n_TOF
Findings on the neutron sensitivity from Geant4 simulations

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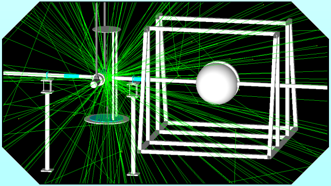
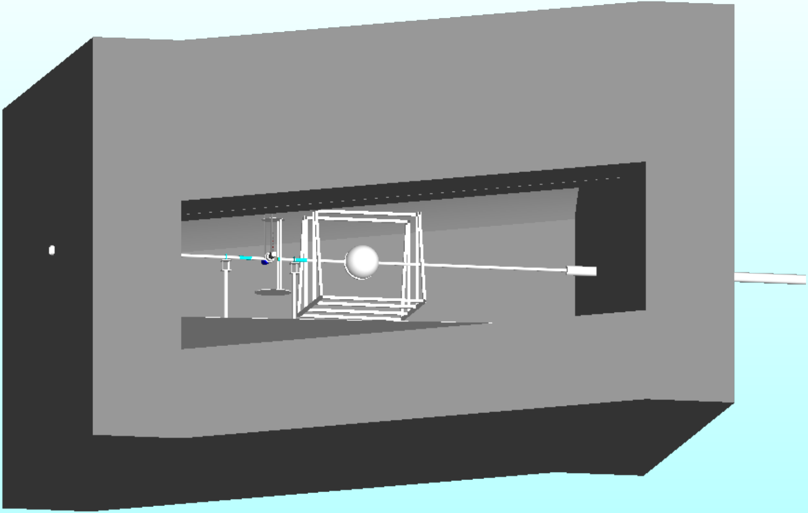


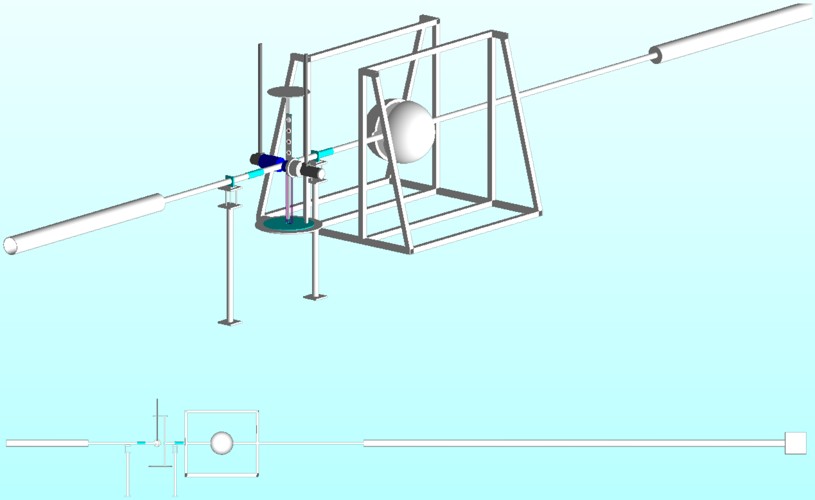
Overview

- Previously...
- Carbon
- Revelations

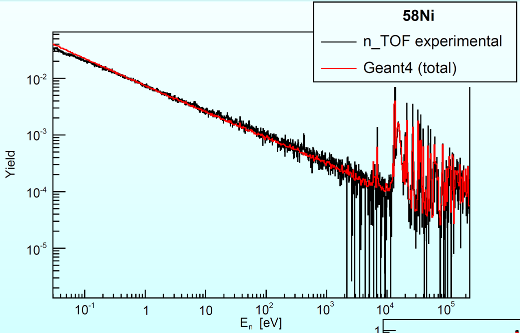
Reminder of what we have...

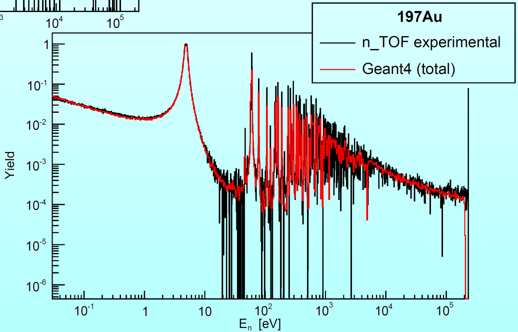


...still of what we have...

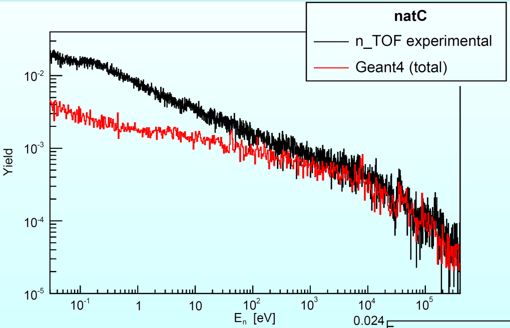


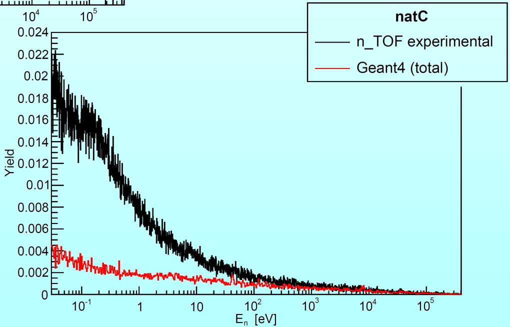
... and what we like!



