Development and Licensing of SFU Neutron Generator Facility

Jonathan Williams

Supervisor: Krzysztof Starosta

Simon Fraser University

Department of Chemistry

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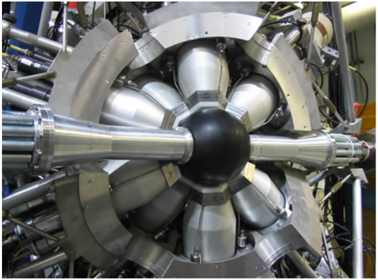
Work in Nuclear Science

We do two types of experiments:

Environmental studies...

- Detecting radiation that exists 'in the wild'.



Production and study of isotopes...

- Often to answer more fundamental questions.

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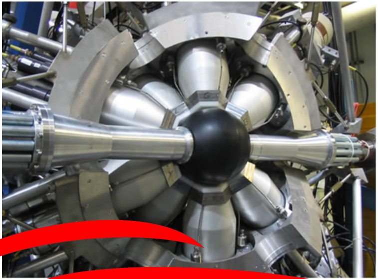


Production and study of isotopes...

- Often to answer more fundamental questions.

Inventory of Stuff We Have

Equipment in our lab:

GEARS *(Germanium detector for Elemental Analysis and Radioactivity Studies)*

8π

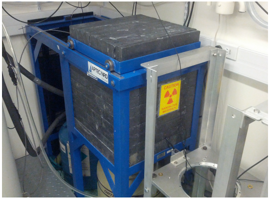
- Array of 20 gamma-ray detectors.

TIFFIN *(Twin Ionization chamber for Fission Fragment INvestigation)*

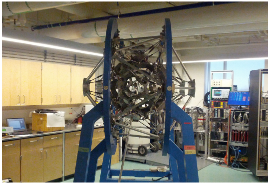
- Charged particle detector.

GRIFFIN *(Gamma-Ray Infrastructure For Fundamental Investigations of Nuclei)*

- Next-gen gamma-ray detectors being tested for TRIUMF.



GEARS.



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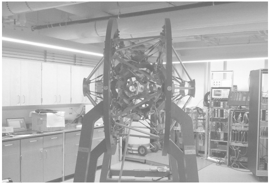


8π.

The neutron generator facility...

We are building a neutron generator facility at SFU.

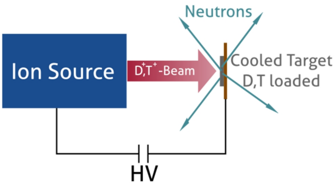
- Location: C7078, vault which previously housed a neutron generator.
- Currently used to store radioactive samples and sources.

What is a neutron generator?

A small linear accelerator which produces neutrons via the D-T reaction:

$$^{2}\mathrm{H} + {}^{3}\mathrm{H} \rightarrow n + \alpha$$

with $E(n) = 14.1$ MeV.

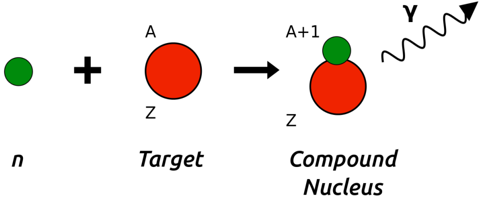


- Reaction yield of up to 3×10^{8} neutrons/s.
- Typically used in industry for elemental analysis.

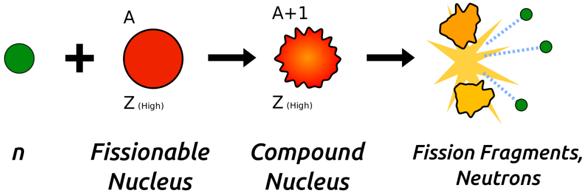
Neutron Reaction Channels

A neutron generator allows us to produce neutron rich isotopes of interest.

- Not currently possible at SFU!



(n, γ) reaction schematic.



