UNIVERSITÀ DI PAVIA

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LIDAL: toward RBE monitoring

WRMISS: Workshop on Radiation Monitorning for the International Space Station

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A. Mentana[1],

I. Guardamagna[1], L. Lonati[1], V. Quaresima[1], L. Di Fino[2], G. Romoli[2], L. Narici[2], G. Guo[3], P. Kundrát[4], W. Friedland[5] and G. Baiocco[1]

[1]*Radiation Biophysics and Radiobiology Lab., Physics Department, University of Pavia, Italy*
[2]*Physics Department, University of Rome Tor Vergata and INFN-Roma2, Rome, Italy*
[3]*School of Earth and Space Science, University of Science and Technology of China, Hefei, China*
[4]*Department of Radiation Dosimetry, Nuclear Physics Institute, Czech Academy of Sciences, Prague, Czech Republic*
[5]*Institute of Radiation Medicine, Helmholtz Zentrum München-German Research Center for Environmental Health, Neuherberg, Germany*

Our goal: quantitative evaluation of biological effects/damage induced by exposure to ionizing radiation in a specific radiation environment, here the ISS

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essential information for an improved risk assessment and for the subsequent development of countermeasures to protect astronauts during manned missions

Outline

- RBE monitoring on the ISS: how and why
- 1. from Space: energy spectra
  - neutrons
  - protons
- 2. from modelling: RBE evaluation on ISS
  - neutrons
  - protons
- Summary and conclusions

RBE monitoring on the ISS

How?

Combining two elements:

1. « Space information » on radiation environment: radiation qualities present and their fluxes as a function of the energy or LET (to be converted into physical dose)

   → experimental measurements: **LIDAL detector**
   → simulations (this work)

2. evaluation of biological effectiveness of different radiation qualities (dependence on energy, LET) & for different targets (organs/tissues of interest, i.e. as vs. depth)

   → **RBE model** through analytical functions of energy or LET describing a variety of radiation-induced DNA damage types **(*)**. (*real time monitorning*!)

↓

RBE for a given DNA damage type of a specific radiation quality characteristic of ISS radiation environment

(*) P. Kundrát et al., *Sci Rep* 10, 15775 (2020) & P. Kundrát et al., *Front Phys* 9, 719682 (2021)

RBE monitoring on the ISS

Why RBE?

LET alone is not sufficient to give an indication of biological effectiveness (overkilling phenomenon)

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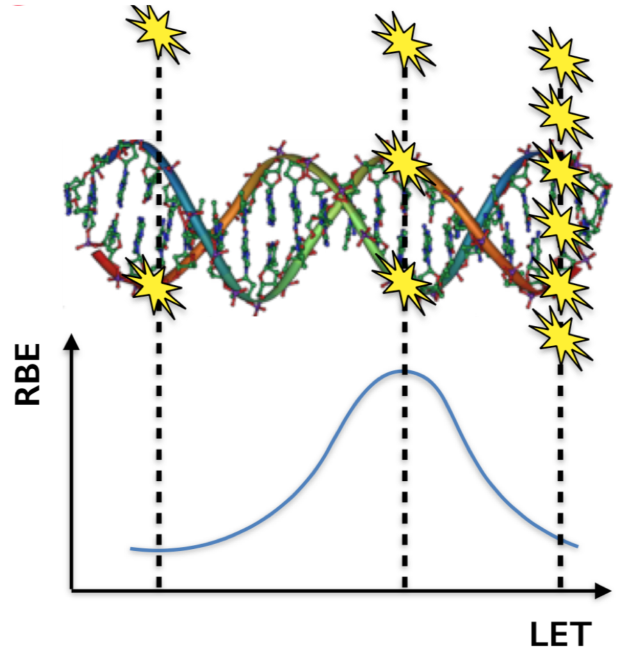
$$\boxed{RBE = \frac{D_{ref}}{D_{test}} \text{ at equal biological effect}}$$



→ example: RBE for the induction of DSB clusters (complex DNA damage), as «representative» of radiation weighting factors (radiation protection), to convert the physical dose into RBE-weighted dose (equivalent dose).

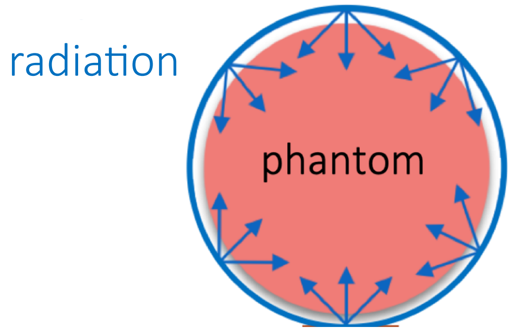
1. from Space: energy spectra

Information on Space radiation:

→ **Experimental data** collected by LIDAL detector on the Columbus module, which will provide a characterization of the ISS radiation environment in terms of identification of radiation components (charged particles/ions present) and energy (or LET) spectra of each of them.

