Neutron induced reaction and neutron sources

Introduction to Nuclear Science

Simon Fraser University
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Outline

1. Neutron-induced reactions

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2. Radionuclide neutron sources

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2. Radionuclide neutron sources
3. Accelerator neutron sources

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1. Neutron-induced reactions
2. Radionuclide neutron sources
3. Accelerator neutron sources
4. The SIMON project at SFU

Nuclear reactions on Earth

- Chemical reaction are commonly observed in the Earth environment.
- There are, however, very few nuclear reactions occurring on Earth.
- There are two reasons accounting for that fact
  - Nuclear reactions between charged ions (for example proton-induced reactions) need to overcome the Coulomb barrier. There is not enough thermal energy at standard temperatures to achieve that.
  - Neutrons, which can penetrate into a nucleus without the Coulomb barrier at standard temperatures, have 614 s ($\sim$ 10 min) half-life and are present in the environment with extremely low quantities.
- Nuclear reactions induced by cosmic rays in the upper parts of the atmosphere are the source of radio nuclides (^{14}C) in the environment.
- Nuclear decays are commonly observed.

Man-made sources of neutrons

- The lack of Coulomb barrier makes neutrons very attractive tool for nuclear transmutation.
- Short neutron lifetime prompted development of man made sources of neutrons.
- These sources fall into four general categories:
    - Neutrons can be produced by nuclear reactions induced by α particles from naturally occurring α emitters.
    - Neutrons can be produced by nuclear reaction induced by accelerated beams of light ions.
    - Neutrons can be produced from a spallation reaction.
    - Neutrons can be produced from fission.
- These different categories provide sources of various characteristics and can be selected and tuned for specific applications.

Pu-Be neutron source

- Let us calculate the Coulomb barrier for the reaction of α particles on beryllium
$$V_C = 1.44 \frac{2 \cdot 4}{1.2(\sqrt[3]{9} + \sqrt[3]{4})} = 2.6 \text{ [MeV]} \quad (1)$$
- This implies that for most of naturally occurring α emitters the energy of α particles is high enough to induce nuclear transmutation of beryllium.
- Such mixtures are useful neutron sources since
$$^{9}Be + \alpha \rightarrow ^{13}C \rightarrow ^{12}C + n \quad (2)$$
- A popular source is a mixture of ^{241}Pu with ^{9}Be.
- It produces 30 neutrons per million of emitted α particles.

Radionuclide neutron sources

- Other radionuclide neutron sources are

Radionuclide	$T_{1/2}$	Neutron Yield [n/Ci]
^{210}Po	138 d	2.5×10^{6}
^{238}Pu	87.8 y	2.2×10^{6}
^{241}Am	433 y	2.2×10^{6}
^{242}Cm	163 d	2.5×10^{6}
^{252}Cf	2.65 y	4.3×10^{9}

- The decay rate conversion is 1 Ci = 3.7×10^{10}Bq = 37 billion decays per second.
- The emission of neutrons is isotropic, meaning has equal probability in any direction.

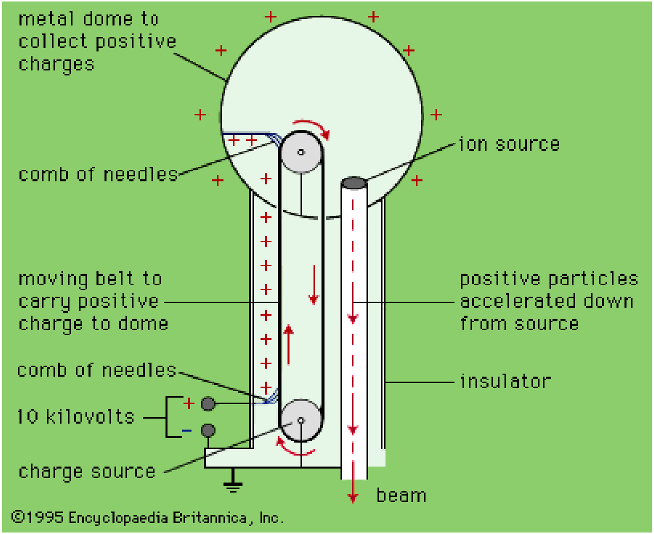
Light ion reactions producing neutrons

- A number of nuclear reaction producing neutrons in the final state have been identified.
- The most common are