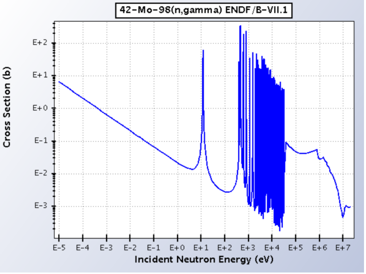
(n, fission) reaction schematic.

Neutron Reaction Channels

As a general rule, low energy neutrons interact more easily with matter.

- This is a consequence of the particle-wave dual nature of matter - as energy decreases, wavelength (or effective particle size[1]) increases:

$$\lambda = \frac{\hbar}{p} = \frac{\hbar}{\sqrt{2mE}}$$

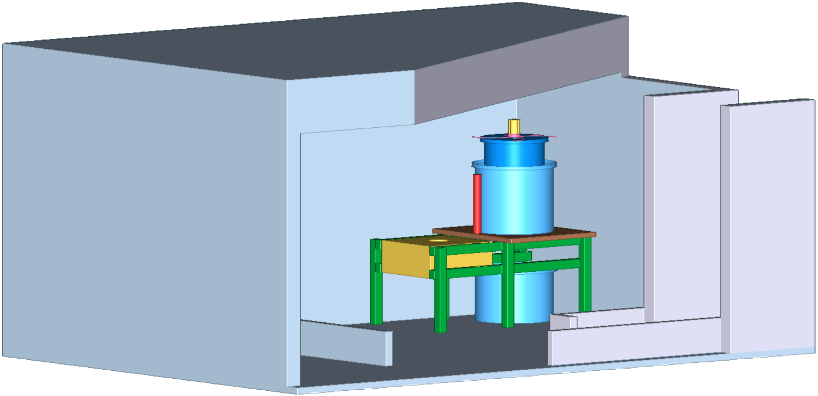


^{98}Mo(n, γ) reaction cross section vs. neutron energy.

[1] Ramsauer model, see Mukhopadhyay et al., Phys. Rev. C 82, 044613 (2010)

What will we do?

We will surround the generator with a moderator which will slow the neutrons passing through it.

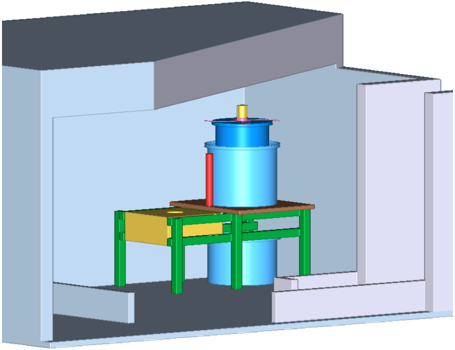


Cut-away view of proposed moderator assembly in vault.

What will we do?

We will surround the generator with a moderator which will slow the neutrons passing through it.

- Generator will be surrounded by cylindrical water tanks (blue).
- Plastic slide-out block (yellow) can hold a detector.
- Reaction target can be in vault space or dispersed in moderator (in solution).



Cut-away view of proposed moderator assembly in vault.

Science we can do...

Nuclear Structure Studies

- Production of isotopes to identify excited states and lifetimes of species of interest.
- Neutron induced fission to get far from stability.

Neutron Activation Analysis

- Nondestructive elemental analysis through irradiation of sample and detection of subsequent decay products.

Medical Isotope Production

- eg. ^{64}Cu (PET) ^{99}Mo/^{99m}Tc (SPECT)

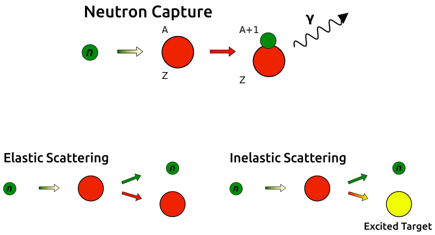
Current Status of Facility

Initial license to construct the facility was granted by the Canadian Nuclear Safety Commission (CNSC) in January 2014.

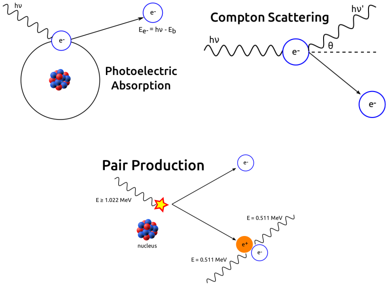
We were required to provide an estimate of the dose rate that will be present in and around the facility when it is operational.