→ GEANT4 **simulations (*)** (this work) to reproduce the particle spectra inside the Columbus module (courtesy of Daniel Matthiä)

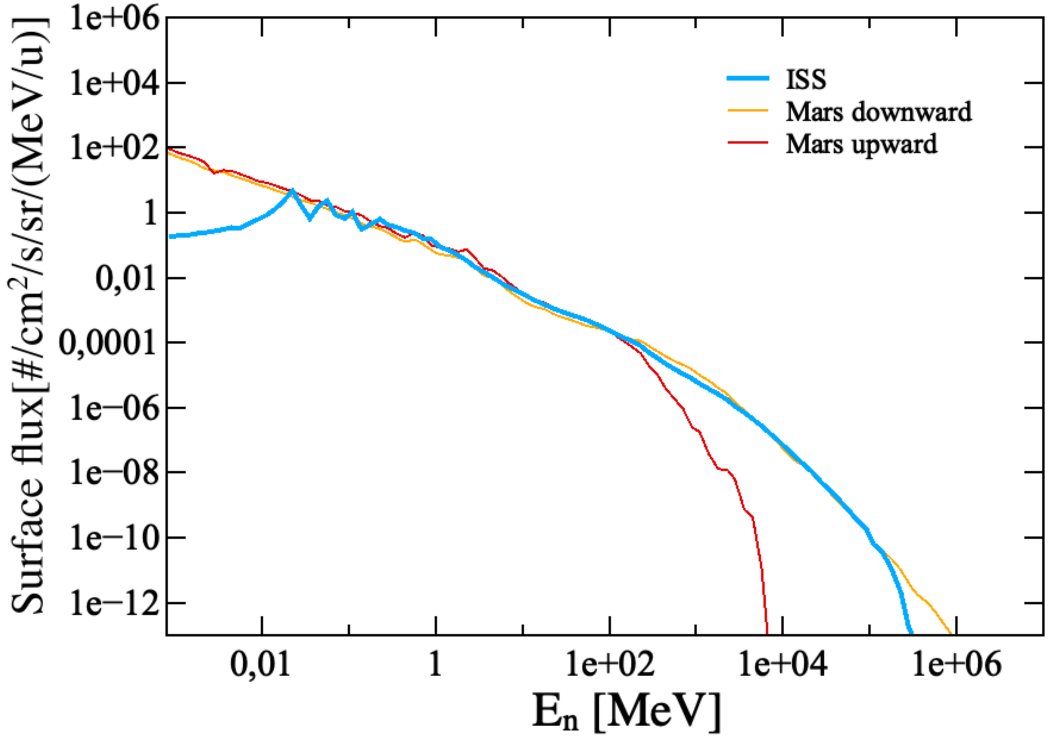
Modelling radiation interaction with a human body (ISS case):

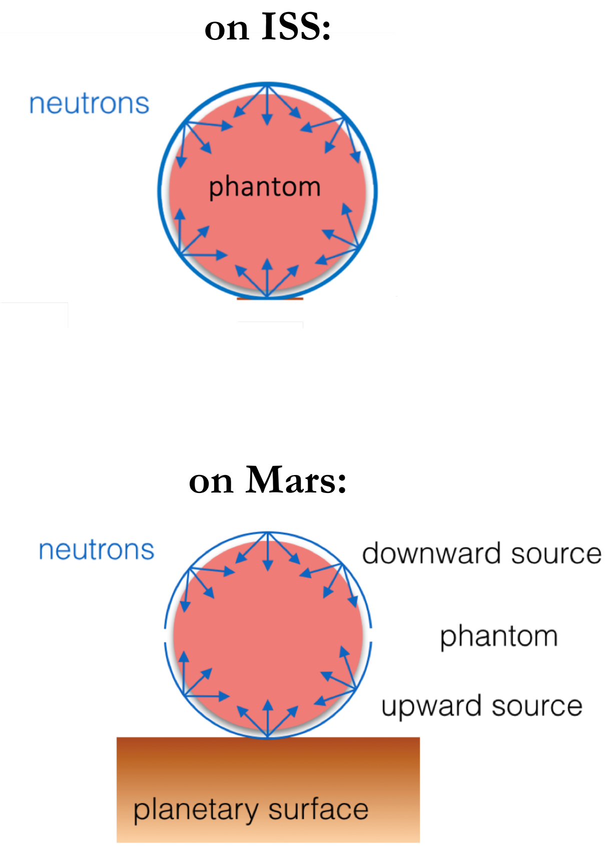


(*) T. Berger et al., *J. Space Weather Space Clim.* 10 (2020)

1. from Space: energy spectra

Neutron energy spectrum on the ISS, inside Columbus module, and on Mars:

