29th International Seminar on Interaction of Neutrons with Nuclei (29 May – 2 June 2023)

Neutronic Chain Reactions in Bismuth Salts

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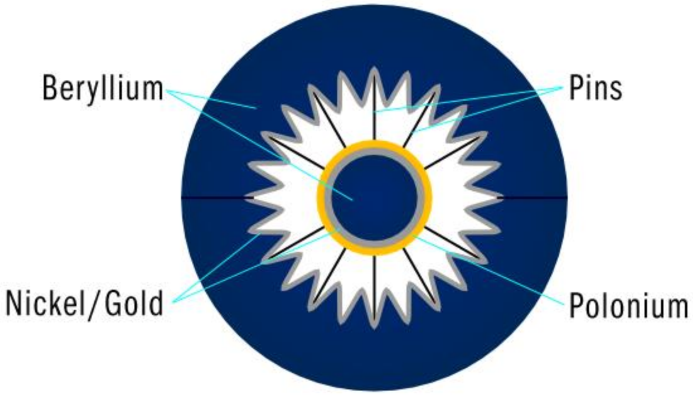
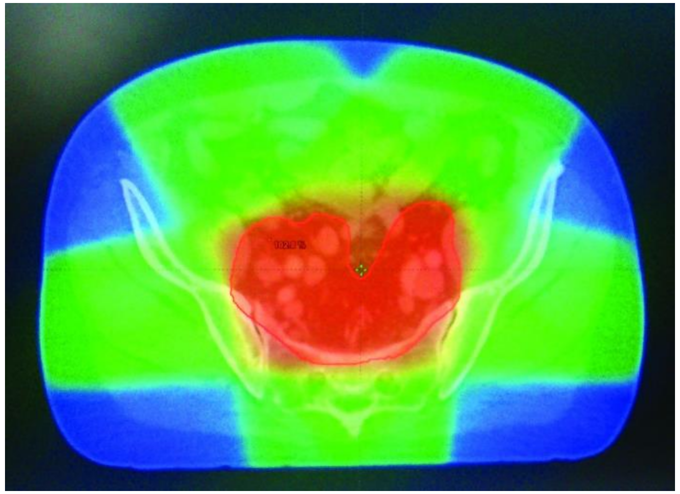
Polonium-210: A Nuclear Oddity

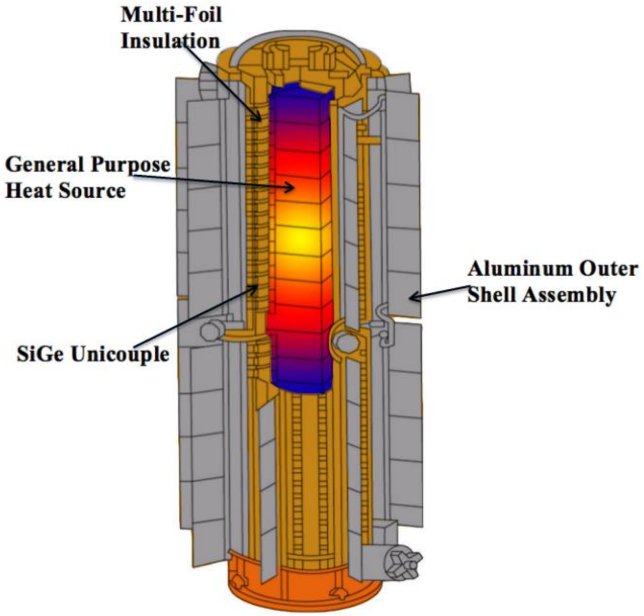
➢ Properties:
- Specific activity of 4490 curies per gram
- Pure alpha-emitter
- Alpha emission energy of 5.41 MeV
- Highly radiotoxic (LD_{50} = 0.89µg)
- "Sublimes" in air due to intense alpha activity

Polonium-210: A Nuclear Oddity

➢Applications:



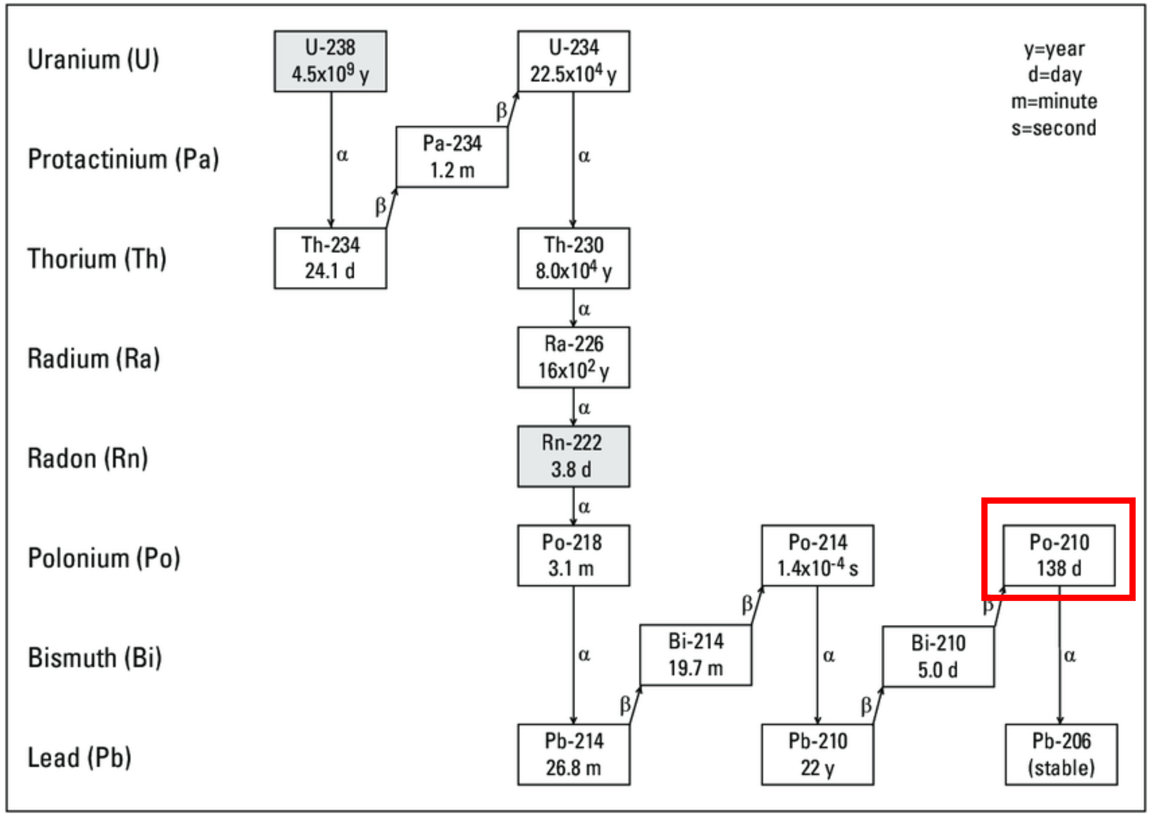




Nuclear weapons | Radiotherapy | Energy generation

Producing Po-210

- Purification from uranium ore
  - Led to its discovery by M. Curie



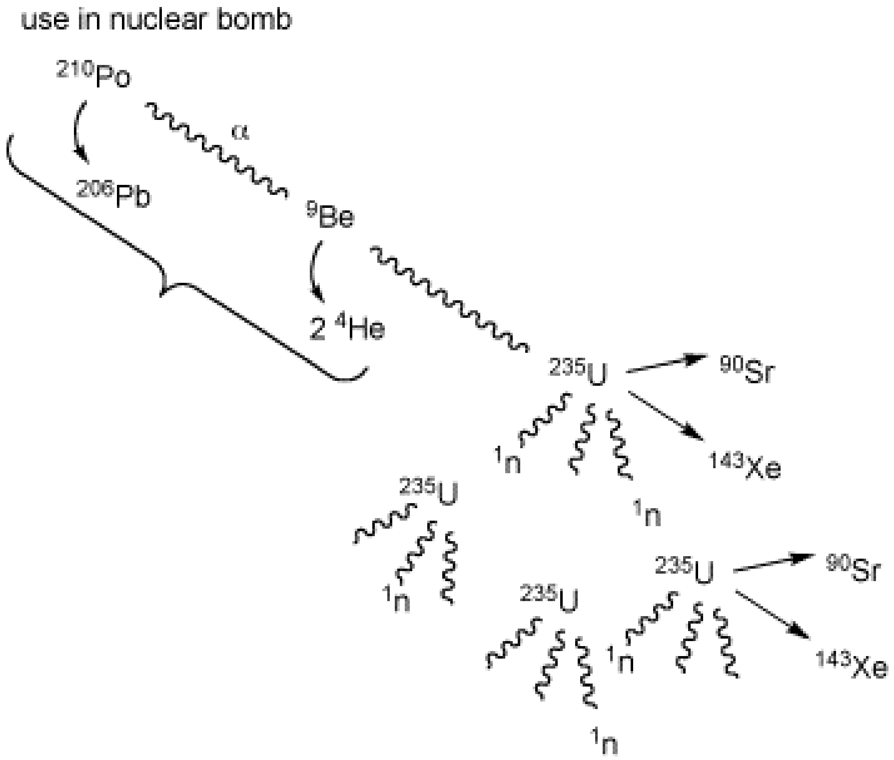
Producing Po-210

➢ Neutron irradiation of bismuth-209
  - Used in the Manhattan Project

$$^{209}Bi + n^0 \rightarrow {}^{210}Bi$$

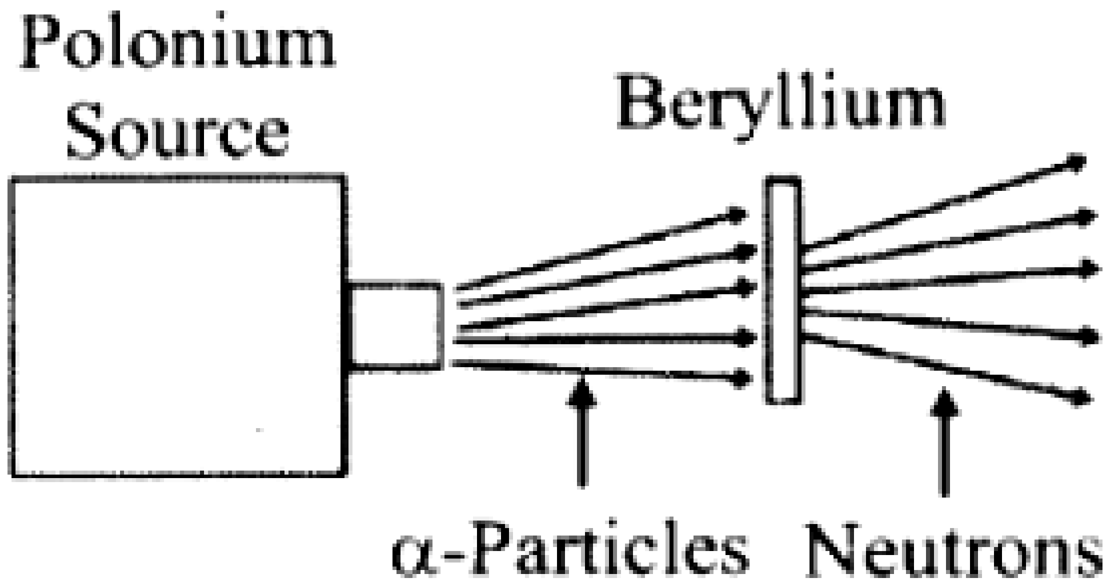
$$^{210}Bi \rightarrow {}^{210}Po + \beta^-$$