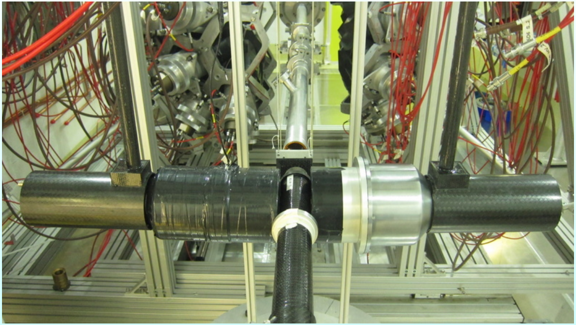


Now, something we didn't like!





What could it be?



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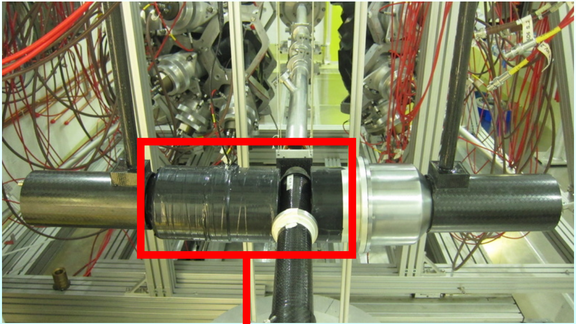
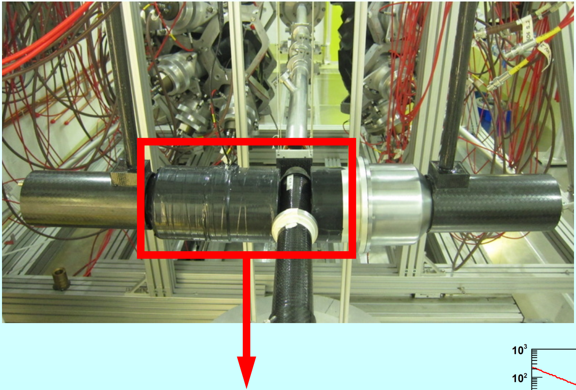


PVC?

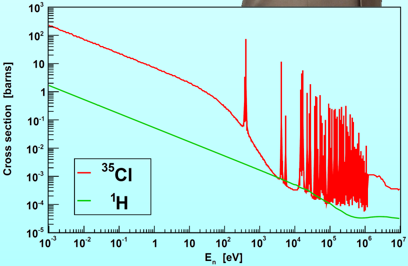
$(\mathbf{C}_2\mathbf{H}_3\mathbf{Cl})_n$

What could it be?

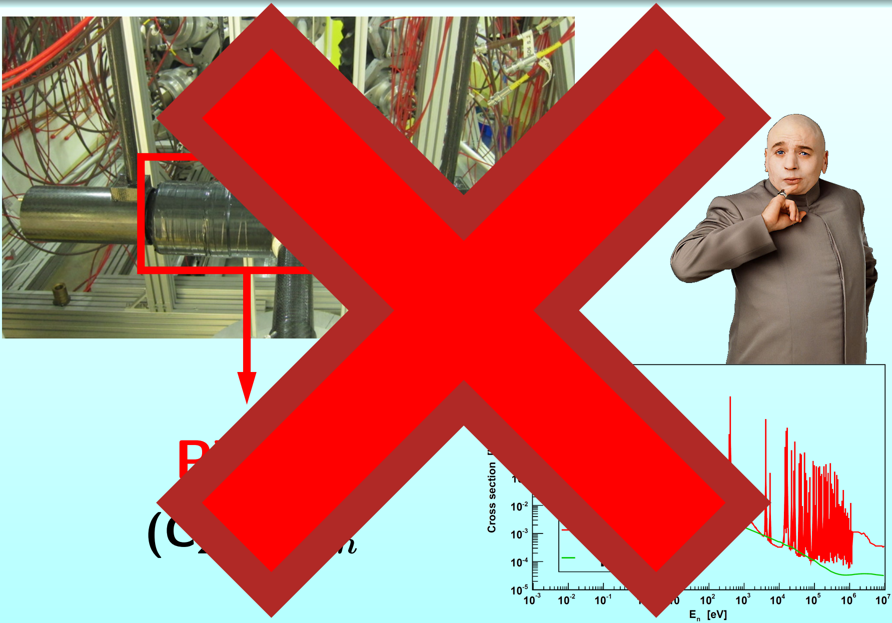


PVC?

