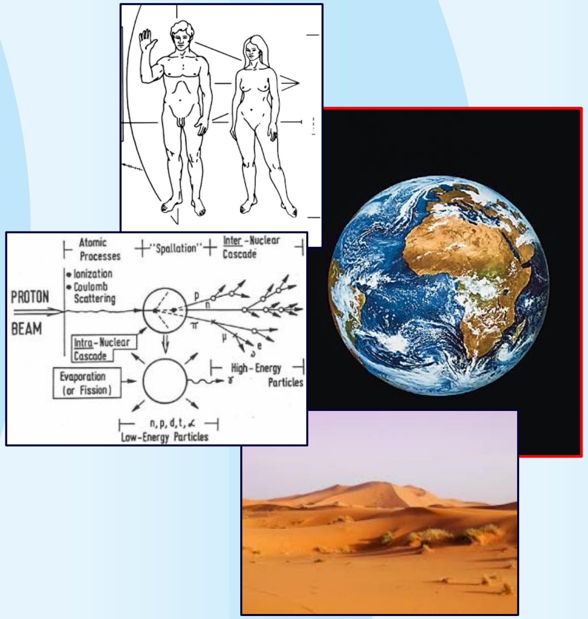
7-8 JULY 2025 - JOINT IAEA–CONSULTATIVE COMMITTEE FOR IONIZING RADIATION WORKSHOP ON NEUTRON BEAMS AT HIGH ENERGY: APPLICATIONS AND METROLOGY



EURADOS TASK ON IMPROVING THE DESCRIPTION OF NUCLEAR REACTIONS BETWEEN NUCLEONS AND LIGHT NUCLEI, NOTABLY ^{12}C, ^{14}N AND ^{16}O

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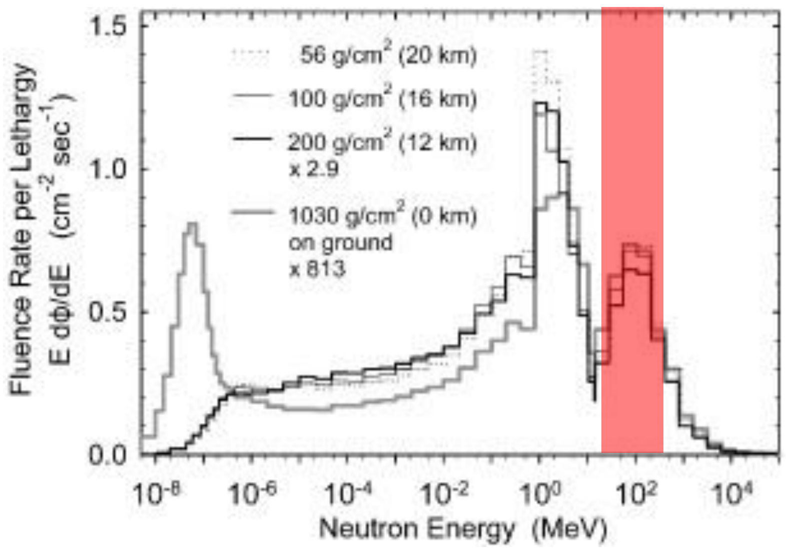
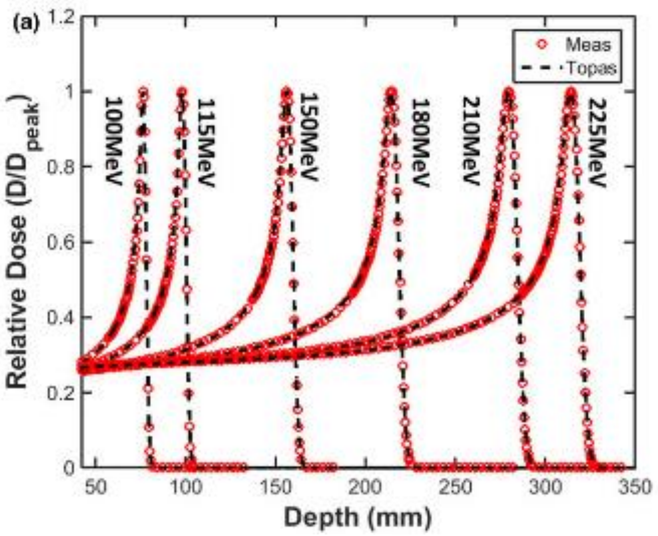
Nucleon energy from 20 MeV to 200 MeV

- The energy spectrum of nucleons for radiation protection or medical issues can reach higher energies than in usual fusion/fission applications, which is from thermal energy to ≈20 MeV.