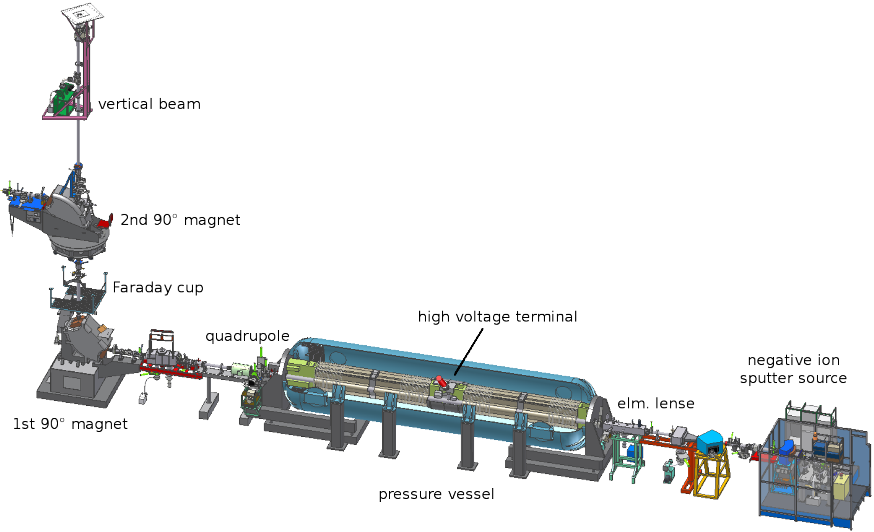
$$\begin{aligned} d + d \rightarrow n + {}^{3}\mathrm{He} \quad Q &= 3.25 \text{ MeV} \\ d + t \rightarrow n + \alpha \quad Q &= 17.60 \text{ MeV} \\ p + {}^{7}\mathrm{Li} \rightarrow n + {}^{7}\mathrm{Be} \quad Q &= -1.65 \text{ MeV} \\ d + {}^{9}\mathrm{Be} \rightarrow n + {}^{10}\mathrm{B} \quad Q &= 3.79 \text{ MeV} \end{aligned}$$

- The light ion beams are accelerated to the energies slightly above the Coulomb barrier by charged particle accelerators.
- Reaction kinematics can be used to tune the outgoing neutron energy based on the energy of the incoming beam.

Van de Graaff accelerator



Tandem Van de Graaff accelerator



Reaction kinematics and neutron energy

- Let us consider the reaction

$$p +^7 \mathrm{Li} \rightarrow n +^7 \mathrm{Be} \quad Q \quad = \quad -1.65 \text{ MeV}$$

- For the neutrons emitted at zero degree

$$\begin{aligned} \vec{p}_p &= \vec{p}_n + \vec{p}_{^7Be} \\ \vec{p}_{^7Be} &= \vec{p}_n - \vec{p}_p \\ p^2_{^7Be} &= p_n^2 + p_p^2 - 2\sqrt{p_p p_n} \end{aligned}$$

- But the energy momentum relation gives

$$T = \frac{p^2}{2m} \implies p^2 = 2Tm \tag{3}$$

- Which leads t0

$$7T_{^7Be} = T_n + T_p - 2\sqrt{T_p T_n} \tag{4}$$

Reaction kinematics and neutron energy

- The Q value definition gives

$$Q = T_{^7Be} + T_n - T_p \tag{5}$$

- Combining the above with

$$7T_{^7Be} = T_n + T_p - 2\sqrt{T_p T_n} \tag{6}$$

leads to

$$\begin{aligned} 7(Q - T_n + T_p) &= T_n + T_p - 2\sqrt{T_p T_n} \\ 8T_n - 6T_p - 2\sqrt{T_p T_n} &= 7Q = -11.52 \ \text{MeV} \end{aligned} \tag{7}$$

- The solution of the above equation gives energy of the mono-energetic neutron beam as a function of the incoming proton energy.