$t_{1/2}$ of ^{210}Bi: 5.012 days



Po-210 as an alpha source

- Mixed with light elements, e.g. Be, Li, F to produce neutrons
- Neutron output depends on (α, n) cross section of light element



Introduction | Significance | Methods | Results | Conclusions

Connecting the Dots: Chain Reaction Mechanism

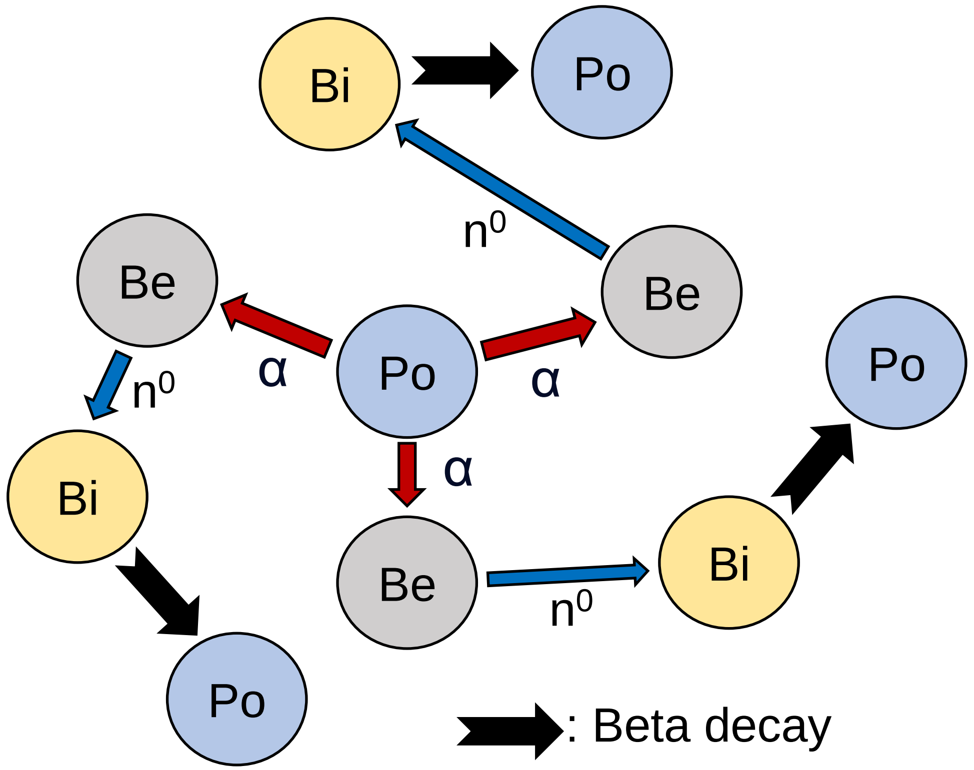
- Alternating (α,n) and neutron absorption reactions:

$$^{210}Po \rightarrow {}^{206}Pb + \alpha$$

$$^{9}Be + \alpha \rightarrow {}^{12}C + n^0$$

$$^{209}Bi + n^0 \rightarrow {}^{210}Bi$$

$$^{210}Bi \rightarrow {}^{210}Po + \beta^-$$



Significance

- ➢Provides a cost-effective and rapid method of producing large quantifies of polonium-210
- ➢Reduces dependence on reactors with high neutron flux for producing polonium-210

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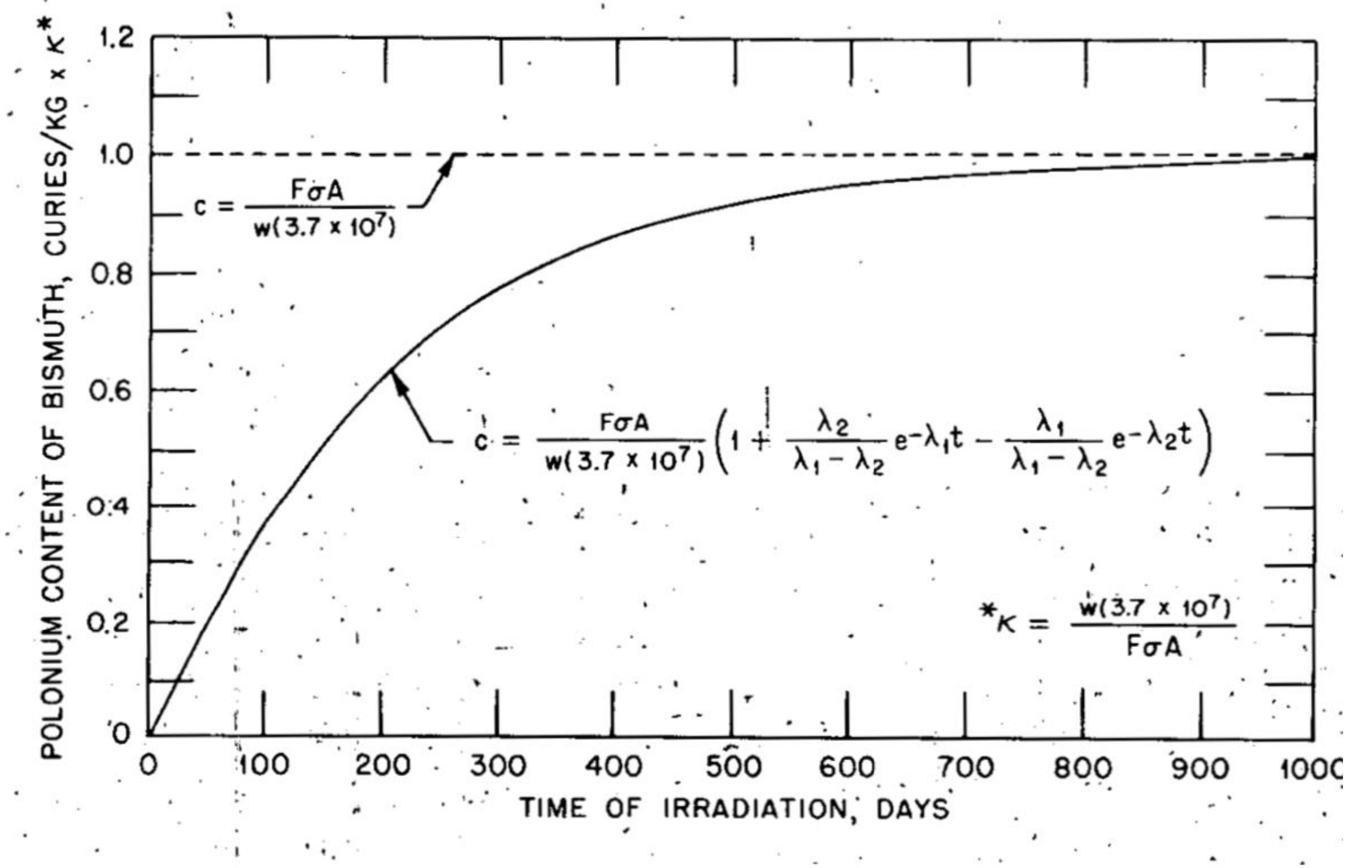
Initiation of chain reaction