Neutrons energy spectrum in atmosphere



Proton dose profile in proton therapy

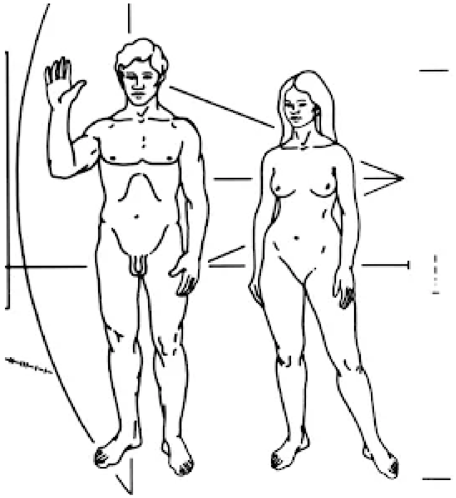


And around some high energy machine !

PSI 500 MeV cyclotron

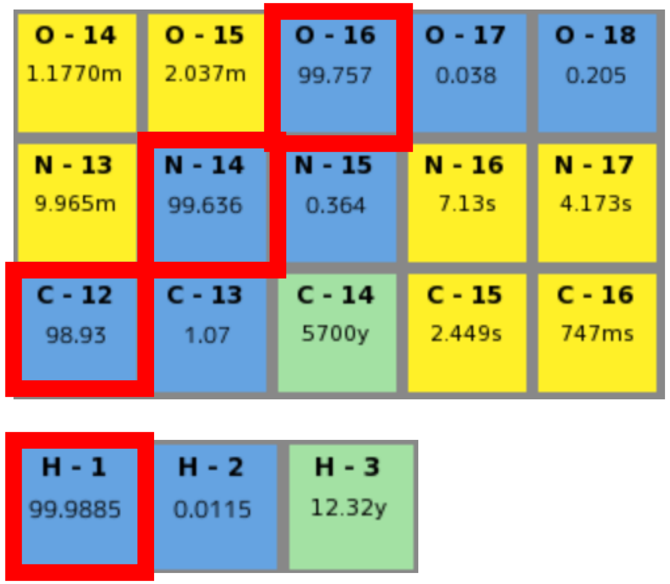
Energy decade between 20 MeV and 200 MeV is important

THE HUMAN BODY



Average chemical cell composition from JP. Alard et al. 2022 as deduced from ICRU 44

Element	Cell Nucleus	Cytoplasm
H	**0.1064**	**0.5960**
O	0.7450	0.2424
C	**0.0904**	**0.1111**
N	0.0321	0.0404
P	0.0261	0.0101



- Only 5 chemical elements (H, C, N, O and P) represent 99.5% of the radiation protection issues for the human body
- Only 5 isotopes (^{1}H, ^{12}C, ^{14}N, ^{16}O and ^{31}P) represent more than 99% of the radiation protection issues for the human body

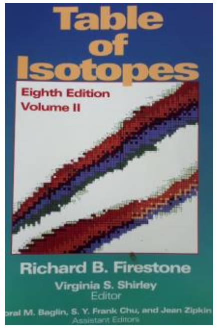
For accurate radiation protection calculations, it is necessary to measure the complete data set on charged particle creation (dose) and secondary neutrons production (transport) for ^{12}C and ^{16}O

OUR USUAL ENVIRONMENT

Composition of the earth's crust

Atoms	% in weigh
O	46.1
Si	28.2
Al	8.2
Fe	5.6
Ca	3.6
Na	2.4
Mg	2.3
K	2.1
Other	1.5

