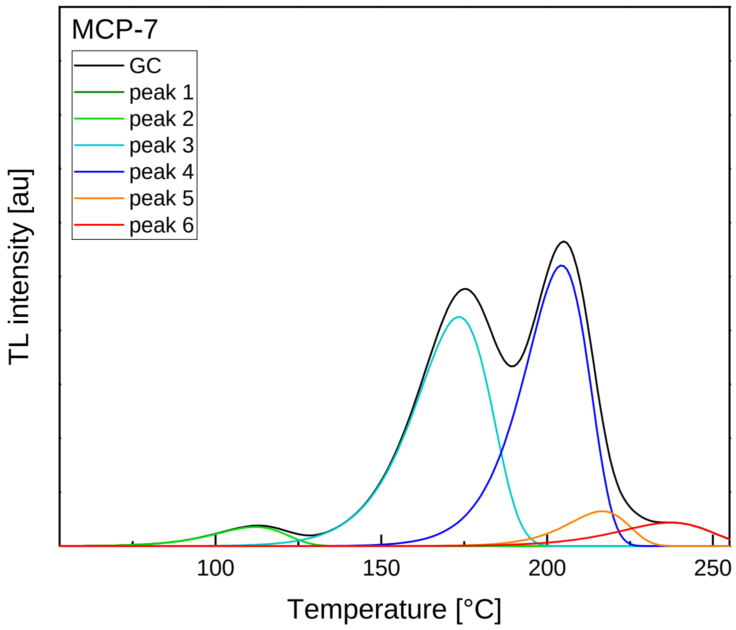
- HIMAC, He 150 MeV/u, LET = 2.2 keV/µm

2010: readout 38 days after irradiation
no pre-heat



$\eta = 0.73$

2016: readout 7 days after irradiation
no pre-heat



$\eta = 0.52$

- Bilski and Puchalska, 2010 (same detector, ion and energy)

$\eta = 0.77$

- Microdosimetric model

$\eta = 0.91$

Conclusions

- A microdosimetric model has been developed with PHITS starting from the work of Olko
  - Slightly different formalism, slowing down considered, particles from ^{1}H to ^{132}Xe, energy up to 1 GeV/u
- Very good agreement with IFJ data for LiF:Mg,Ti (MTS)
  - Model validation to be completed for LiF:Mg,Ti (MTT), LiF:Mg,Cu,P (MCP) and later Al_2O_3:C
- Next step: space radiation simulations to provide efficiency corrected dose values
  - For a specific DOSIS 3D mission, simulations of the space radiation field and its interaction with the ISS and the detectors inside it
  - Using the microdosimetric model the efficiency of the detectors can be determined
  - Comparison of the efficiency corrected dose values with the ones obtained combining luminescent detectors and TEDs

Thank you for your attention

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