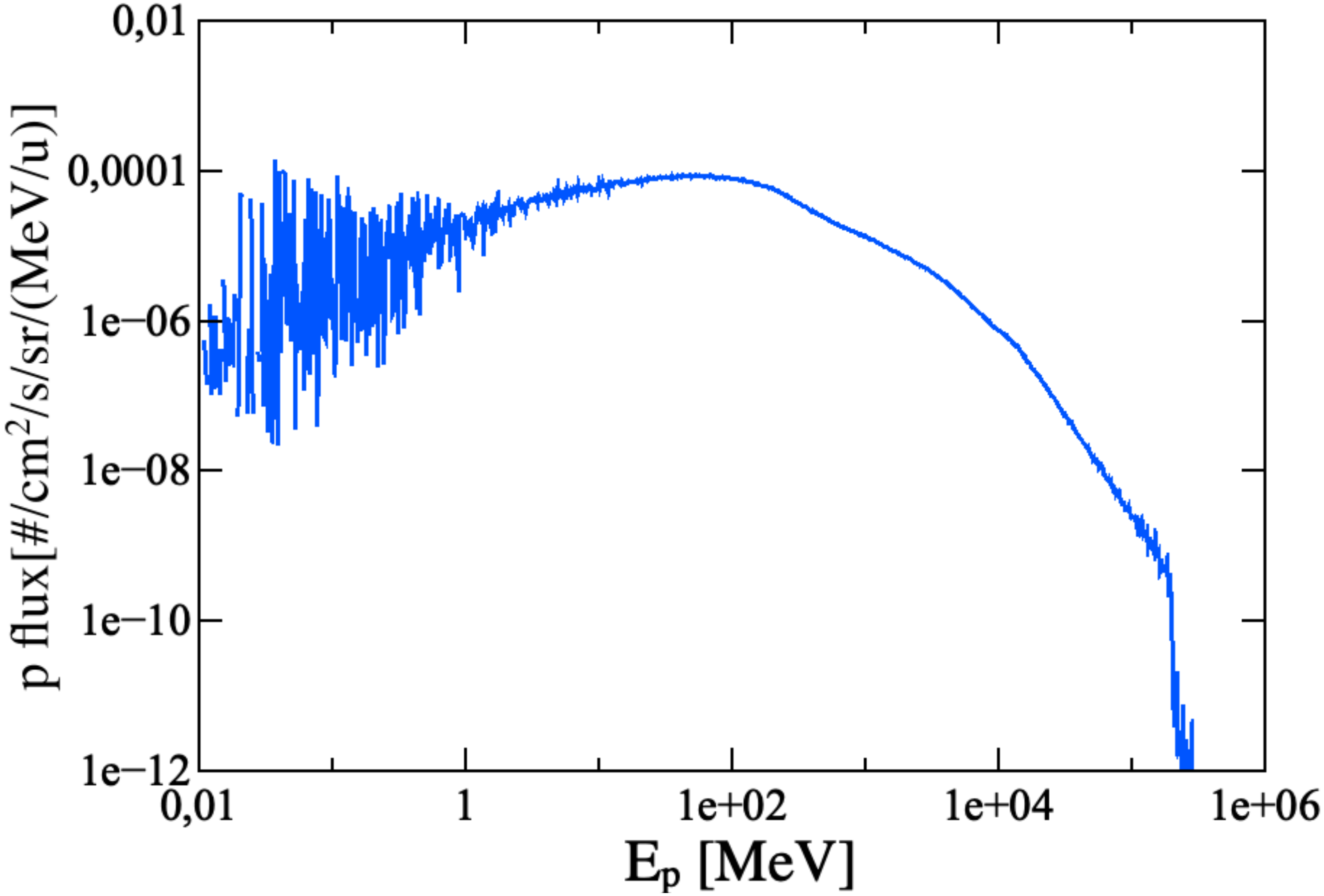




ISS: GEANT4 simulations (courtesy of Daniel Matthiä)
Mars: GEANT4/AtRIS simulations of n-flux due to GCR

1. from Space: energy spectra

Proton energy spectrum on ISS, inside Columbus module:

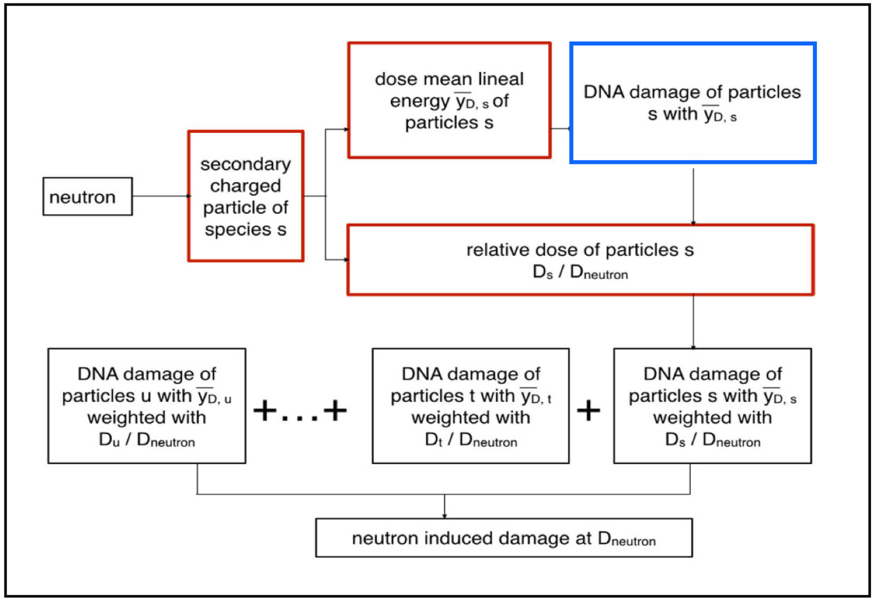


GEANT4 simulations (courtesy of Daniel Matthiä)

2. from modelling: n-RBE

Neutrons represent a major issue for radiation protection and for the estimate of associated healt-risks and their biological effectiveness varies a lot with their energy

→ *Ab-initio* model to evaluate neutron RBE for DNA damage induction **(DSB clusters)** as a function of neutron energy and depth inside the body



*G. Baiocco et al., ***Sci Rep*** 6, 34033 (2016)

coupling of two different simulation approaches (different spatial scales):