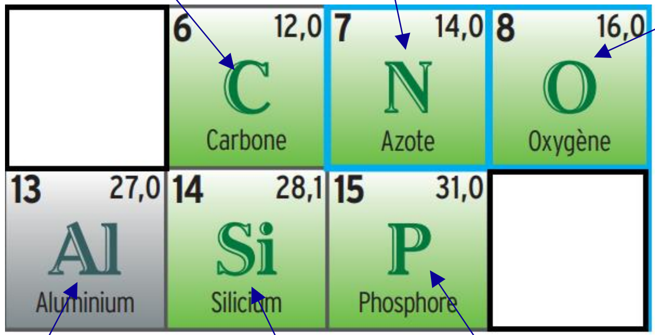
Source



- Human body
- Detectors

- Human body
- Air

- Human body
- Water / concrete
- Many Oxyde molecule



- Space and aerospace

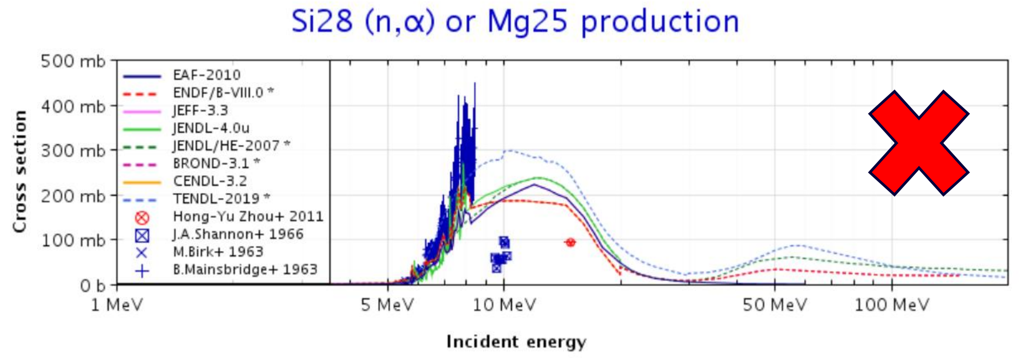
- Space and aerospace
- Detector and IT
- Concrete et many molecule

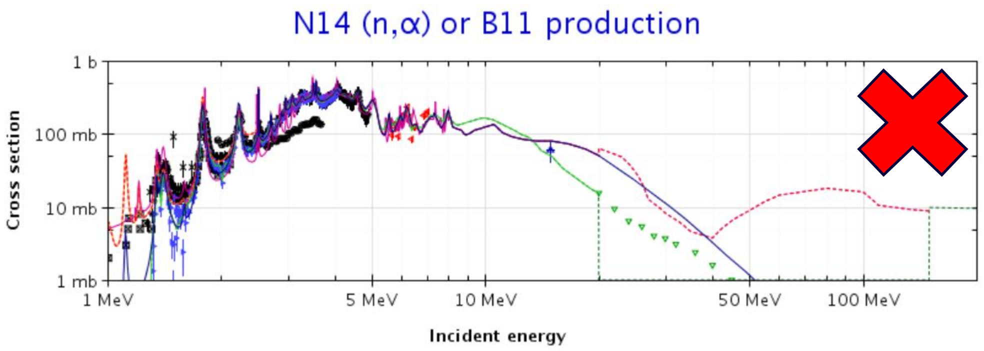
- Human body

Only 5 chemical elements below Z=14 (O, Si, Al, Na and Mg) account for 87.2% by weight of the environment and therefore of the ‘usual’ calculations in radiation transport.