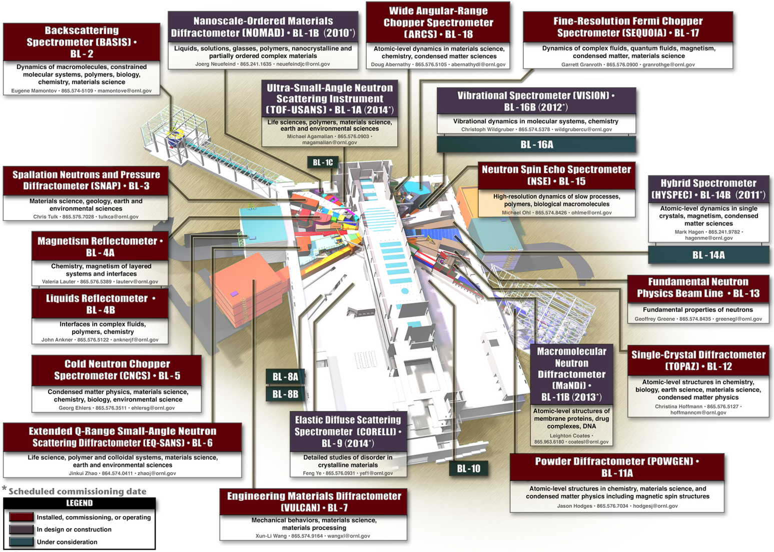
Properties of neutrons from accelerator sources

- Emission of neutrons from accelerator sources is anisotropic (not isotropic).
- Reaction kinematics focuses neutrons in the direction of the incoming beam.
- On the top of that there is a correlation between the direction of a neutron and its energy, larger angles give smaller energy neutrons.
- Neutron beams can be provided using collimation.
- Neutron beam energies can be tuned using the energy of the incoming ions and energy-angle correlation.
- Neutron beams are used for basic and applied research, in particular, studies of material properties.

The Spallation Neutron Source

- The Spallation Neutron Source is an accelerator-based neutron source that provides the most intense pulsed neutron beams in the world for scientific and industrial research and development.
- It is located in Oak Ridge Tennessee in US.
- The accelerator is 1 GeV proton linear accelerator.
- The beam is pulsed with the bunch time width of 1 μs.
- The spallation target is liquid mercury.
- 20-30 neutrons are emitted per spallation.
- Neutron beams are formed by slowing down in moderators and by collimation.

Spallation Neutron Source Instruments



Backscattering Spectrometer (BASIS) • BL - 2
Dynamics of macromolecules, constrained molecular systems, polymers, biology, chemistry, materials science
Eugene Mamontov • 865.574-5109 • mamontove@ornl.gov

Nanoscale-Ordered Materials Diffractometer (NOMAD) • BL - 1B (2010*)
Liquids, solutions, glasses, polymers, nanocrystalline and partially ordered complex materials
Joerg Neuefeind • 865.241.1635 • neuefeindjc@ornl.gov

Wide Angular-Range Chopper Spectrometer (ARCS) • BL - 18
Atomic-level dynamics in materials science, chemistry, condensed matter sciences
Doug Abernathy • 865.576.5105 • abernathydl@ornl.gov

Fine-Resolution Fermi Chopper Spectrometer (SEQUOIA) • BL - 17
Dynamics of complex fluids, quantum fluids, magnetism, condensed matter, materials science
Garrett Granroth • 865.576.0900 • granrothge@ornl.gov