→ **from PHITS simulations:**
- Dose
- $\overline{y_D}$ (~LET in cell nucleus)

of each secondary spcies

→ **from analytical functions of LET:**
- DNA damage

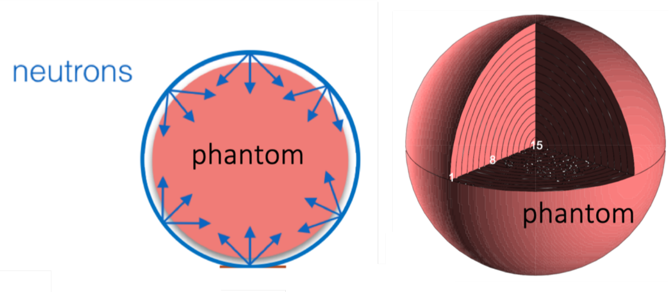
of each secondary species

$$\Rightarrow \quad \text{n-RBE} = \frac{\text{neutron induced damage at Dneutron}}{\text{low}-\text{LET radiation induced damage at Dneutron}} = \frac{\text{Yield}_n}{\text{Yield}_{\text{low}-\text{LET}}}$$

2. from modelling: n-RBE

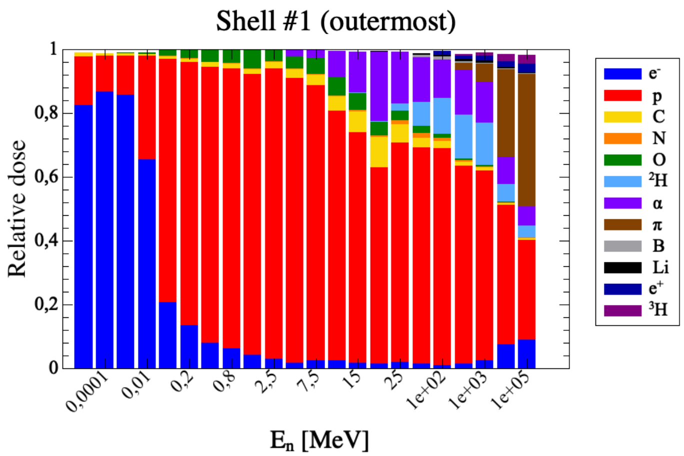
→ from PHITS simulations (v. 3.22)

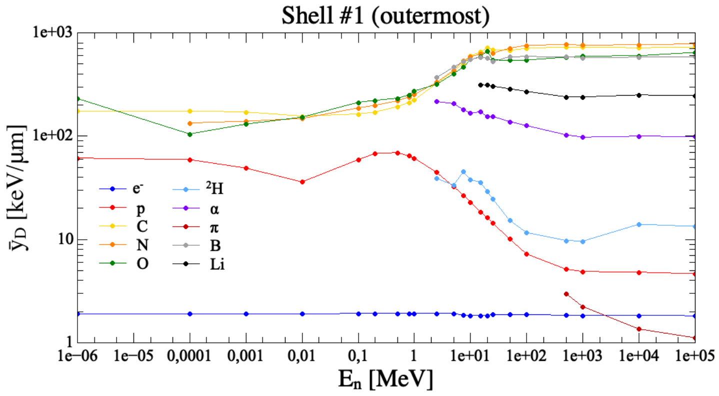
Isotropic flux of monoenergetic neutrons...
E_n: 10^{-6} - 10^5 MeV



…on an ICRU44 spherical phantom (R=15cm), divided into 15 isocentric shells

For each shell: dose relative contribution, D_s, and dose mean lineal energy, $\overline{y_{D,s}}$, of each secondary species s of the neutron-induced mixed field **as a function of E_n**





*A. Mentana et al., *in preparation*

2. from modelling: n-RBE

→ from analytical functions of the LET in cell nucleus (PARTRAC)

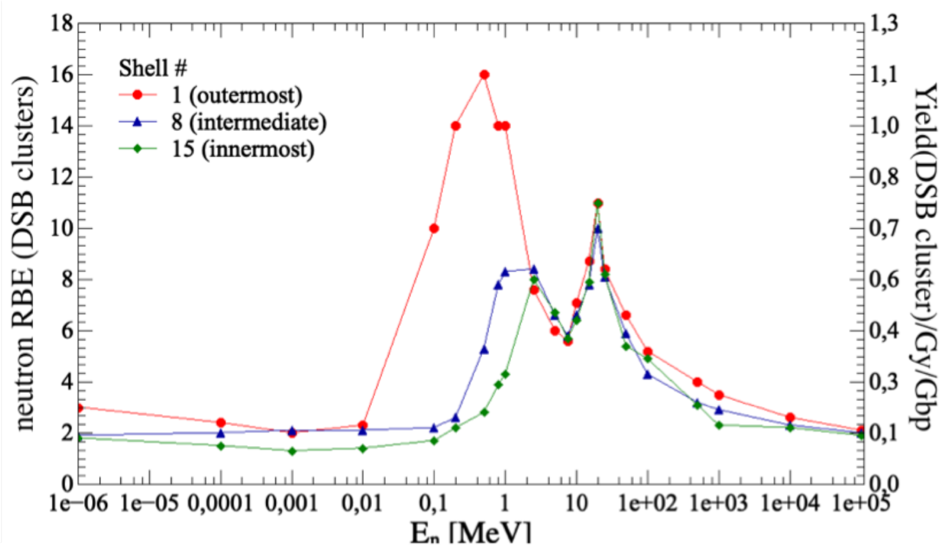
Estimate of DNA damage yield, **clusters of DSB**:

(*) $$\text{Yield}_s[/\text{Gy}/\text{Gbp}] = \frac{(p_1 + (p_2\,\text{LET}_s)^{p_3}}{(1 + (p_4\,\text{LET}_s)^{p_5}}$$

p_1-p_5 : damage and radiation dependent parameters

→ $\text{Yield}_n = \sum_s (\text{Ds}/\text{Dneutron})\text{Yields}$

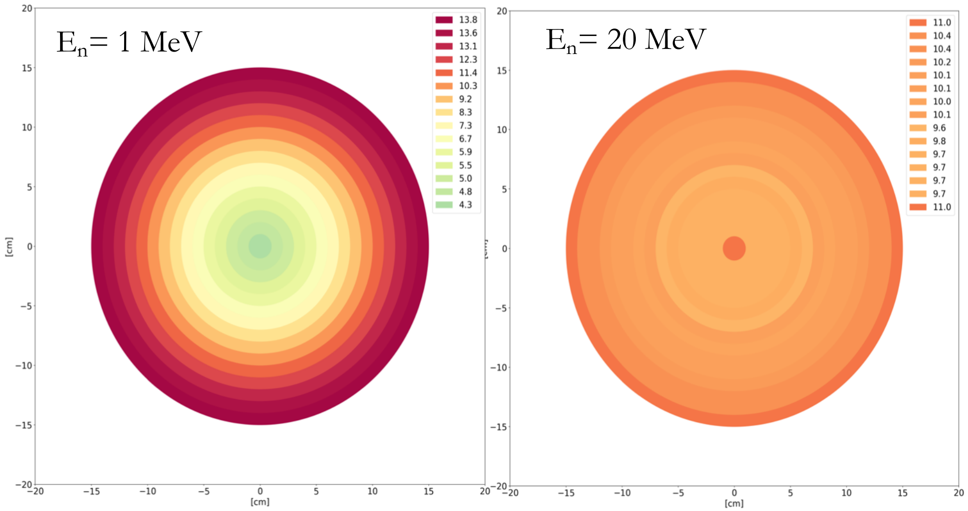
→ $$\text{n-RBE} = \frac{\text{Yield}_n}{\text{Yield}_{\text{low-LET}}} = \frac{\text{Yield}_n}{p_1}$$



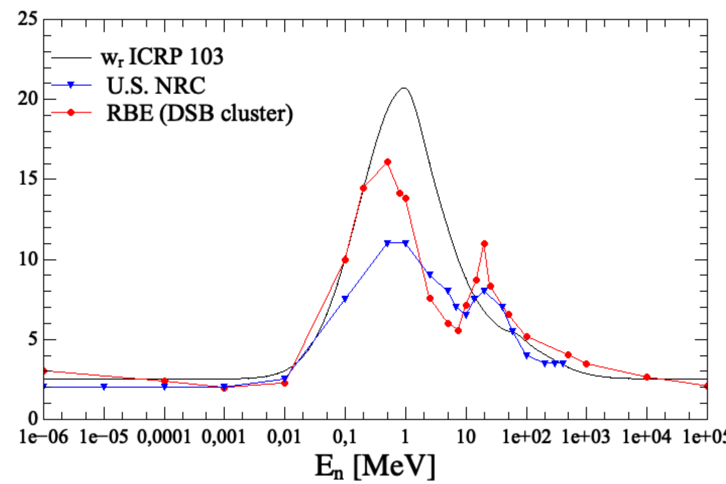
(*) P. Kundrát et al., *Sci Rep* 10, 15775 (2020)

2. from modelling: n-RBE

n-RBE for the induction of DSB clusters:



→ successful qualitative comparison with current standards for n-weighting factors



Application: in combination with a definite neutron flux spectum → neutron RBE for a specific neutron environment

2. from modelling: n-RBE on the ISS

...combining the *ab-initio* n-RBE model to the (simulated) neutron flux on the ISS

calculation scheme:

n-flux on the ISS * n-dose due to monoenergetic neutrons

GEANT4 simulations

from the model

n-dose spectrum on the ISS * **n-RBE vs E_n**

n-RBE on the ISS

n-RBE:

→ vs. E_n

→ vs. depth in the phantom

to be matched with different organs

e.g.:

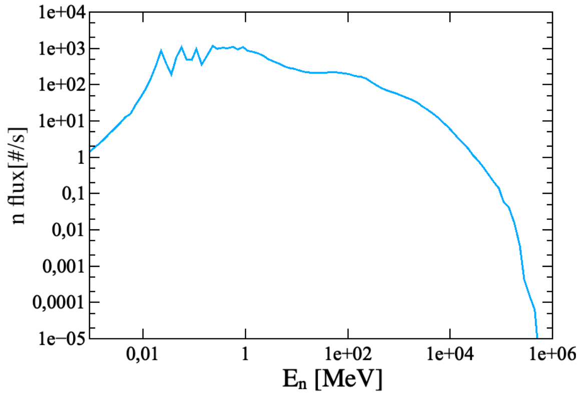
shell 1 (outermost) ⟷ breast

shell 15 (innermost) ⟷ heart-wall

2. from modelling: n-RBE on the ISS

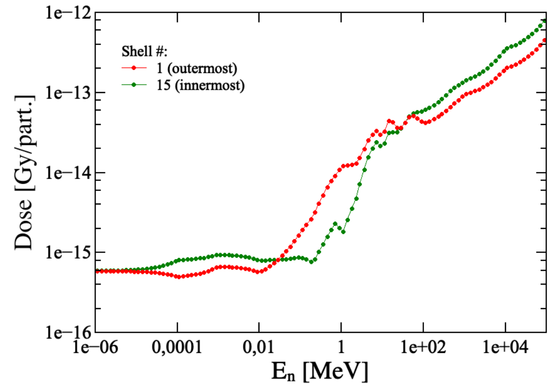
Neutron flux [part./s] on the ISS

GEANT4 simulations

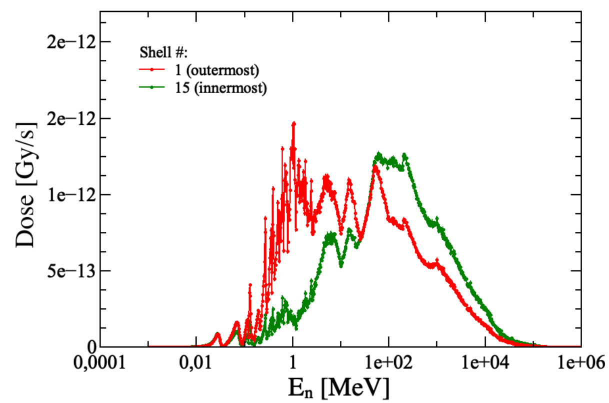


*

Neutron dose [Gy/part.] due to monoenergetic neutrons



PHITS simulations (*ab-initio* model)



integrated n-dose rate onboard the ISS
shell #1: 9 μGy/day
shell #15: 8 μGy/day

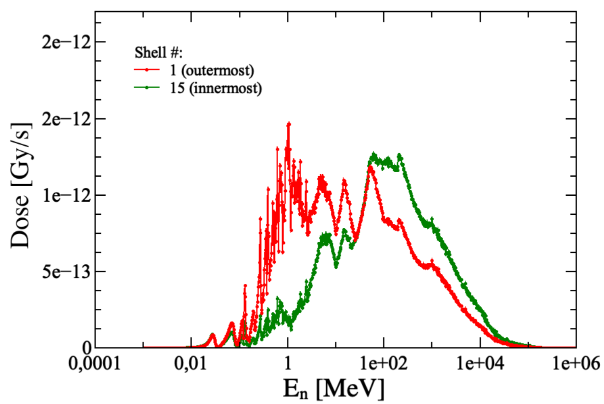
Preliminary

Neutron dose [Gy/s] on the ISS

2. from modelling: n-RBE on the ISS

Neutron dose [Gy/s] on the ISS

Neutron RBE vs. E_n



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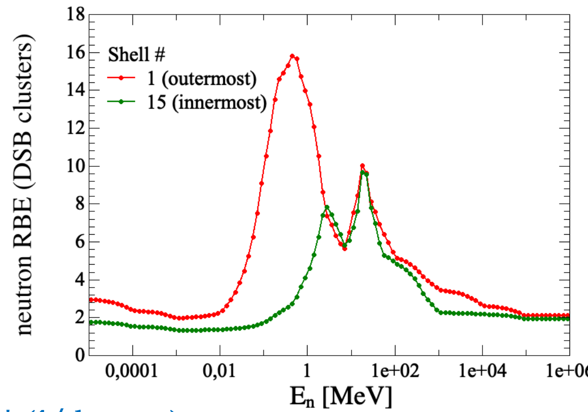
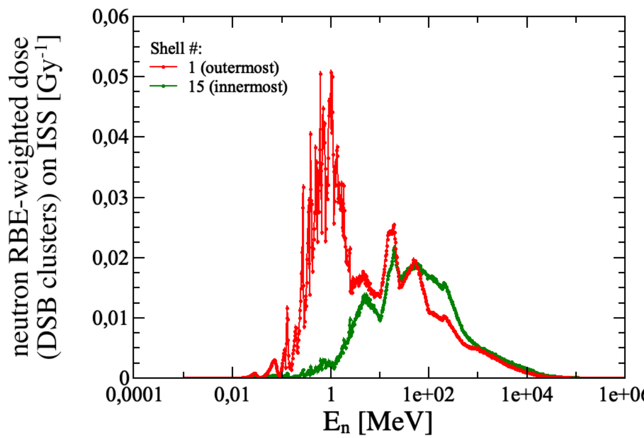


PHITS simulations (*ab-initio* model)

* (1/dose$_{n,tot}$)



n-RBE onboard the ISS
shell #1: 7.8
shell #15: 4.7

Neutron RBE on the ISS

2. from modelling: n-RBE on the ISS & Mars

Preliminary

ISS

→ integrated neutron dose rate
shell #1: 9 μGy/day
shell #15: 8 μGy/day

→ n-RBE
shell #1: 7.8
shell #15: 4.7

Mars

→ integrated neutron dose rate
shell #1: 14 μGy/day
shell #15: 12 μGy/day

→ n-RBE
shell #1: 7.5
shell #15: 4.7

Can we establish a shell-organ correlation?

For the Martian scenario, the correlations:

shell 1 (outermost) ↔ breast & shell 15 (innermost) ↔ heart-wall

have been tested, comparing our model dose results with dose calculated using «fluence-to-dose» conversion coefficients, D_T/Φ, for a specific organ (from ICRP 103).