Dose rate predictions

GEometry ANd Tracking (GEANT4)[1] is a code framework used to simulate neutron and gamma-ray interactions with barriers (air, concrete).



Neutron interaction processes.



Gamma-ray interaction processes (secondary).

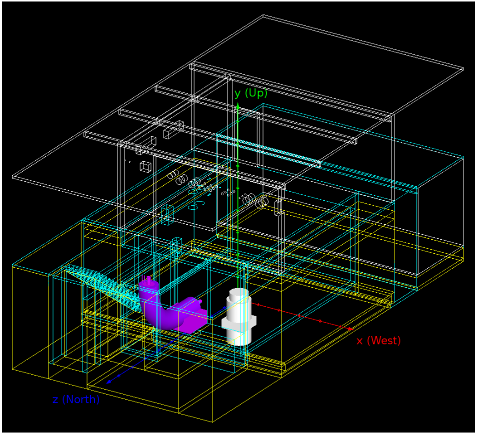
[1] http://geant4.web.cern.ch/geant4/

Dose rate predictions

We created a computer model of the facility, containing information relevant to the simulation:

- geometry of barriers and conduits
- barrier composition (concrete, sand, air...)
- barrier density
- location of radiation sources

Moderator assembly housing the neutron generator shown in solid white.



GEANT4 model of facility.

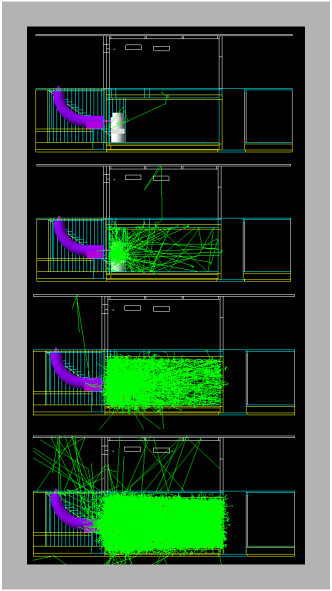
Computing fluence and dose rate...

We simulate a point source of 14.1 MeV neutrons in the C7078 vault.

GEANT4 computes tracks for each particle due to interactions with matter in the model, including secondary (gamma) radiation.

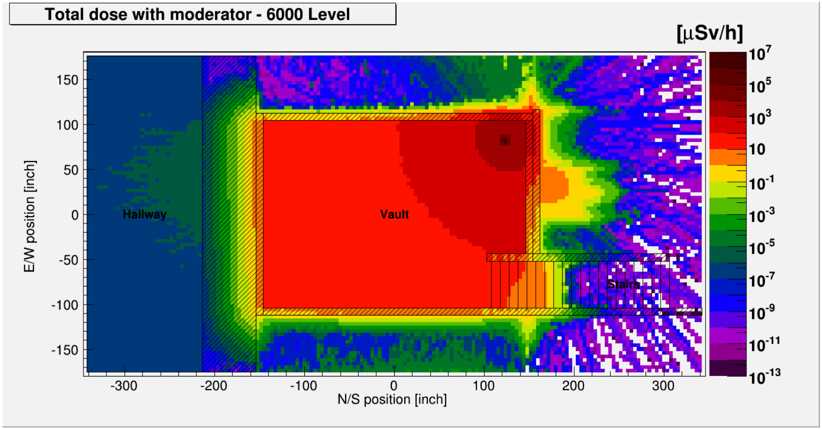
- Convert to dose rate using ICRP74 factors.

3×10^8 neutrons simulated is equivalent to 1 s of neutron generator operation.