Ultra-Small-Angle Neutron Scattering Instrument (TOF-USANS) • BL - 1A (2014*)
Life sciences, polymers, materials science, earth and environmental sciences
Michael Agamalian • 865.576.0903 • magamalian@ornl.gov

Vibrational Spectrometer (VISION) • BL - 16B (2012*)
Vibrational dynamics in molecular systems, chemistry
Christoph Wildgruber • 865.574.5378 • wildgrubercu@ornl.gov

BL - 16A

BL - 1C

Spallation Neutrons and Pressure Diffractometer (SNAP) • BL - 3
Materials science, geology, earth and environmental sciences
Chris Tulk • 865.576.7028 • tulkca@ornl.gov

Neutron Spin Echo Spectrometer (NSE) • BL - 15
High-resolution dynamics of slow processes, polymers, biological macromolecules
Michael Ohl • 865.574.8426 • ohlme@ornl.gov

Hybrid Spectrometer (HYSPEC) • BL - 14B (2011*)
Atomic-level dynamics in single crystals, magnetism, condensed matter sciences
Mark Hagen • 865.241.9782 • hagenme@ornl.gov

BL - 14A

Magnetism Reflectometer • BL - 4A
Chemistry, magnetism of layered systems and interfaces
Valeria Lauter • 865.576.5389 • lauterv@ornl.gov

Liquids Reflectometer • BL - 4B
Interfaces in complex fluids, polymers, chemistry
John Ankner • 865.576.5122 • anknerjf@ornl.gov

Fundamental Neutron Physics Beam Line • BL - 13
Fundamental properties of neutrons
Geoffrey Greene • 865.574.8435 • greenegl@ornl.gov

Cold Neutron Chopper Spectrometer (CNCS) • BL - 5
Condensed matter physics, materials science, chemistry, biology, environmental science
Georg Ehlers • 865.576.3511 • ehlersg@ornl.gov

BL - 8A

BL - 8B

Macromolecular Neutron Diffractometer (MaNDi) • BL - 11B (2013*)
Atomic-level structures of membrane proteins, drug complexes, DNA
Leighton Coates • 865.963.6180 • coatesl@ornl.gov

Single-Crystal Diffractometer (TOPAZ) • BL - 12
Atomic-level structures in chemistry, biology, earth science, materials science, condensed matter physics
Christina Hoffmann • 865.576.5127 • hoffmanncm@ornl.gov

Extended Q-Range Small-Angle Neutron Scattering Diffractometer (EQ-SANS) • BL - 6
Life science, polymer and colloidal systems, materials science, earth and environmental sciences
Jinkui Zhao • 864.574.0411 • zhaoj@ornl.gov

Elastic Diffuse Scattering Spectrometer (CORELLI) • BL - 9 (2014*)
Detailed studies of disorder in crystalline materials
Feng Ye • 865.576.0931 • yef1@ornl.gov

BL - 10

Powder Diffractometer (POWGEN) • BL - 11A
Atomic-level structures in chemistry, materials science, and condensed matter physics including magnetic spin structures
Jason Hodges • 865.576.7034 • hodgesj@ornl.gov

Engineering Materials Diffractometer (VULCAN) • BL - 7
Mechanical behaviors, materials science, materials processing
Xun-Li Wang • 865.574.9164 • wangxl@ornl.gov

* Scheduled commissioning date

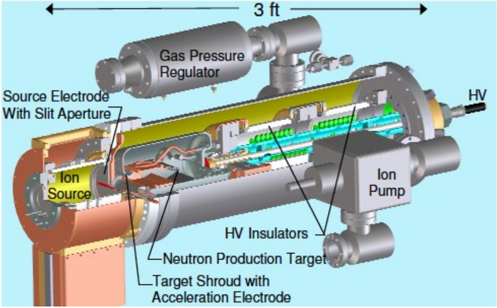
LEGEND
🟥 Installed, commissioning, or operating
🟪 In design or construction
🟦 Under consideration