↓

Despite its simplicity, our phantom is **representative of the human body for the organs tested**

2. from modelling: p-RBE on the ISS

Several approaches can be used to estimate the RBE on the ISS of charged particles (**here protons**):

→ «full» Monte Carlo: *Ab-initio* model (analogous to the neutron case): p-RBE for DSB clusters induction as a function of proton energy and depth inside the body

→ Monte Carlo + analytical: p-RBE from analytical functions of E_p/LET_p + dose from simulation of the interaction of ISS proton energy spectrum with the phantom

→ «full» analytical: p-RBE from analytical functions of E_p + dose from «fluence-to-dose» conversion coefficients (ICRP 103)

2. from modelling: p-RBE on the ISS

Several approaches can be used to estimate the RBE on the ISS of charged particles (**here protons**):

→ «full» Monte Carlo: *Ab-initio* model (analogous to the neutron case): p-RBE for DSB clusters induction as a function of proton energy and depth inside the body

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→ «full» analytical: p-RBE from analytical functions of E_p + dose from «fluence-to-dose» conversion coefficients (ICRP 103)

2. from modelling: p-RBE

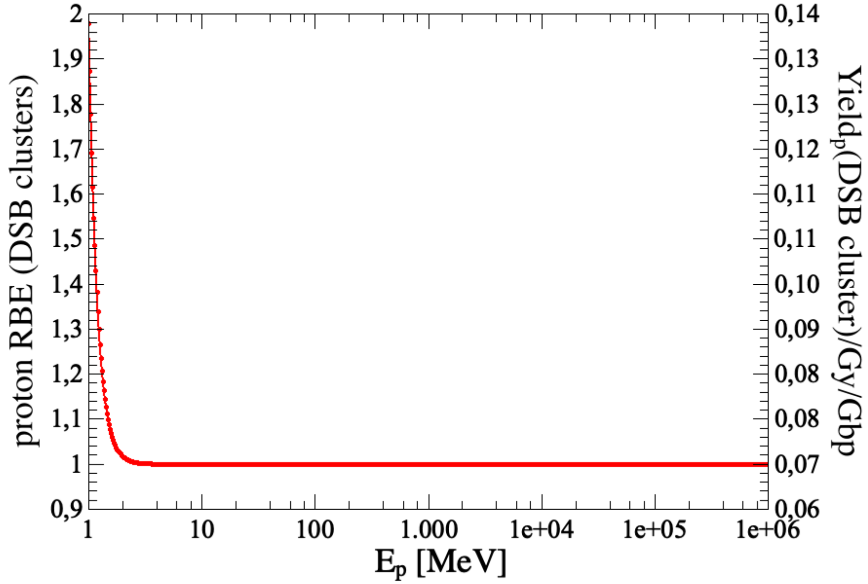
→ from analytical functions of the proton energy (PARTRAC)

Estimate of DNA damage yield, **clusters of DSB**:

$$^{(*)}\ \mathrm{Yield}_p\ [/\mathrm{Gy}/\mathrm{Gbp}] = p_1 + \frac{p_2}{1 + (\,Ep\ \exp(p_3))^{p_4}}$$

p_1-p_4 : damage and radiation dependent parameters

→ $$\text{p-RBE} = \frac{\mathrm{Yield}_p}{\mathrm{Yield}_{\mathrm{low-LET}}} = \frac{\mathrm{Yield}_p}{p_1}$$

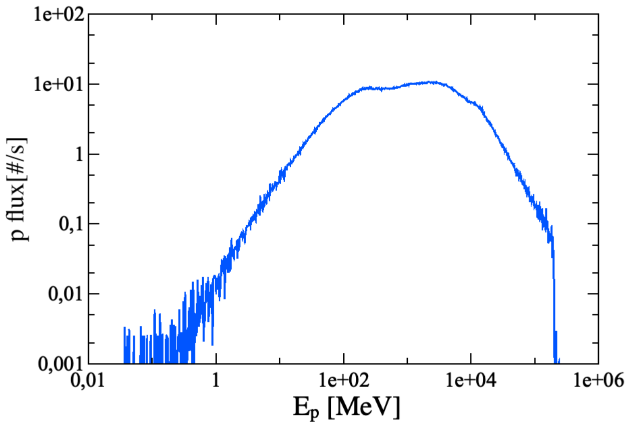


(*) **P. Kundrát et al., *Front Phys* 9, 719682 (2021)**

2. from modelling: on the ISS

Proton flux [part./s] on the ISS

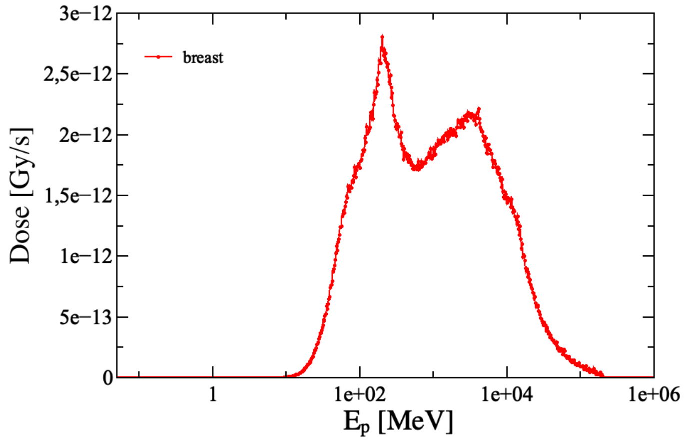
GEANT4 simulations



*

«fluence-to-dose» conversion coefficients, D_T/Φ, in energy bins for a specific organ **(breast)**