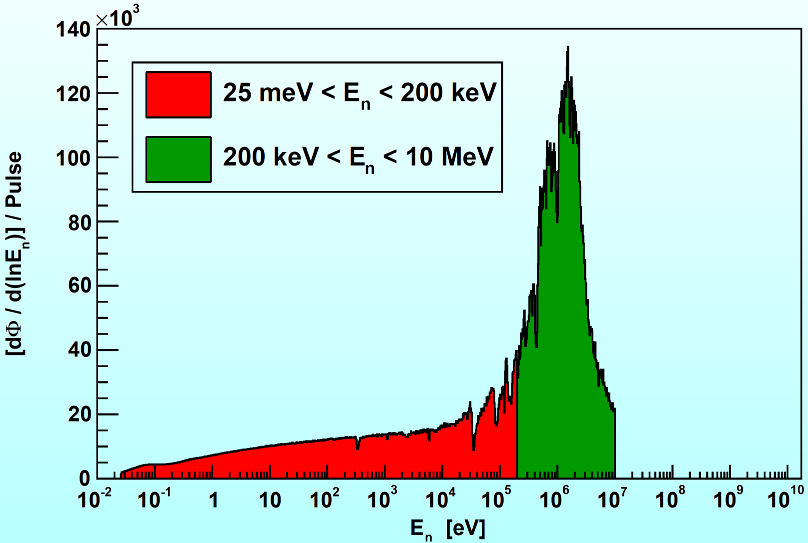
$(C_2H_3Cl)_n$



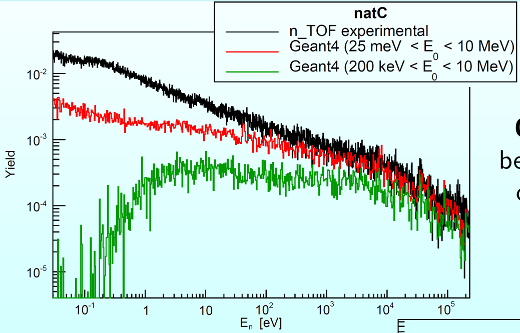
What could it be?



Neutron flux

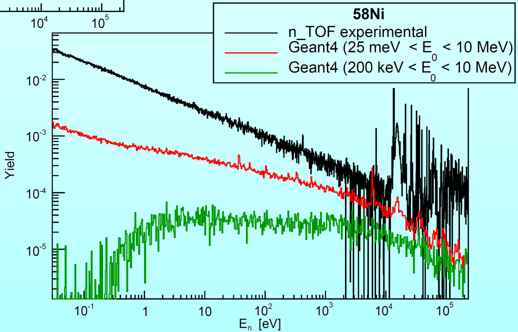


Delayed component (from above 200 keV)

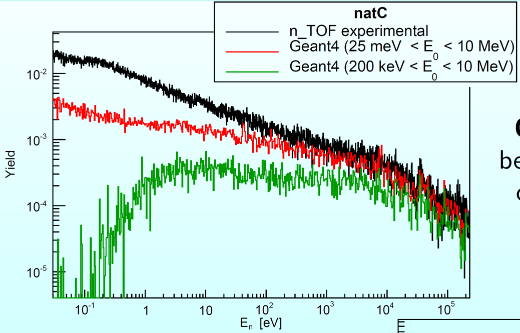


Observe: primary neutrons between 200 keV and 10 MeV contribute down to ∼1 eV!

Notice:
different relative contribution of the delayed component to $^{\mathrm{nat}}$C and ^{58}Ni data!



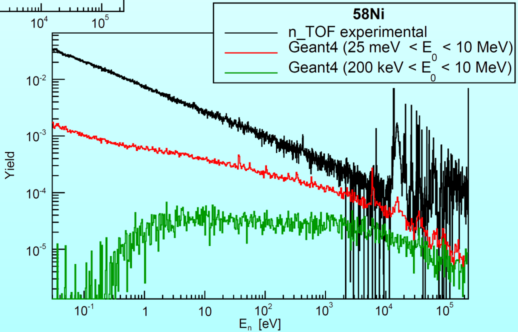
Delayed component (from above 200 keV)



Observe: primary neutrons between 200 keV and 10 MeV contribute down to ~1 eV!

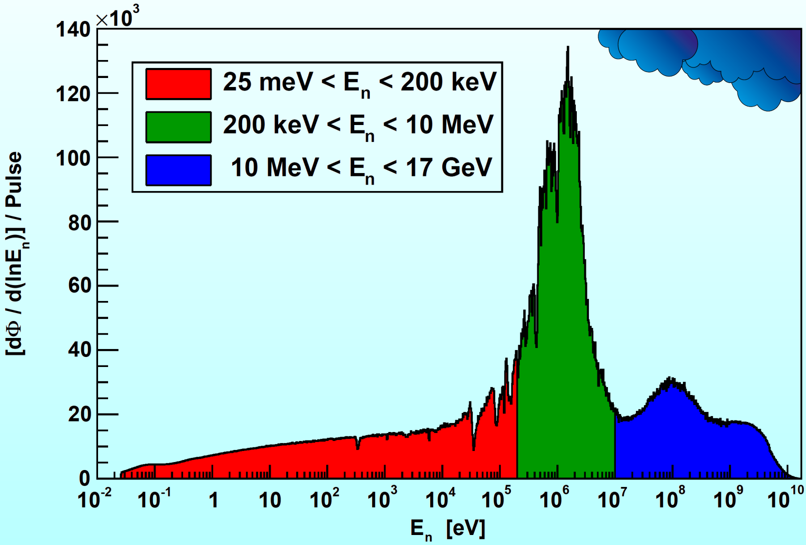
Notice:
different relative contribution of the delayed component to ^{nat}C and ^{58}Ni data!

Increased multiple scattering for thicker ^{nat}C sample!

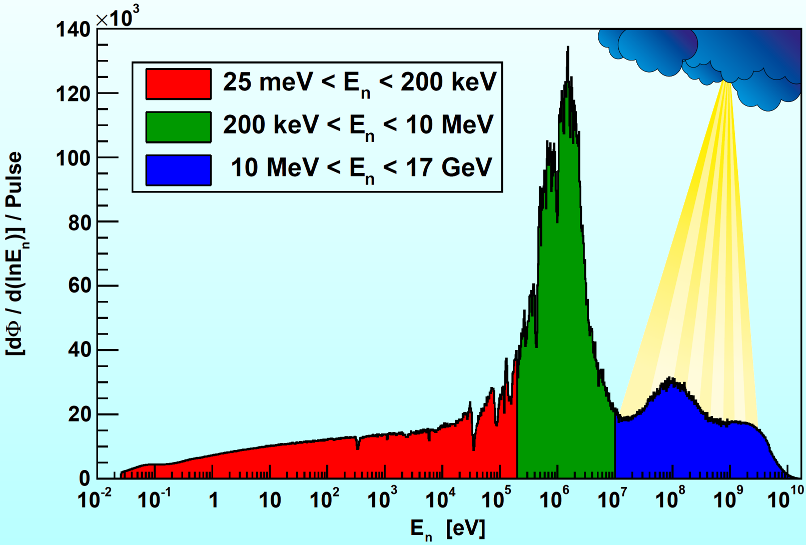


...4 months later...