- ➢Achieved via neutron irradiation of bismuth salt
- ➢Compared to normal polonium accumulation curve

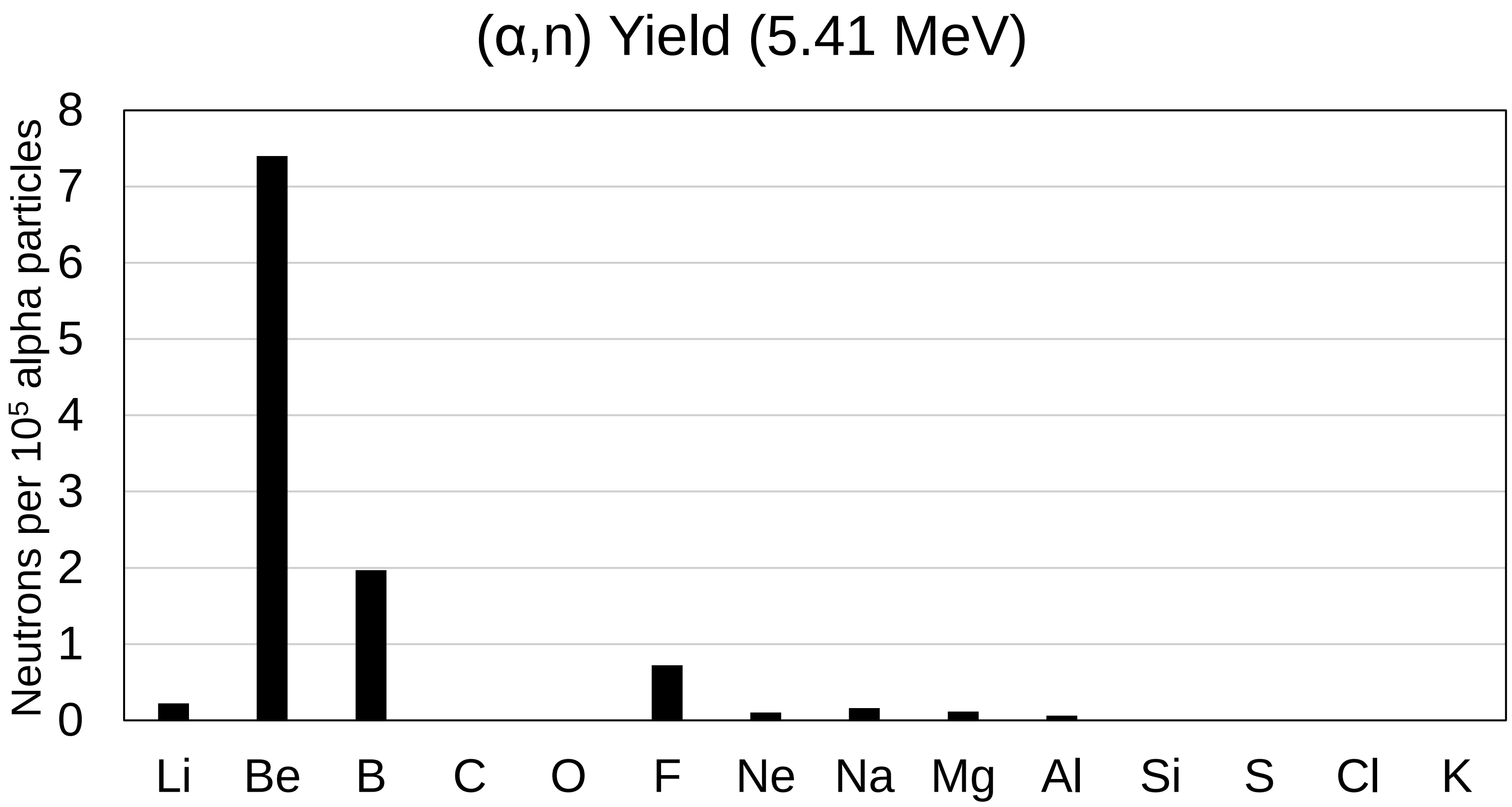


Selection of bismuth salt

- Criteria for bismuth salt to be able to sustain the chain reaction:
  - High Bi density to increase polonium production rate
  - Neutron multiplication to sustain neutron population
  - Neutron moderation for bismuth neutron capture
  - High (α,n) reaction yield