Dose rate prediction results

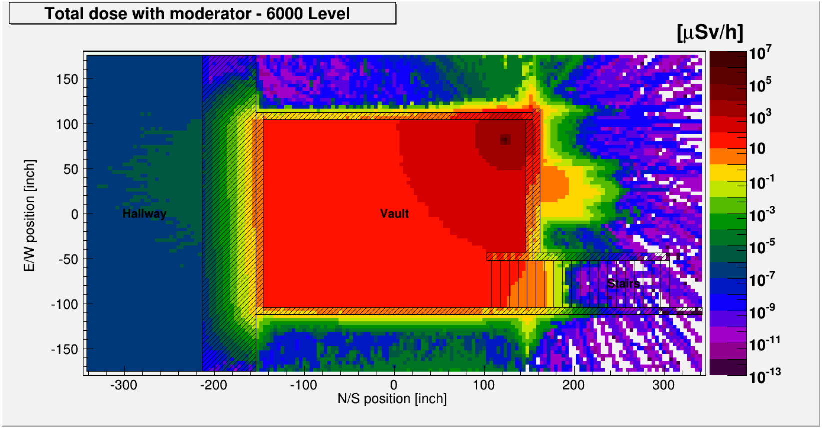
Simulated *equivalent absorbed radiation dose* in sieverts (Sv, units J/kg) per hour of the facility was mapped:



6000 level top-down view.

Dose rate prediction results

- Natural background radiation in Vancouver area is 1.3 mSv/year[1].
- Health Canada's dose limit to the public is an additional 1 mSv/year[2].



[1] http://www.nuclearsafety.gc.ca/eng/readingroom/factsheets/background-radiation.cfm
[2] http://www.hc-sc.gc.ca/hc-ps/ed-ud/event-incident/radiolog/info/details-eng.php

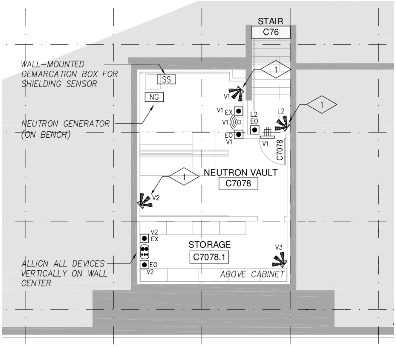
Current Status of Facility Revisited

Initial license to construct the facility was granted by the Canadian Nuclear Safety Commission (CNSC) in January 2014.

- Dose calculations accepted by CNSC.
- License to commission the facility (test the neutron generator) received.
- Current/Upcoming Work:
  - Construction of the facility!
  - Verify dose calculations via radiation survey!

The Next Steps...

Interlock/safety systems have been installed in the laboratory space.

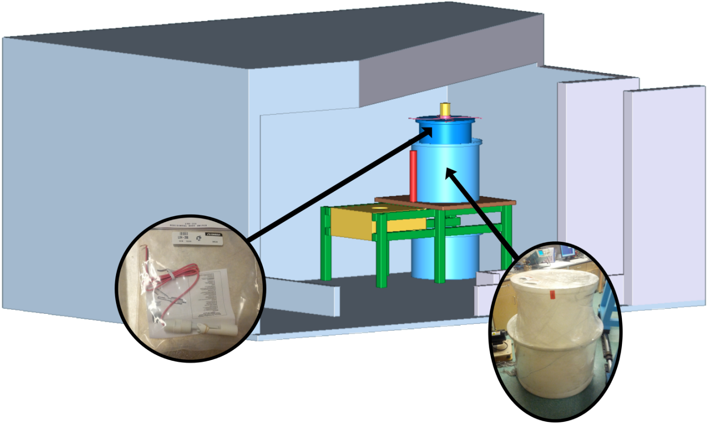


Left: Schematic of sensor locations by Acumen Engineering.
Right: Installed electronics.

The Next Steps...

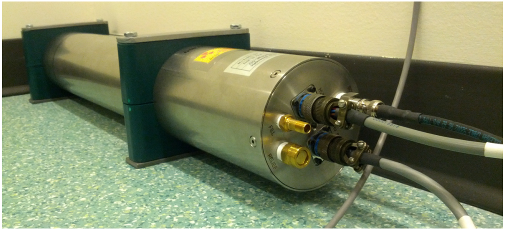
Constuction of the moderator assembly is starting.