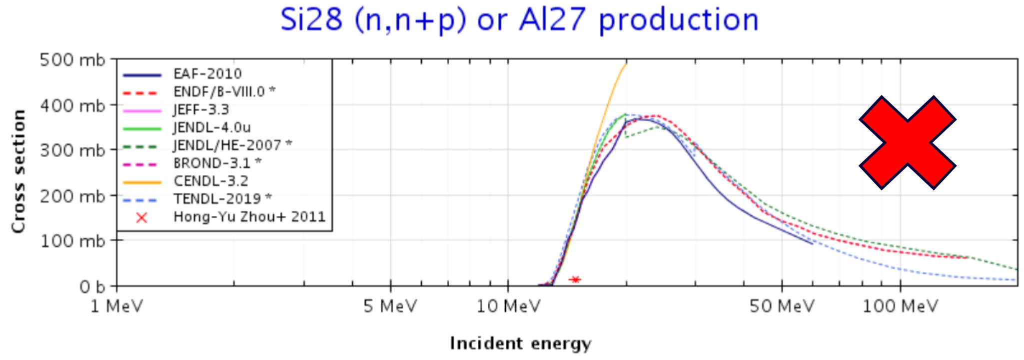
For "common" calculations, it is necessary to have a nuclear model for (n,x) and (p,x) reactions between nuclei from ^{12}C to ^{31}P

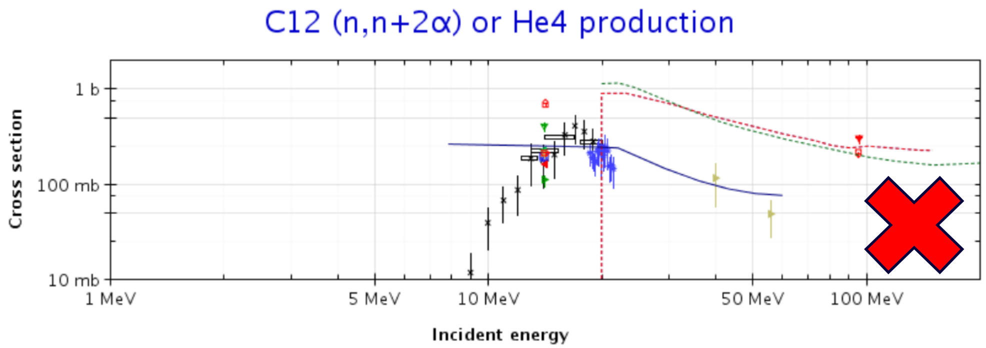
The (n,x) reaction for ^{12}C, ^{14}N, ^{16}O and ^{28}Si : Status from JANIS





^{28}Si = 92% of ^{nat}Si

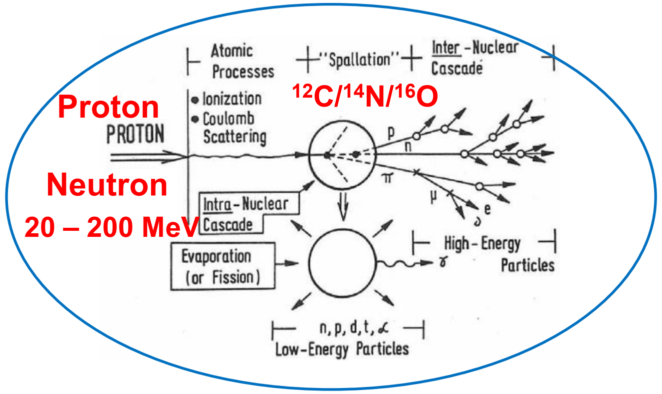




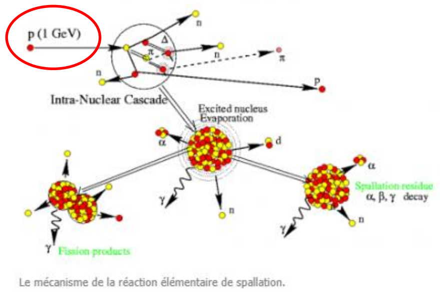
WHAT ABOUT NUCLEAR MODELS ?