- Bismuth salt chosen: **<u>Bismuth beryllium acetate</u>**

Selection of element for (α,n) reaction



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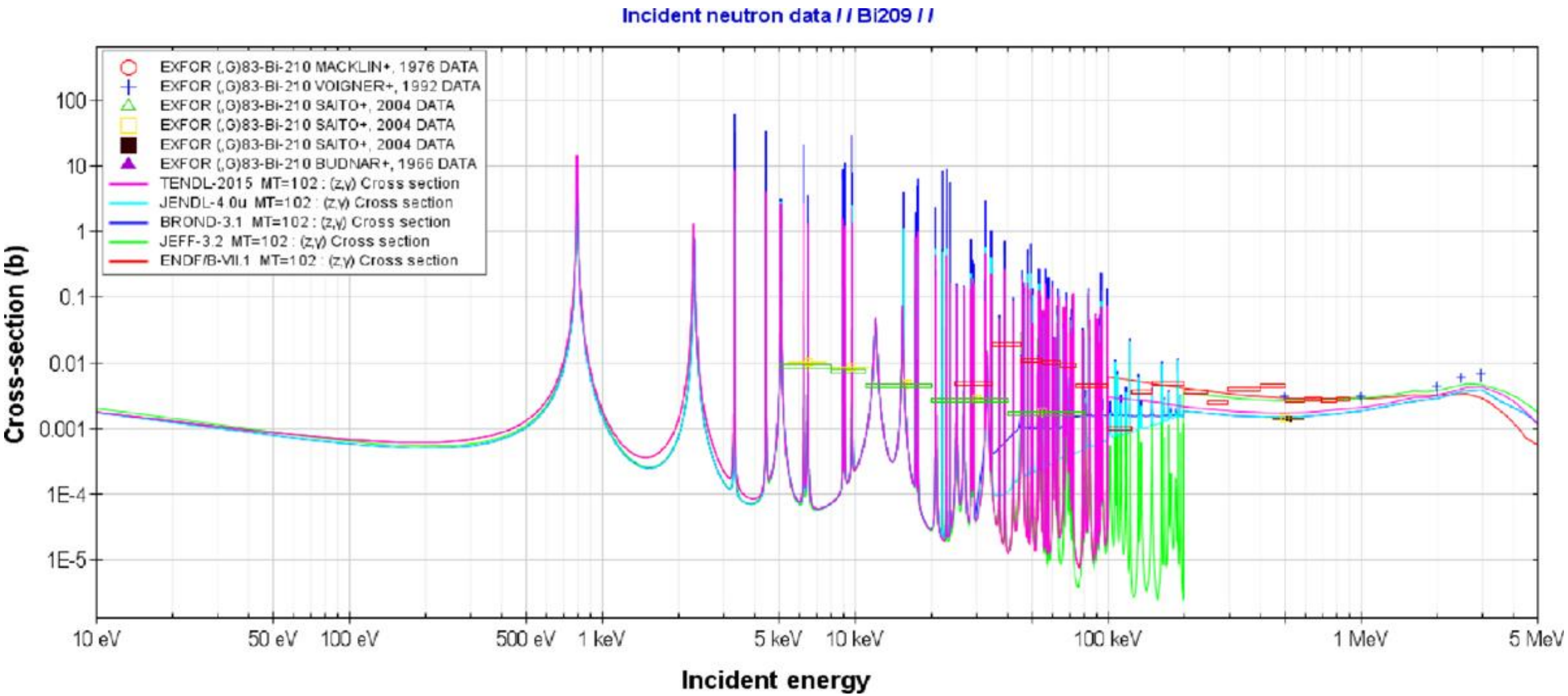
Vlaskin, G. N., Khomyakov, Y. S., & Bulanenko, V. I. (2015). Neutron Yield of the Reaction (α, n) on Thick Targets Comprised of Light Elements. *Atomic Energy*, *117*(5), 357–365. https://doi.org/10.1007/s10512-015-9933-5