- Moderator frame to be built by SFU machine shop.
- Level sensors to continuously monitor water level.



The Next Steps...

The neutron generator arrived at SFU in early June.

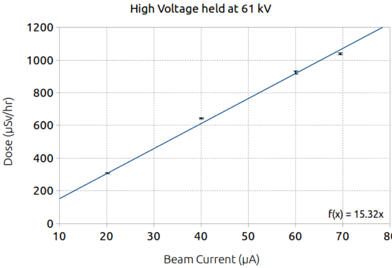


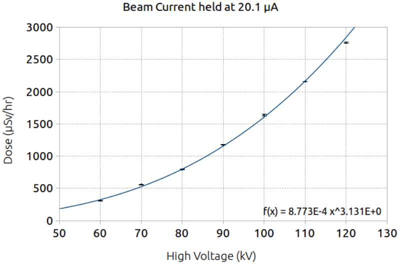
Turning the Generator On...

We monitored the neutron dose rate at a distance of 1m from the generator target.

- Extrapolated value at maximum current/voltage is 17% higher than prediction.

Experimental setup.





The Next Steps...

Verification of neutron dose at several locations in facility:

- Detector measurements to determine dose rate profile.
- Activation foil experiment to determine absolute neutron yield.

Once facility is operational:

- Incorporate neutron monitor into interlock system.
- Continuously monitor at one location.

FHT 762 Wendi-2 Neutron Detector, by Thermo-Fisher.

Putting It All Together...

We are building a neutron generator facility, which will open the door to interesting science:

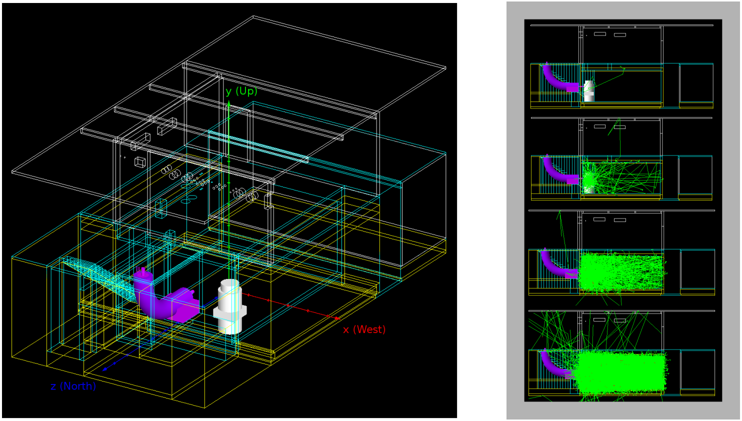
- Nuclear structure studies.
- Non-destructive elemental analysis.
- Medical isotope production.

Location of the facility.

Neutron generator.

Putting It All Together...

Dose predictions for the facility were implemented in GEANT4 and accepted by the CNSC.



GEANT4 model of the facility.

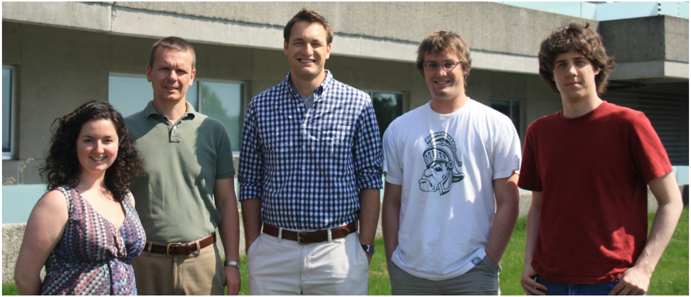
Putting It All Together...

Construction of the facility is underway, with commissioning of the generator to take place over the summer.

Present state of the vault.

Neutron generator
electronics test station.

Acknowledgements



+ Usman...
+ Thomas...