06-G00400N/arm

Sealed tube neutron generators

- Sealed tube neutron generators are small accelerators which generate neutrons via

$$\begin{aligned} d + d &\rightarrow n +^3\text{He} \\ d + t &\rightarrow n + \alpha \end{aligned} \tag{8}$$



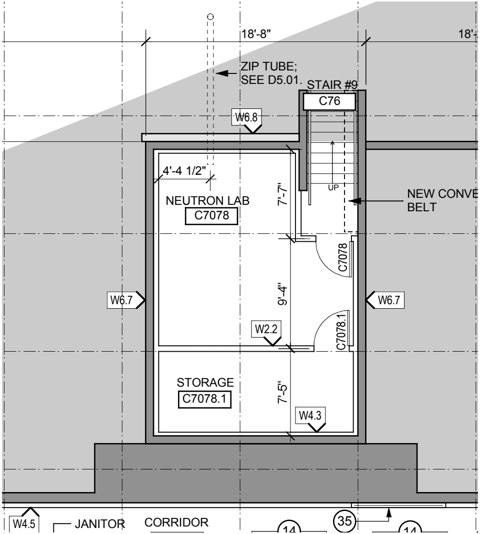
Sealed tube neutron generators

- Sealed tube neutron generators are portable neutron sources.
- They generate quasimonoenergetic beams of neutrons with 14.1 MeV energy for the d/t and 2.5 MeV energy for the d/d.
- Neutrons from the d/t generator are emitted isotropically, while for the d/d generator the emission is slightly focused towards the beam direction.
- Yields are on the order of 10^8 neutrons/s for the sealed tube d/t generators, a factor of 50-100 smaller for the d/d generators.
- The use of radioactive tritium is a concern in application of d/t generators, this is a reason for the sealed tube solution.
- Other technical implementations of d/t neutron generator can reach fluxes of 10^{11} particles per second.

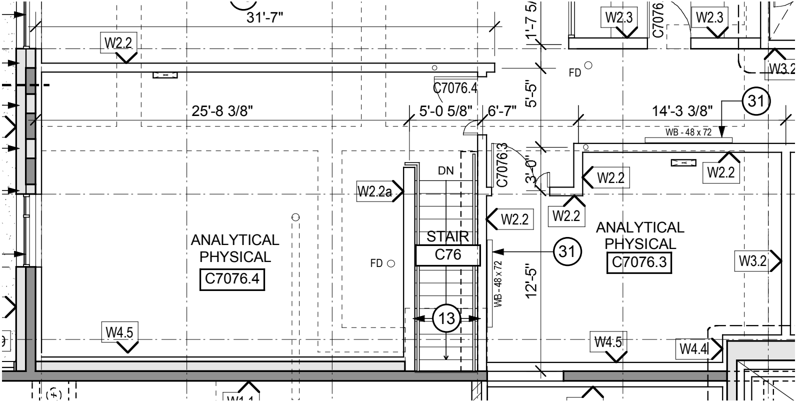
Nuclear Science facilities

- The SFU's Chemistry building is renovated as a part of the \$50M Chemistry building renovation funded by the provincial government and Industry Canada's Knowledge Infrastructure Program.
- Renovation will be completed in the spring of 2011, new laboratories will be operational in the summer of 2011.
- Nuclear Science facilities of ~\$750,000 value will include
    - A renovated underground radiation vault, ready to host a D/T or D/D neutron generator.
    - A radio-chemistry laboratory above the vault, with a fume-hood, glove-box and other equipment set up for chemical reprocessing of radioactive materials.
    - Conduits between the radiation vault and the radio-chemistry lab designed to accommodate gas jet and a pneumatic system (a rabbit) for transportation of radioactive samples.
    - A separate laboratory for detector development and testing.