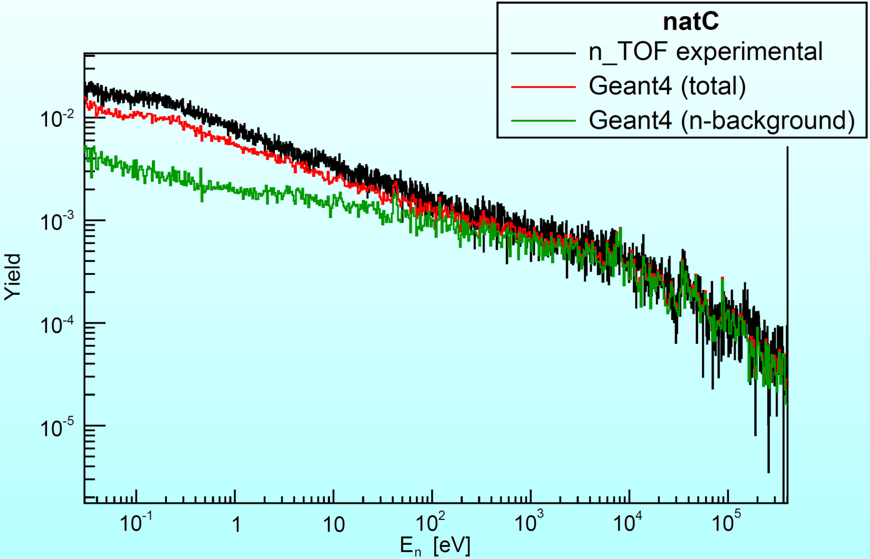
Extended neutron flux



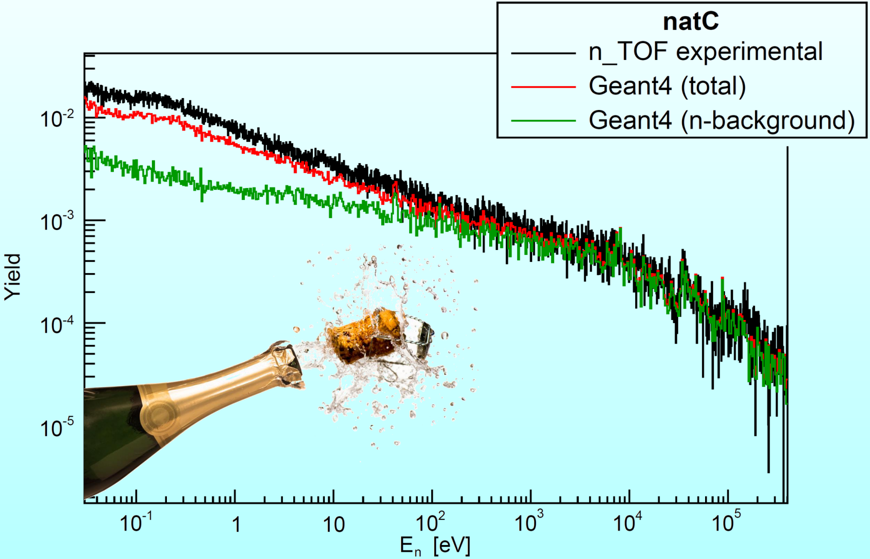
Extended neutron flux



Tadaaaa!


natC
n_TOF experimental
Geant4 (total)
Geant4 (n-background)
Yield
10-2
10-3
10-4
10-5
10-1
1
10
10^2
10^3
10^4
10^5
E_n [eV]

Tadaaaa!


natC
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1
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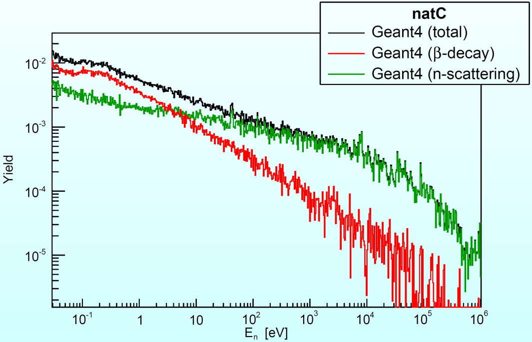
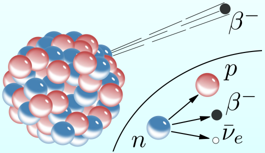
10^3
10^4
10^5
E_n [eV]

J'accuse... β-rays!