Thanks to:

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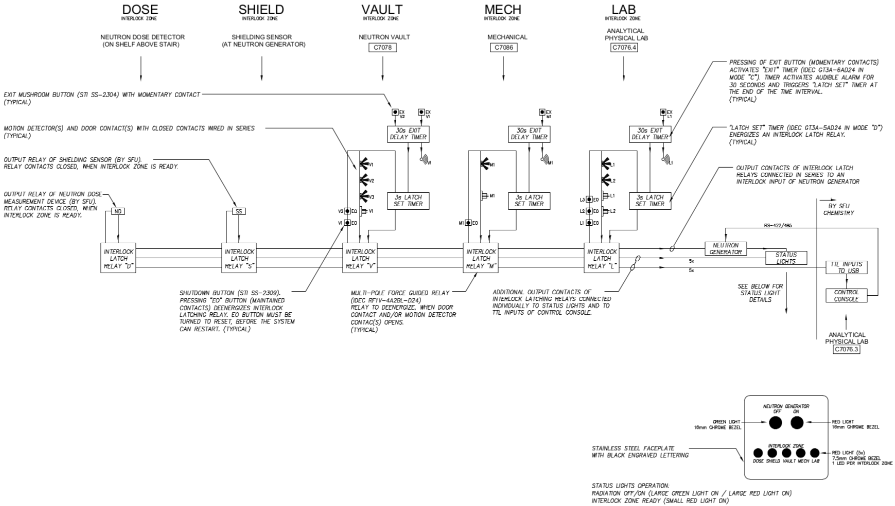
Phillip Voss

SFU Radiation Safety Office

Andrew Barton
Kate Scheel

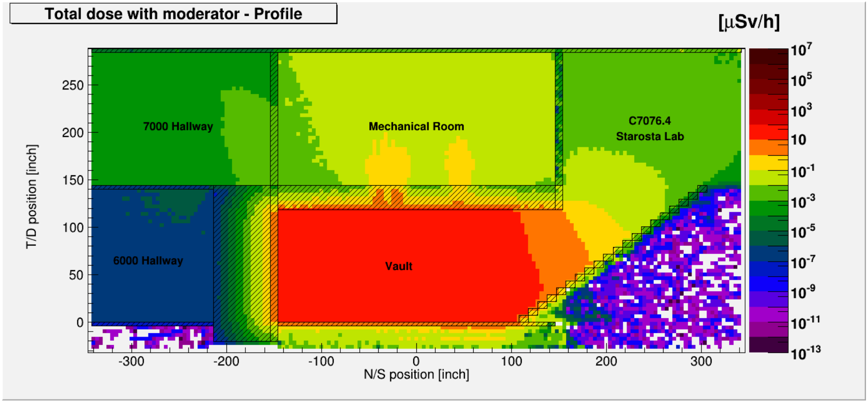
SFU Mechanical and Electronics Shops

Interlock system engineering schematic



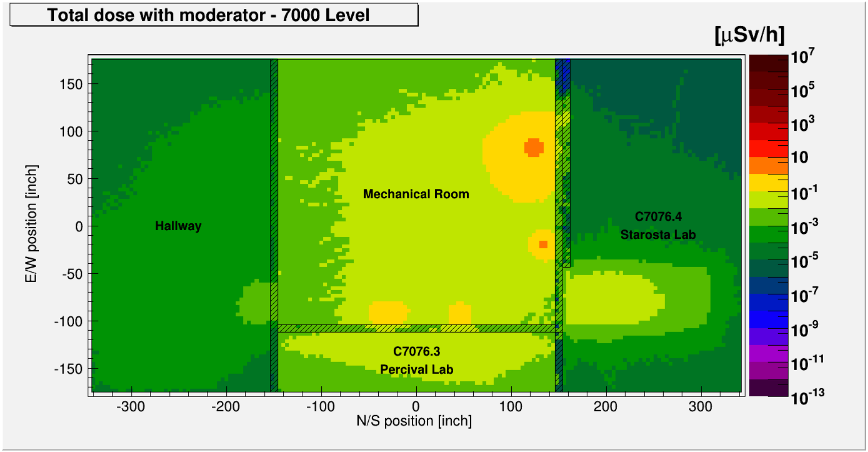
Dose rate prediction results (cont.)