The radiation vault



The Nuclear Science Laboratories



The current status

The SIMON project

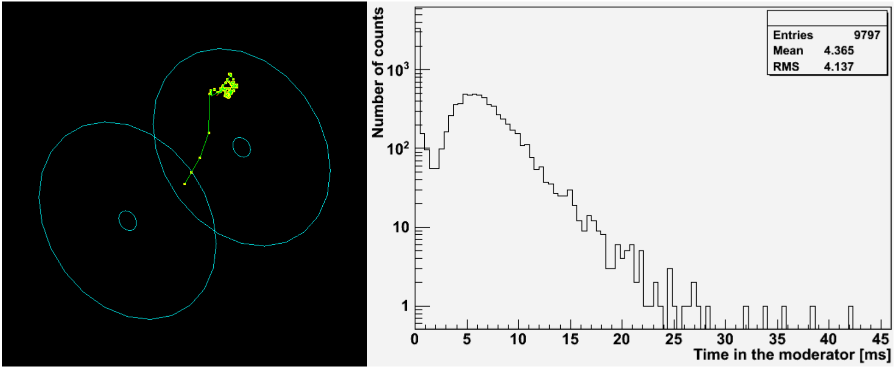
- The role of SIMON is to provide access to high intensity neutron beams without a nuclear reactor or spallation source.
- SIMON will comprise of
  - D/T or D/D generator of fast neutrons
  - Beryllium shroud multiplying fast neutrons through the (n,2n) reaction
  - a Heavy-Water moderator
  - low-enriched Uranium for multiplication of moderated neutrons through the neutron-induced fission.
- The goal is to develop a medium-size device (less then 7 m long, 3 m diameter), fitting the floor-plan of the radiation vault at SFU.
- The achievable flux is being examined, the target is 10^{13} n/cm^2/s.

The road map for SIMON: 2011

- A $150K Canadian Foundation of Innovation/ British Columbia Knowledge Development Fund proposal for a commercial neutron generator has been awarded
- GEANT4 Monte-Carlo simulation codes for the neutron moderator and multipliers developed based on the high-precision models available from GEANT4 for $E < 20$ MeV neutrons.
- Optimization of the moderator and multiplier geometry based on the GEANT4 simulations is currently pursued.
- A 3×10^8 commercial generator will be acquired.
- Licensing process for the renovated vault and a generator to be acquired will be initiated in early 2011.
- Funds for construction of a test moderator will be sought.

Moderation of neutrons in GEANT4

(Left)Simulated random walk, (Right) Simulated time in the moderator.



Simulated average time in a heavy-water moderator is ∼4 [ms].

SIMON: back on the envelope estimates

- The volume of 100 [cm] long moderator with 50 [cm] radius and a bore for inserting the generator with 5 [cm] radius is

$$V = 100 * \pi * (50^2 - 5^2) \ \ [\mathrm{cm}^3] = 7.8 \times 10^5 \ \ [\mathrm{cm}^3]$$

- Number of neutrons in the moderator is equal to the generator output f times the lifetime in the moderator τ

$$n = f\tau = 3 \times 10^8 \ \ [\mathrm{part./s}] * 4 \times 10^{-3} \ \ [\mathrm{s}] = 1.2 \times 10^6 \ \ [\mathrm{part.}]$$

- Number density of the neutrons in the moderator is

$$N = \frac{n}{V} = \frac{1.2 \times 10^6}{7.8 \times 10^5} = 1.5 \ \ [\mathrm{part./cm}^3]$$

SIMON: back on the envelope estimates

- Assuming thermal neutrons with energy 0.025 [eV] and speed v of 2.2 [km/s]=2.2×10^5 [cm/s] the neutron flux in the moderator without any neutron multiplication is

$$\phi = N * v = 1.5 * 2.2 \times 10^5 \ \text{[part./cm}^2\text{/s]} = 3.3 \times 10^5 \ \text{[part./cm}^2\text{/s]}$$