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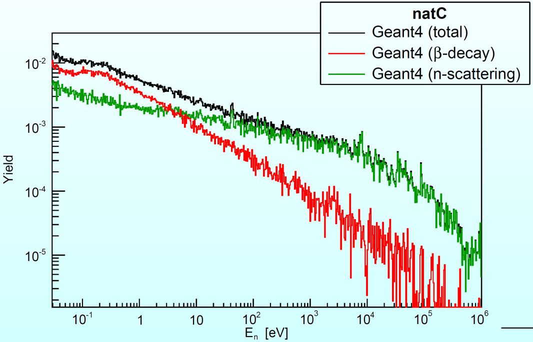
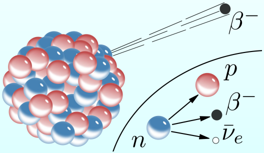




Reaction examples:

^{12}C$(n,p)^{12}$B
^{12}C$(n,p+\alpha)^{8}$Li
^{12}C$(n,p+d+\alpha)^{6}$He
^{12}C$(n,2n)^{11}$C

		$\langle E_\beta \rangle$	$T_{1/2}$
β^-	^{12}B	6.35 MeV	20 ms
	^{13}B	6.35 MeV	17 ms
	^{8}Li	6.20 MeV	838 ms
	^{9}Li	5.70 MeV	178 ms
	^{6}He	1.57 MeV	807 ms
β^+	^{11}C	0.38 MeV	20.4 min
	^{10}C	0.81 MeV	19.3 s
	^{9}C	6.43 MeV	127 ms

Radioactive decay spectrum

From normalized decay distribution:

$$f(t) = \frac{1}{\tau} e^{-t/\tau}$$

and time-energy correlation:

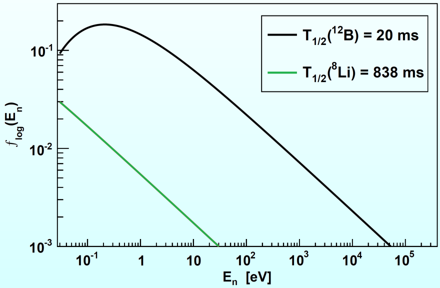
$$E_n = \frac{m_n L^2}{2t^2}$$

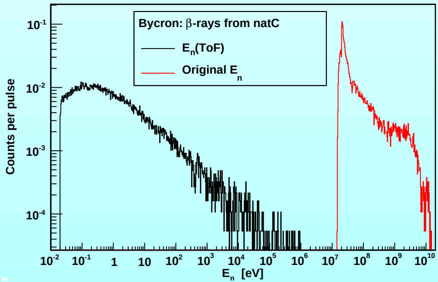
defining:

$$\varepsilon \equiv \frac{L}{\tau}\sqrt{\frac{m_n}{2}}$$

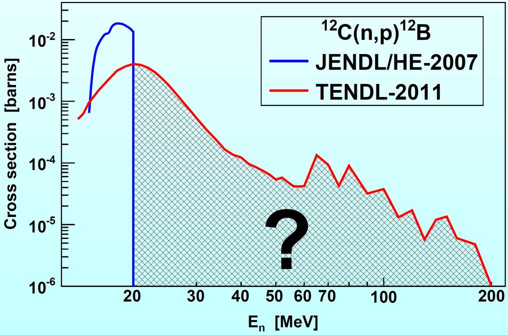
we have:

$$f_{\log}(E_n) = \frac{\varepsilon}{2} \cdot \frac{e^{-\varepsilon/\sqrt{E_n}}}{\sqrt{E_n}}$$





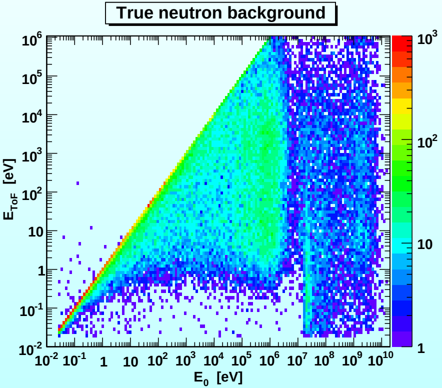
Inelastic scattering cross section

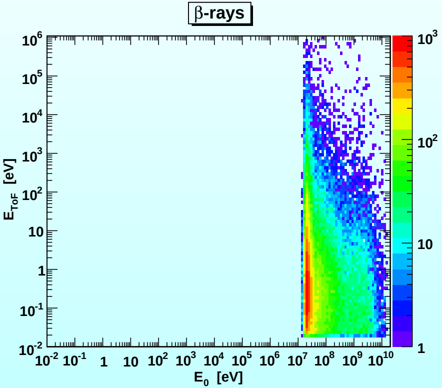


- In Geant4 output data, inelastic reactions (creating β-radioactive isotopes) start contributing at $\sim$15 MeV, strongly increasing at 20 MeV.
- Geant4 high-precision models stop at 20 MeV! Above this energy, parameterizations and limited cross section extensions do exist. However, effective models are used for handling physical interactions.
- Huge discrepancies for dominant $^{12}\mathrm{C}(n,p)^{12}\mathrm{B}$ reaction throughout the evaluated libraries.

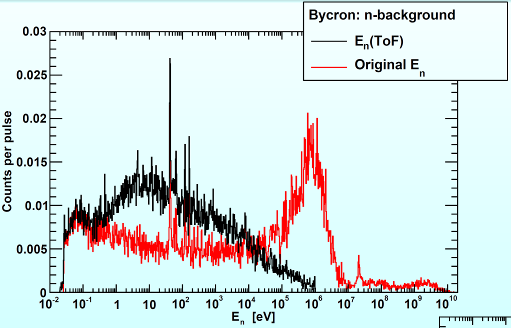
Carbon measurements can not be used for evaluating the neutron background below 1 keV!