from ICRP 103

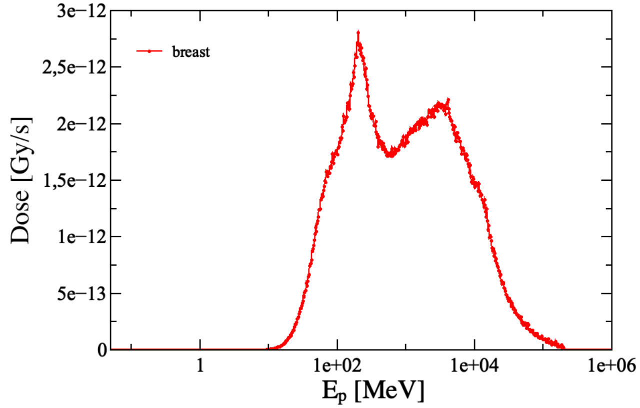


Proton dose [Gy/s] on the ISS

integrated p-dose rate onboard the ISS
breast: 51 μGy/day

2. from modelling: n-RBE on the ISS

Proton dose [Gy/s] on the ISS



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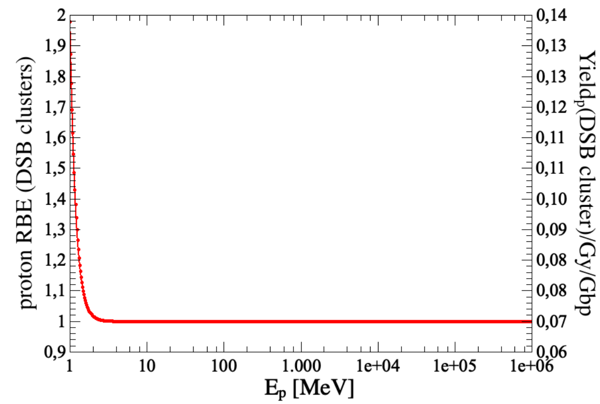
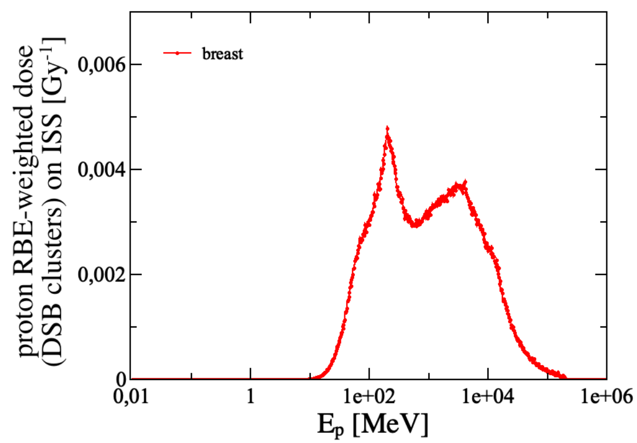
Proton RBE vs. E_p



(model)

* $(1/\text{dose}_{n,tot})$



Proton RBE on the ISS

p-RBE onboard the ISS
breast: 1

Summary and conclusions

We aim at monitoring the biological effects/damage induced by exposure to ionizing radiation on the ISS

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estimate of radiation RBE for chosen DNA damage type characteristic of the ISS environment starting from:

1. experimental data/simulations of energy(/LET) spectra of the different radiation components

2. RBE models:
   - **neutrons:** «*ab-initio*» model of RBE as a function of the energy and the depth inside the body (strong energy dependence of n-RBE)
   - charged particles (**protons**): p-RBE from analytical functions of E_p + dose from «fluence-to-dose» conversion coefficients (ICRP 103)
     → «ready-to-use» solution among several possibilities in view of potential real-time radiation monitoring

Summary and conclusions

We aim at monitoring the biological effects/damage induced by exposure to ionizing radiation on the ISS

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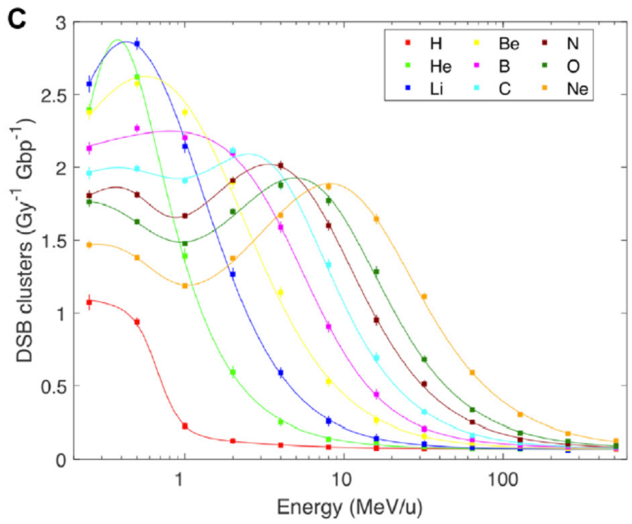
estimate of radiation RBE for chosen DNA damage type characteristic of the ISS environment starting from:

1. experimental data/simulations of energy(/LET) spectra of the different radiation components

2. RBE models:
   - **charged particles:** RBE from analytical functions are available till Ne, under development for heavier species



(*) P. Kundrát et al., *Front Phys* 9, 719682 (2021)

thank you for your attention!

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[1]Radiation Biophysics and Radiobiology Lab., Physics Department, University of Pavia, Italy
[2]Physics Department, University of Rome Tor Vergata and INFN-Roma2, Rome, Italy
[3]School of Earth and Space Science, University of Science and Technology of China, Hefei, China
[4]Department of Radiation Dosimetry, Nuclear Physics Institute, Czech Academy of Sciences, Prague, Czech Republic
[5]Institute of Radiation Medicine, Helmholtz Zentrum München-German Research Center for Environmental Health, Neuherberg, Germany