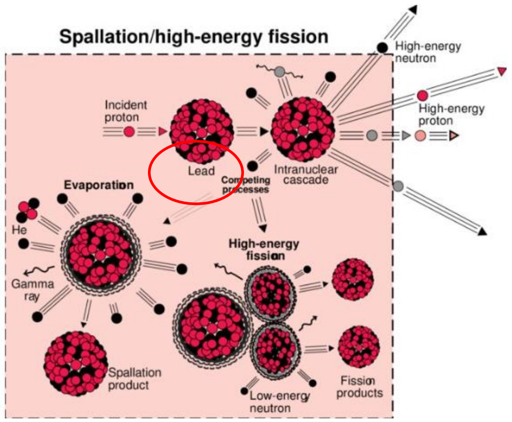
NUCLEAR MODELS

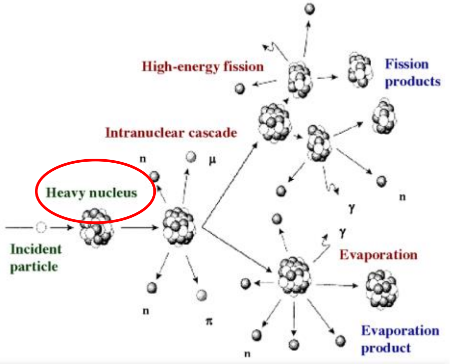
The need

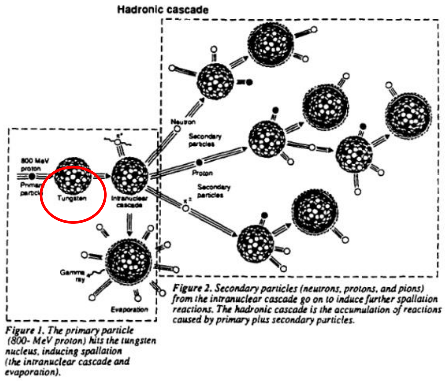


What exist









- A very complex model
  - Some strong internal links (=> magic number impact A=2, A=6? and A=8)
  - Many channels open (bonding energy of $^{16}O \approx 130$ MeV)
  - The wavelength of the neutron leads the neutron to interact with only a fraction of the nucleus

The nuclear models available were not designed for this purpose.
This nuclear interaction model is probably one of the most complex.

EURADOS ACTION

Eurados letter to the nuclear data community "JEFF" - April 2023

European Radiation Dosimetry Group EURADOS

Description of requirements for improvement of nuclear reactions between a nucleon and light nuclei; and notably ^{12}C, ^{14}N, ^{16}O

Introduction

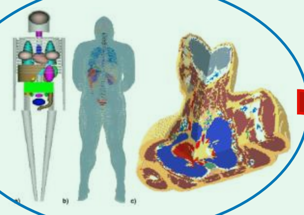
Light nuclei as ^{1}H, ^{12}C, ^{14}N or ^{16}O are extremely abundant in nature. The ^{16}O alone represents 46% of the mass of the earth's crust [1] and even more considering water. Life uses these elements abundantly and almost exclusively. Thus, the human body is composed of ~96% by mass of these four isotopes and even reaches ~75% for ^{16}O alone in the cell nucleus [2]. Any radiation transport calculation for radiation protection, focusing on man and nature, is therefore highly dependent on these isotopes.

Radiation fields around fusion or fission reactors do not exceed about 20 MeV, but in other scenarios in which individuals are exposed it is possible to have protons or neutrons with energies up to several tens, or even hundreds, of MeV, or more. For example, neutron spectra at high altitudes, induced by very high energy cosmic photons, can reach 1000 MeV with a maximum around 100 MeV [3]. This radiation generates significant doses in the space and aviation fields. More, in some radiotherapy procedures, charged particles are directed towards the patient's body after being accelerated to energies of several hundred MeV [4].

(...)