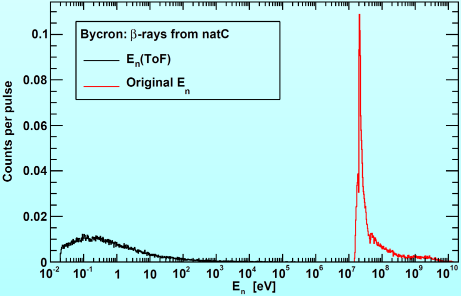
Time-energy correlation



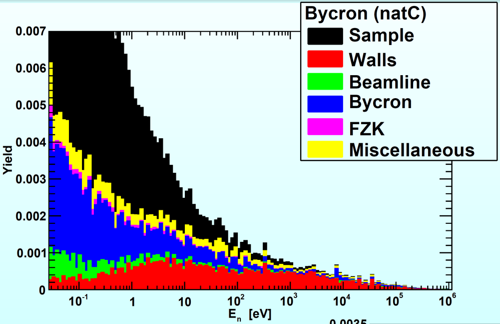


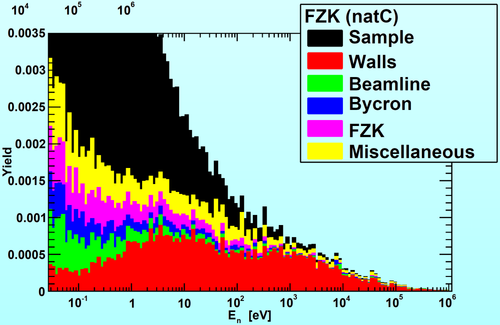
Projections



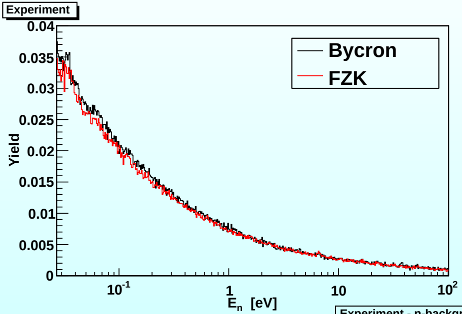


Components analysis



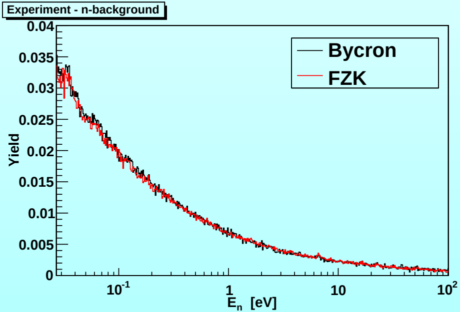


^{58}Ni - with and without the neutron background

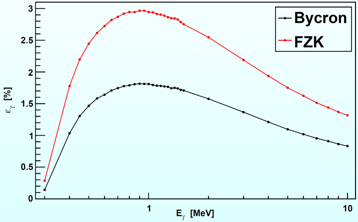


Observe: clear difference between the detectors before correcting for the neutron background!

Notice: the difference disappears upon subtracting the neutron background!



Neutron sensitivity (conventional definition)



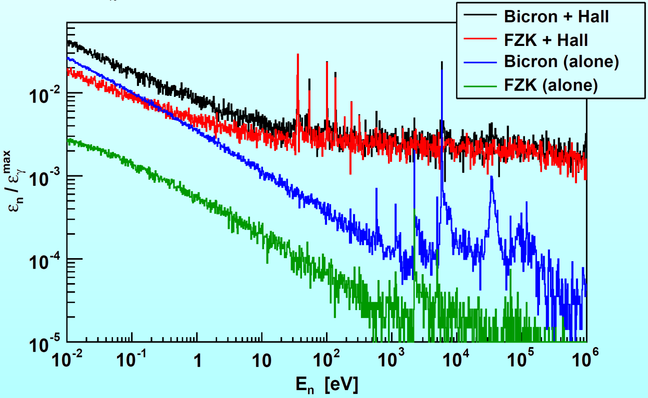
Total efficiency = intrinsic × geometrical

Threshold: 200 keV

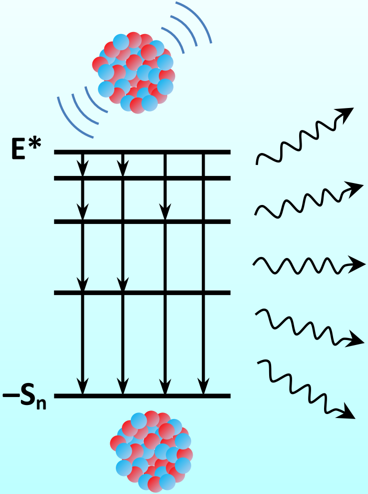
Bycron: $\varepsilon_\gamma^{\max} = 1.81\%$

FZK: $\varepsilon_\gamma^{\max} = 2.97\%$

Thus defined, the neutron sensitivity is the detector response to the neutrons **of** certain energy, not **at** the given energy!



γ-cascades



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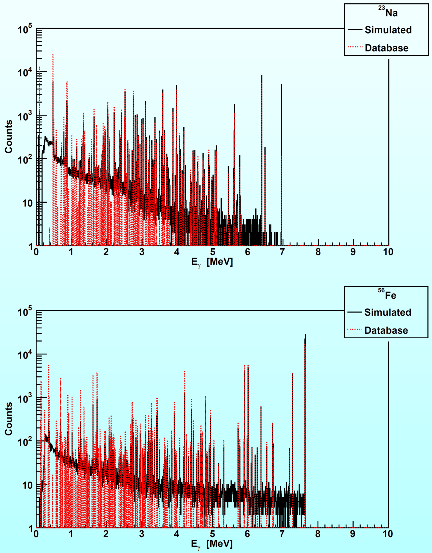
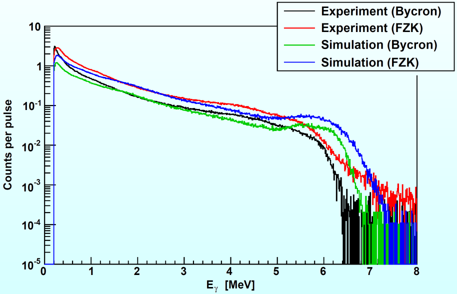
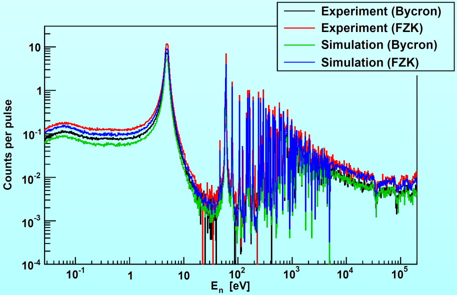