Profile view showing both 6000 and 7000 levels of the chemistry building:



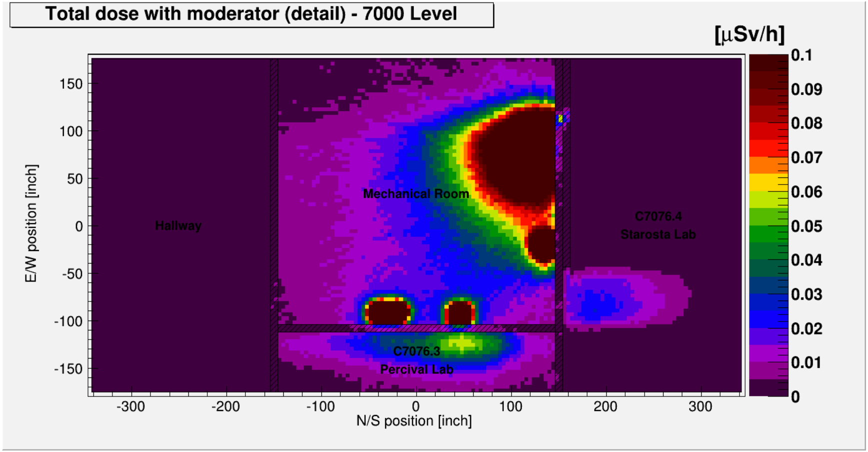
Total dose maps with moderator

Total dose map with moderator (7000 level top-down view):



Total dose maps with moderator (Percival lab detail)

Total dose map with moderator (7000 level top-down detailed view):



Science we can do...

Medical Isotope Production

^{98}Mo to ^{99m}Tc pathway.

- Many medical isotopes such as ^{99m}Tc are produced via neutron capture reactions:

$$^{98}\text{Mo} + \text{n} \rightarrow {}^{99}\text{Mo} + \gamma$$
$$^{99}\text{Mo} \rightarrow {}^{99m}\text{Tc} + \text{e}^{-} + \bar{\nu}_e$$

- Presently produced in reactors (from high neutron fluxes generated through fission) and cyclotrons (from ^{100}Mo(p,2n)^{99m}Tc).
  - Can investigate feasibility of accelerator-based production via neutron capture.

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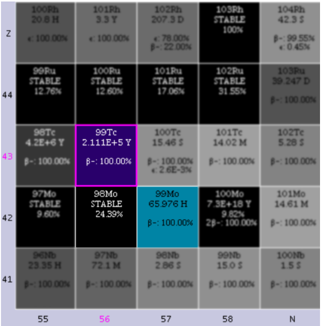

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Science we can do...

Neutron Activation Analysis

- By irradiating a sample and detecting decay products of species produced, we can determine the elemental composition of the sample.
- Ex. ^{90}Sr, present in the environment from 1960s nuclear testing and waste from reactor incidents[1].
  - Cancer risk, accumulates in bone in place of calcium.
  - Decays via β^- (no characteristic decay spectrum).

[1] http://emergency.cdc.gov/radiation/isotopes/pdf/strontium.pdf

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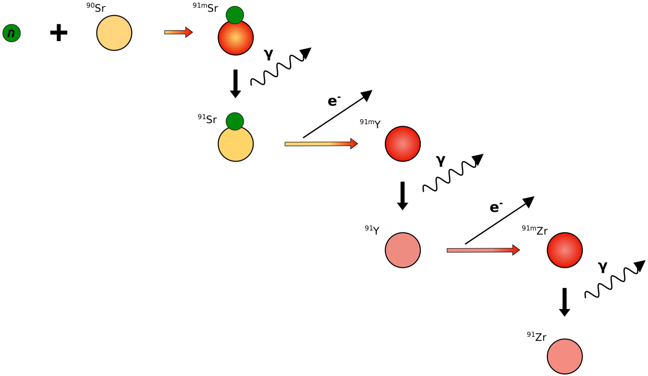
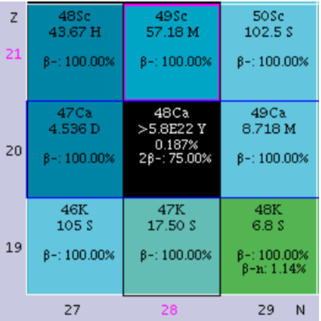


^{90}Sr activation scheme.