- If there is a reaction in the moderator which contributes Δn neutrons per second into the full moderator the number density in the moderator will grow in a unit time according to

$$N + \Delta N = N + \frac{\Delta n \tau}{V} = N(1 + \frac{\Delta n \tau}{NV}) = N(1 + \lambda) \ \text{with} \ \lambda = \frac{\Delta n \tau}{NV}$$

- Growth in time is described by

$$N(t) = N(0)(1 + \lambda)^t$$

SIMON: back on the envelope estimates

- Let us assume thermal neutron induced fission of natural Uranium as the multiplication reaction.
- Number of thermal-neutron induced fission per second is

$$\Delta n = \phi \kappa a d \bar{\nu} \sigma \frac{\rho}{\mu} N_A = N v \kappa a d \bar{\nu} \sigma \frac{\rho}{\mu} N_A$$

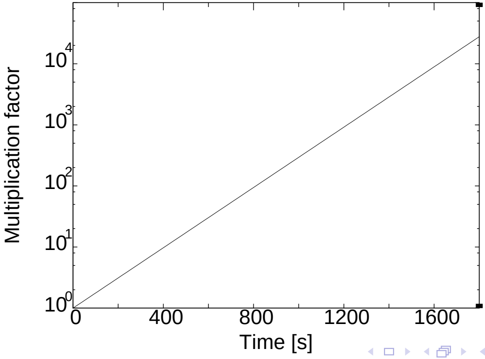
with

  - $\kappa = 0.007$ being ^{235}U content in $^{\mathrm{nat.}}$U,
  - a and d being $^{\mathrm{nat.}}$U target area and thickness, respectively, with the $ad = 60$ [cm^3] representing the volume of $^{\mathrm{nat.}}$U in the moderator in 0.5 cm thick, 2 cm long bars, 10 cm from the centre,
  - $\bar{\nu} = 2.5$ being the average number of neutrons per ^{235}U fission,
  - $\sigma = 600$ [b]=6×10^{-22} [cm^2] is the cross section for 0.025 [eV] thermal neutron capture on ^{235}U,
  - $\rho = 19$ [g/cm^2] is the density of $^{\mathrm{nat.}}$U,
  - $\mu = 239$ [g/mol] is the molar mass of $^{\mathrm{nat.}}$U,
  - $N_A = 6 \times 10^{23}$ is the Avogadro number.

SIMON: back on the envelope estimates

- Combining above equations the multiplication factor for 800 kg of heavy water and 1.2 kg of $^{\text{nat.}}$U becomes

$$F(t) = \frac{N(t)}{N(0)} = (1+\lambda)^t \quad \text{with} \quad \lambda = \kappa\bar{\nu}\frac{ad}{V}v\tau\sigma\frac{\rho}{\mu}N_A = 5.7\times10^{-3}$$



The road map for SIMON: long-range

- GEANT4 codes will be validated using results obtained with the low-flux generator and the test moderator.
- Working parameters for the final neutron generator and the moderator will be specified and the final design will be defined based on the validated calculation.
- Nuclear engineering assistance will be sought in regard to shielding, design, manufacturing and operation of the final neutron generator and moderator assembly.
- Utility of the SIMON for fundamental and applied research program will be examined.

The utility of SIMON

- SIMON is a project with significant discovery potential
    - Can become a driver for production of rare isotopes with large neutron excess via neutron-induced fission.
    - Consequently, it can support state of the art nuclear research probing the beginning of the Universe and answering key fundamental scientific questions regarding nucleosynthesis and distribution of elements.
- SIMON provides an ideal training opportunities for future generation of Highly Qualified Personnel in Nuclear Science.
- SIMON may open a way to produce important radioisotopes for medical and commercial applications without use of reactors.
- For material sciences SIMON will enable neutron activation analysis providing information on elemental composition on a particle-per-billion level in a non-destructive way.
- SIMON may also become a tool for neutron scattering aiding research in material sciences.