Effect on counts (^{197}Au)

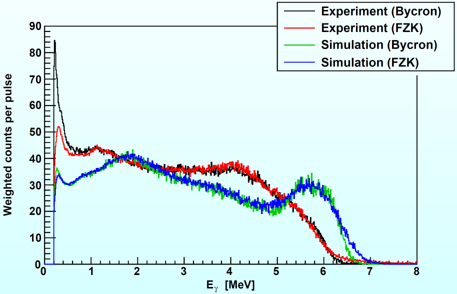
- Due to the lack of γ-correlations, simulated cascade path is different from the experimental one.
- Different γ-distribution affects the average detection efficiency due to the efficiency being dependent on γ-ray energy.
- Consequence: clear difference in the number of simulated and experimental counts!

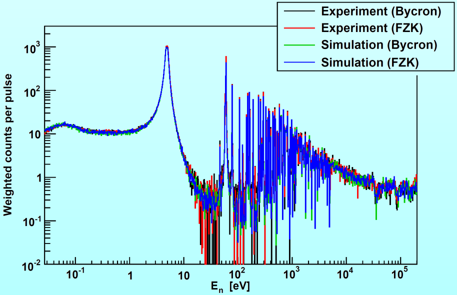




Weighting function saves the day!

- The purpose of the weighting function is to make the yield independent of the cascade path.
- Indeed, the weighting procedure brings the weighted counts from simulation and experiment into a perfect agreement!
- Conclusion: weighting function is the final bridge between the simulation and experiment!





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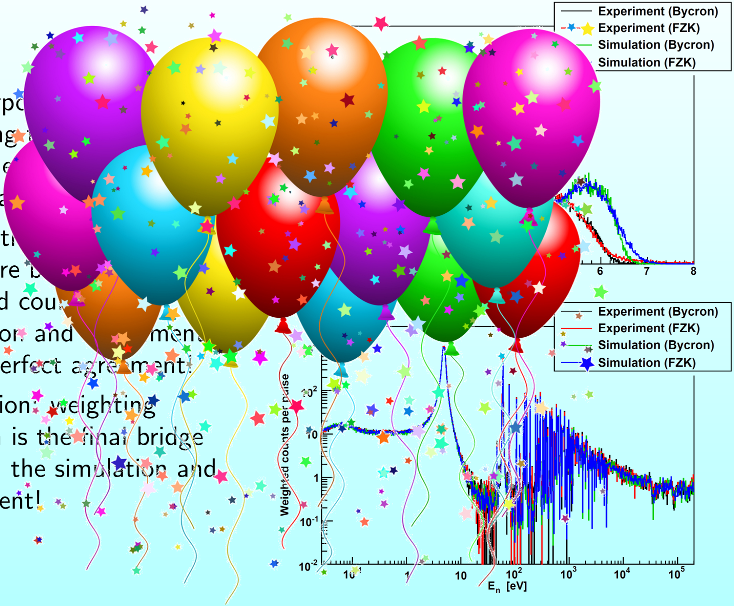
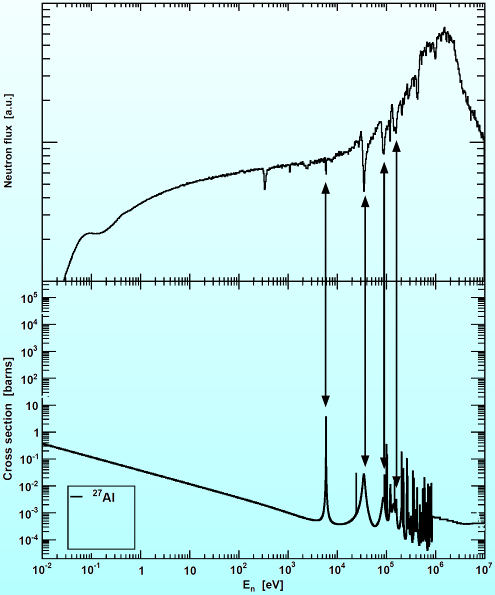


Totally unrelated fun fact



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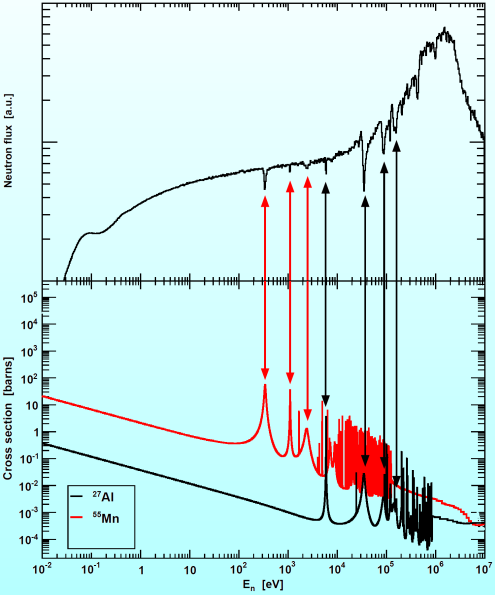