Neutron capture cross section of ^{209}Bi



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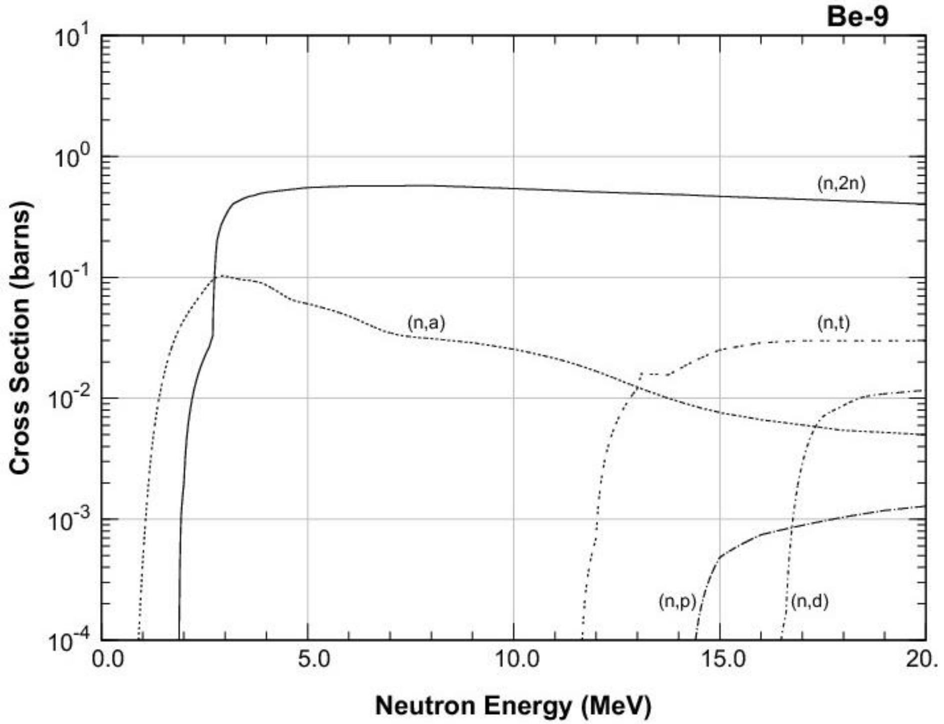
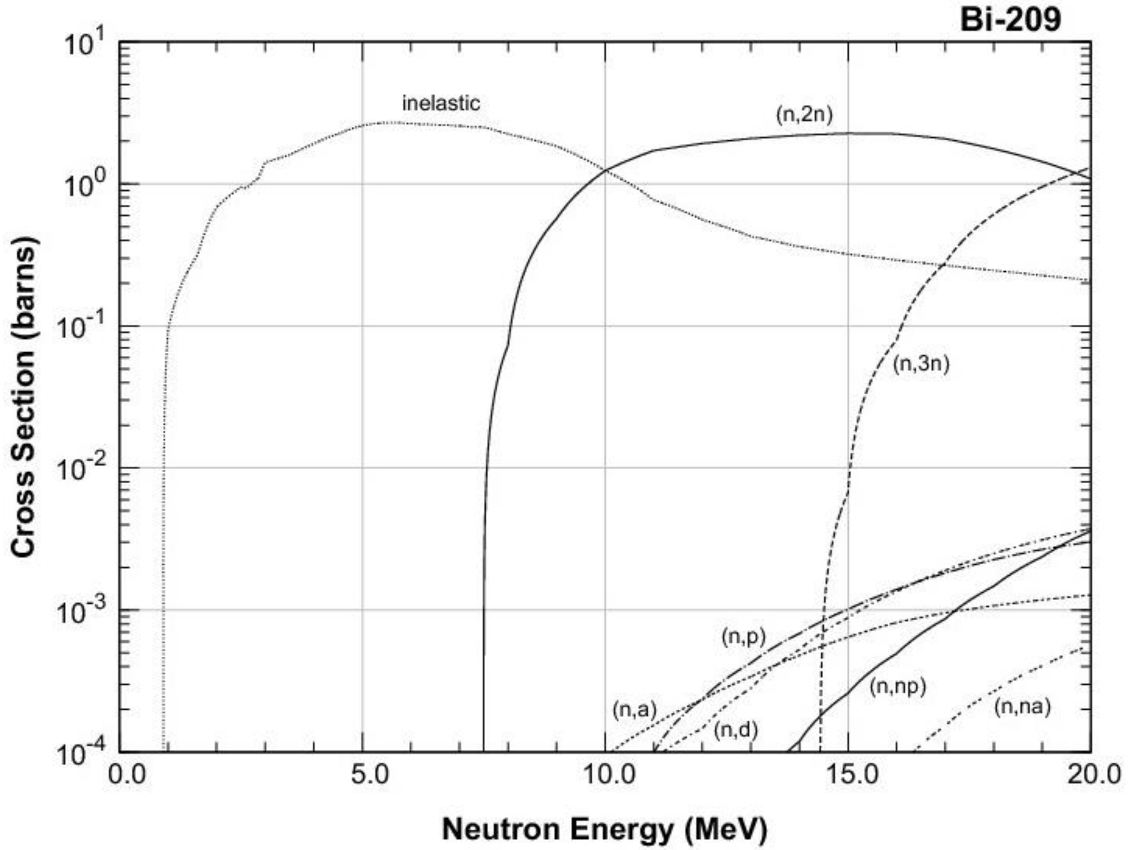
Nuclear data uncertainty analysis for the Po-210 production in MYRRHA | *EPJ N*. (n.d.). https://www.epj-n.org/articles/epjn/full_html/2018/01/epjn170080/F2.html

Neutron multiplication

- ^{209}Bi and ^{9}Be atoms undergo a (n,2n) reaction to increase neutron population with fast neutrons