Needs assessment

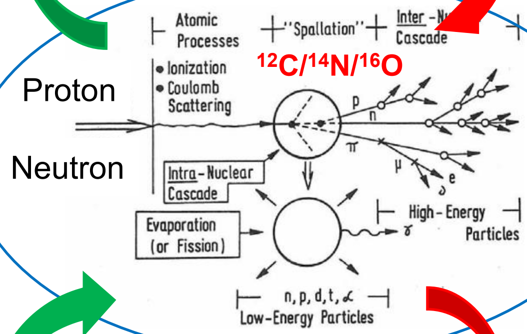
All these needs can be grouped around a common requirement: to have complete nuclear interaction models between a nucleon (neutron or proton in the first place) and the light nuclei, in particular ^{12}C and ^{16}O. These models, whose energy must be able to reach a few hundred MeV or more, must account for all possible nuclear reaction pathways (charged particles and neutrons) by including cross sections in differential form. It is necessary to have uncertainties as low as reasonably possible, with a target of 5% being highly desirable. With a lower priority, the models must also be able to describe correctly the nuclear interactions for other possible incident particles (alpha, deuteron; photon, etc.) as well as for other target nuclei of interest, ^{1}H, ^{14}N and ^{31}F in particular.



Users EURADOS

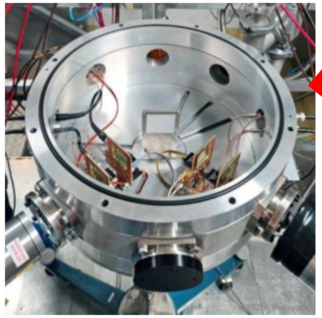
-> Radioprotection benchmark to test dedicated nuclear models -> pianoforte call Similarly to ICSBEP (International Criticality Safety Benchmark Evaluation Project).

PIANOFORTE



Who could take in charge this action and in which frame ?

Nuclear model community (theoretician and evaluator)



Measurements community

The model needs validation points -> request for measurements -> OECD/NEA/HPRL $^{16}O(n,x)$ (2023), $^{12}C(n,x)$, $^{14}N(n,x)$ and $^{28}Si(n,x)$ (2025)

WHAT BENCHMARK FOR EURADOS ACTIVITY

^{16}O, ^{12}C, ^{28}Si, etc. ≈ 1 liter

Fission detector
^{235}U and ^{238}U

Proton beam
> 20 MeV

^{235}U(n,f) and ^{238}U(n,f) are the only standard between 20 and 200 MeV

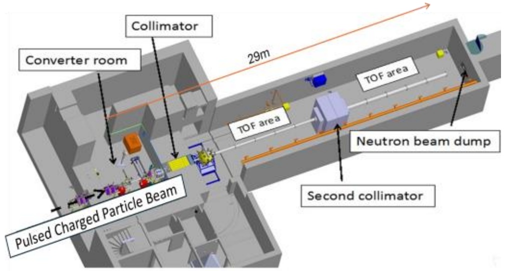
Measurement of the integral of the flux between thermal and 1 MeV and above 1 MeV

^{16}O, ^{12}C, ^{28}Si, etc. ≈ 1 liter

Pulsed Proton beam > 20 MeV

Time of fly or
time of transport

Measuring the shape of the fast component of the neutron flux by ToF (time of transport) measurement



Neutron "monoenergetic" in ToF mode

^{16}O, ^{12}C, ^{28}Si, etc.

Study the neutron scattering using time of transport

CONCLUSIONS PROPOSED

- **A dedicated nuclear model for Describing the interaction between a nucleon and light nuclei between carbon and silicon between 20 and 200 MeV is not available. However, this model is imperative for radioprotection, medical applications and probably multiple other as space and IT applications.**
- **Nuclear data is very sparse and datalibrary are disparate.**
- **The measurement of nuclear reactions between a nucleon and a light nucleus (^{12}C, ^{14}N, ^{16}O and ^{28}Si) between 20 MeV and 200 MeV was asked at the OECD/NEA/HPRL list.**
- **It is necessary for one or more teams of evaluators/theorists to work on the nuclear model.**
- **Radioprotection benchmarks close to the needs was proposed by the EURADOS community (AM2025) for testing the models and will likely feature in its next SRA**
  - Testing nucleus by nucleus and energy by energy
  - Using $^{235}U(n,f)$ and $^{238}U(n,f)$ reactions for neutrons measurements
  - With 3 types of possible benchmark (for now)