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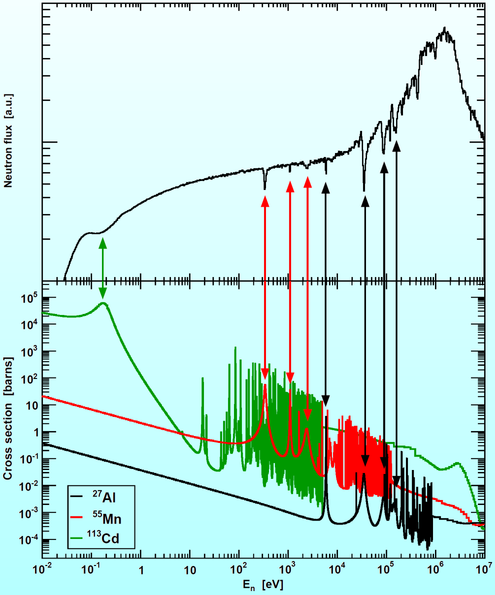

Summary

We have:

- verified the accuracy of Geant4 simulations of the neutron sensitivity (agreement between C data and simulations above 1 keV)
- solved the C mystery below 1 keV (large contribution from ^{12}B 20 ms decay)
- investigated and better understood the neutron physics section in Geant4 both at low energy and above 20 MeV

Main conclusions from our work:

- Geant4 can be reliably used to simulate the neutron background from thermal to 1 MeV
- C measurement cannot be used to determine the neutron background below 1 keV
- Bicron C_6D_6 has a neutron sensitivity $\sim$10 times larger than the FZK (Al housing)
- the neutron sensitivity of the whole setup is up to a factor of 100 higher than the FZK detector alone (for $E_n > 1$ keV)
- at low energy, the overall neutron background in Bicron C_6D_6 is more than a factor of 2 higher than the FZK one

A paper on the simulations of the neutron background is in preparation.

Thank you for listening!

Inelastic reactions creating β-radioactive isotopes

Carbon (β^+)

$^{12}\mathrm{C}(n,2n)^{11}\mathrm{C}$
$^{12}\mathrm{C}(n,3n)^{10}\mathrm{C}$
$^{12}\mathrm{C}(n,4n)^{9}\mathrm{C}$

Boron (β^-)

$^{12}\mathrm{C}(n,p)^{12}\mathrm{B}$
$^{13}\mathrm{C}(n,p)^{13}\mathrm{B}$
$\rightarrow$ visible ^{13}C content in $^{\mathrm{nat}}$C

Lithium (β^-)

$^{12}\mathrm{C}(n,p+\alpha)^{8}\mathrm{Li}$
$^{12}\mathrm{C}(n,n+3p)^{9}\mathrm{Li}$
$^{12}\mathrm{C}(n,n+2p+\pi^+)^{9}\mathrm{Li}$
$\rightarrow$ above 10 GeV only theoretical string models are available: even the (exotic) mesons are created

Helium (β^-)

$^{12}\mathrm{C}(n,n+3p+t)^{6}\mathrm{He}$
$^{12}\mathrm{C}(n,n+2p+\alpha)^{6}\mathrm{He}$
$^{12}\mathrm{C}(n,2p+d+t)^{6}\mathrm{He}$
$^{12}\mathrm{C}(n,p+d+\alpha)^{6}\mathrm{He}$
$^{12}\mathrm{C}(n,{}^{3}\mathrm{He}+\alpha)^{6}\mathrm{He}$
$^{12}\mathrm{C}(n,{}^{7}\mathrm{Be})^{6}\mathrm{He}$
$^{13}\mathrm{C}(n,2n+2p)^{6}\mathrm{He}$
$^{13}\mathrm{C}(n,n+p+d+\alpha)^{6}\mathrm{He}$
$\vdots$

$\rightarrow$ does not contribute much to the total yield, but interesting for all of these reactions having been observed in Geant4

Radioactive decay distribution

Starting from a normalized radioactive decay distribution:

$$f(t) = \tfrac{1}{\tau} e^{-t/\tau}$$

probability conservation dictates:

$$f(t)|\mathrm{d}t| = f(E_n)|\mathrm{d}E_n|$$

therefore:

$$f(E_n) = f(t)\left|\frac{\mathrm{d}t}{\mathrm{d}E_n}\right|$$

From a nonrelativistic time-energy correlation (with $L = 184$ m) it follows:

$$E_n = \frac{m_n L^2}{2t^2} \quad \Rightarrow \quad t = \sqrt{\frac{m_n L^2}{2E_n}}$$

Differentiating:

$$\left|\frac{\mathrm{d}t}{\mathrm{d}E_n}\right| = \sqrt{\frac{m_n L^2}{8E_n^3}}$$

and defining:

$$\varepsilon \equiv \frac{L}{\tau}\sqrt{\frac{m_n}{2}}$$

we are left with:

$$f(E_n) = \frac{\varepsilon}{2} \cdot \frac{e^{-\varepsilon/\sqrt{E_n}}}{\sqrt{E_n^3}}$$

Histogramming over the logarithmic scale, the successive bin widths are increased linearly, amplifying the histogrammed distribution:

$$f_{\log}(E_n) = E_n f(E_n) = \frac{\varepsilon}{2} \cdot \frac{e^{-\varepsilon/\sqrt{E_n}}}{\sqrt{E_n}}$$