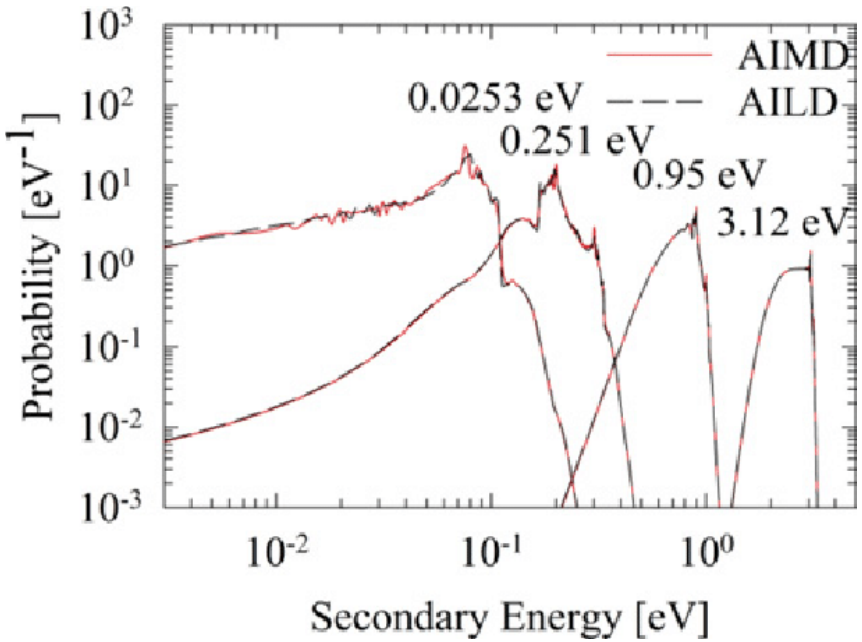


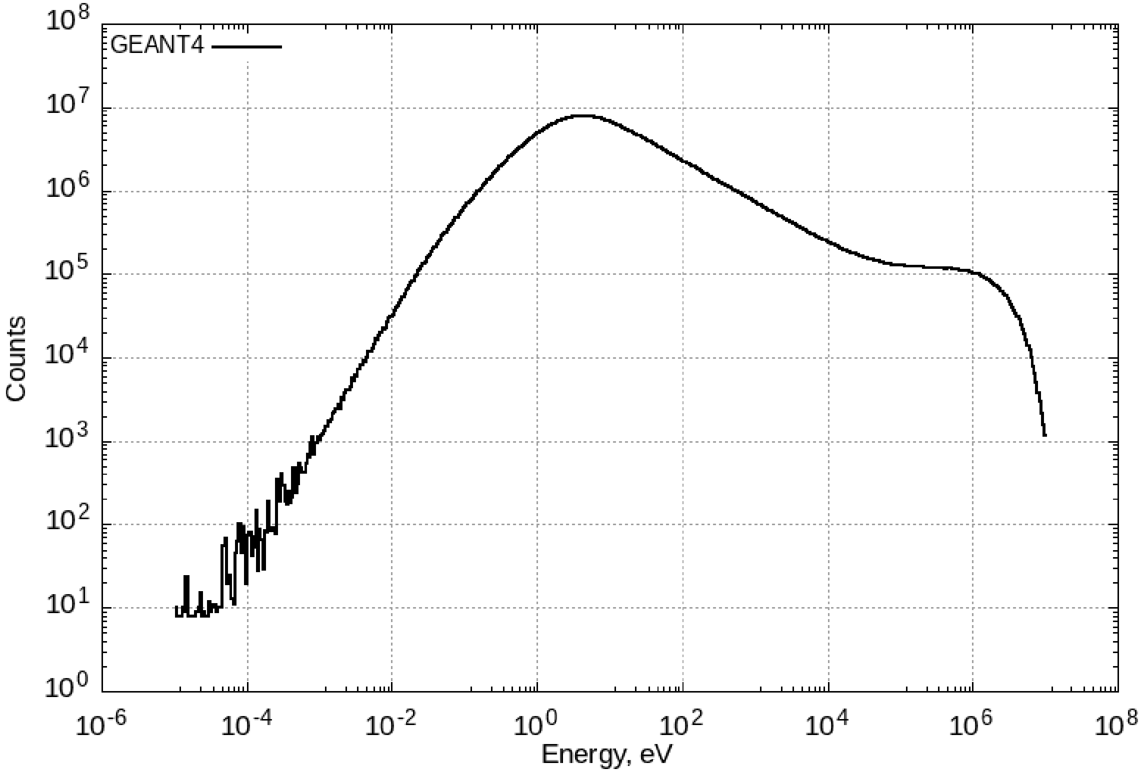


Nuclide Information. (n.d.). https://wwwndc.jaea.go.jp/cgi-bin/nuclinfo2014

Neutron moderation

- High hydrogen and beryllium density allows for efficient neutron moderation to thermal velocities