Nuclear Structure Studies

By measuring the lifetimes/energies of excited states of species produced, structure information can be obtained.

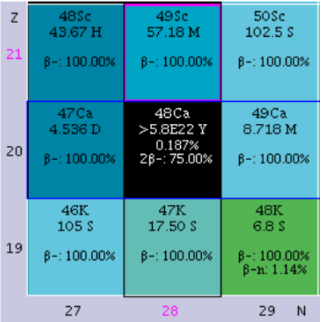
- The mean time τ taken to transition between two states is inversely related to the overlap between the two states: $\frac{1}{\tau} \propto |\langle\psi_f|U|\psi_i\rangle|^2$



Nuclear Structure Studies

Nuclei near shell closures such as ^{49}Sc are of particular interest:

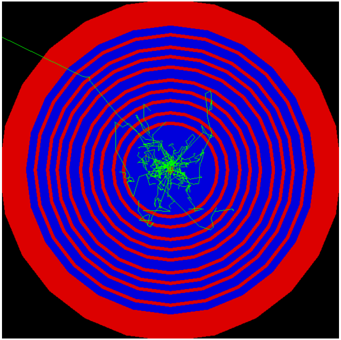
- Can be produced via neutron capture on ^{48}Ca.
- Since a single proton exists above the shell closure, the interaction between it and the remainder of the nucleus can be isolated and studied.



Validation against MCNP (K. Starosta)

We compared dose transmission factors computed in MCNP[1] and National Council on Radiation Protection publication data[2] to our own GEANT4 calculations with various interaction models:

- Parametrized cross sections (Low Precision)
- Evaluated cross sections (High Precision)[3]
  - No thermal neutron cutoff
  - 0.3 eV low energy cutoff
  - 5 keV low energy cutoff



Spherical 'shell' geometry consisting of air (blue) and water (red) layers.

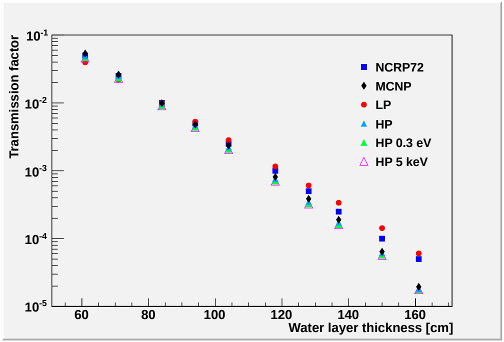
[1] Courtesy Angel Licea, CNSC.
[2] NCRP Report No. 72 (1983)
[3] From the National Nuclear Data Center, http://www.nndc.bnl.gov/

Validation against MCNP (K. Starosta)

Good agreement was seen between MCNP and the GEANT4 High Precision (HP) physics list.

- Low energy cutoffs do not significantly affect dose transmission.

We used the HP list with a 5 keV cutoff for the facility dose calculations in the interest of computation time.



Total dose transmission factors through water.

Computing fluence and dose rate...

A particle track of length dL_i going through the volume V contributes a fluence $d\Phi_i(E)$:

$$d\Phi_i(E) = \frac{dL_i}{V} \times w$$

The fluence contribution $d\Phi(E)$ is converted into a dose contribution dD_i using the International Commission on Radiation Protection (ICRP74) fluence to dose conversion factors $H^*(10, E)/\Phi$:

$$dD_i = d\Phi_i(E) \times H^*(10, E)/\Phi$$

The dose in volume V is the sum of dose contributions:

$$D = \sum_i dD_i$$

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Event biasing

CNSC requires $\leq$5 % accuracy behind the primary barriers of the facility!

Faster convergence to statistical accuracy in regions of interest is achieved by simulating more particle tracks there. Regions are prioritized by giving them different weights:

Weight / Importance Factor	Number of Particles Simulated
$w = \frac{1}{N}$	N

As w increases, dose rate remains the same but accuracy increases.