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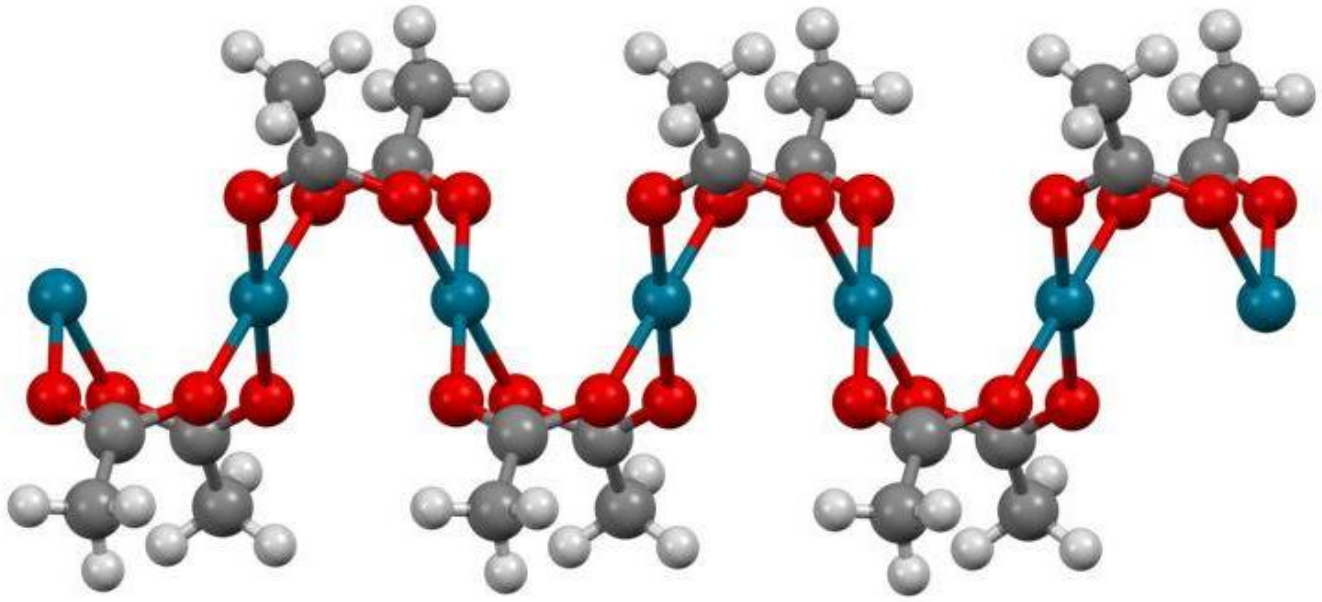
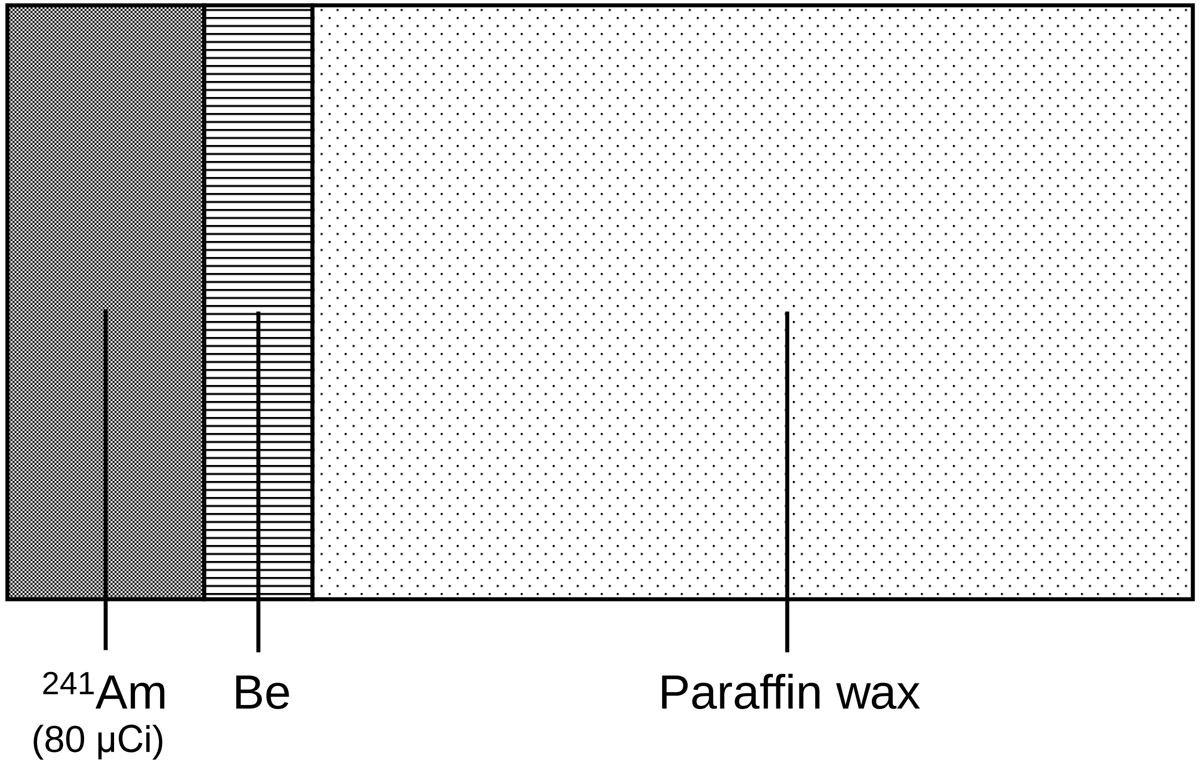
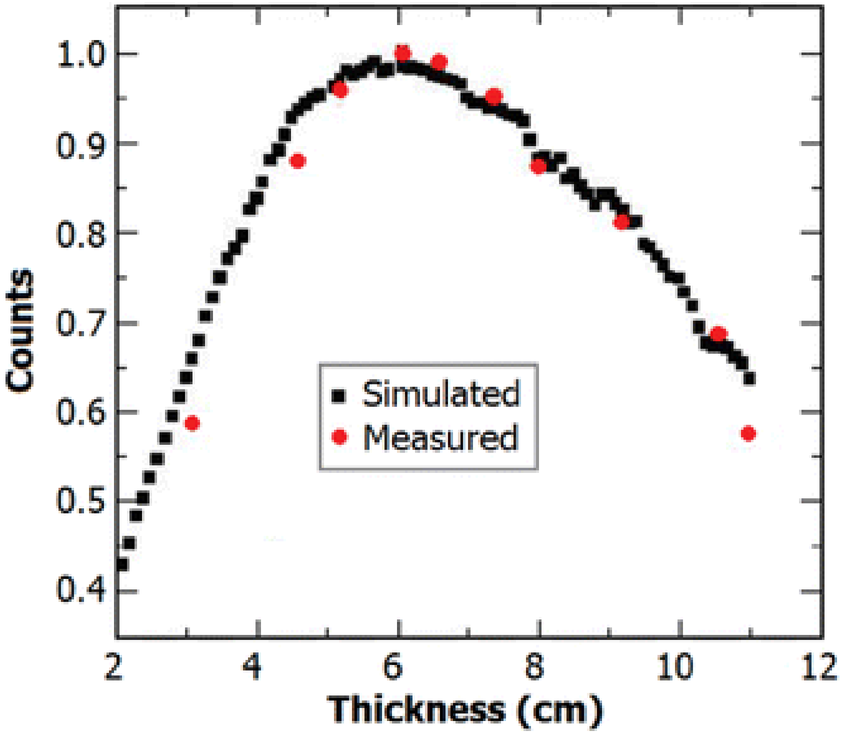
Why acetate?

- Relatively high hydrogen density by mass
- Bismuth beryllium hydroxide was considered due to its higher hydrogen density, but was found to quickly decompose to bismuth beryllate



Neutron Source Construction





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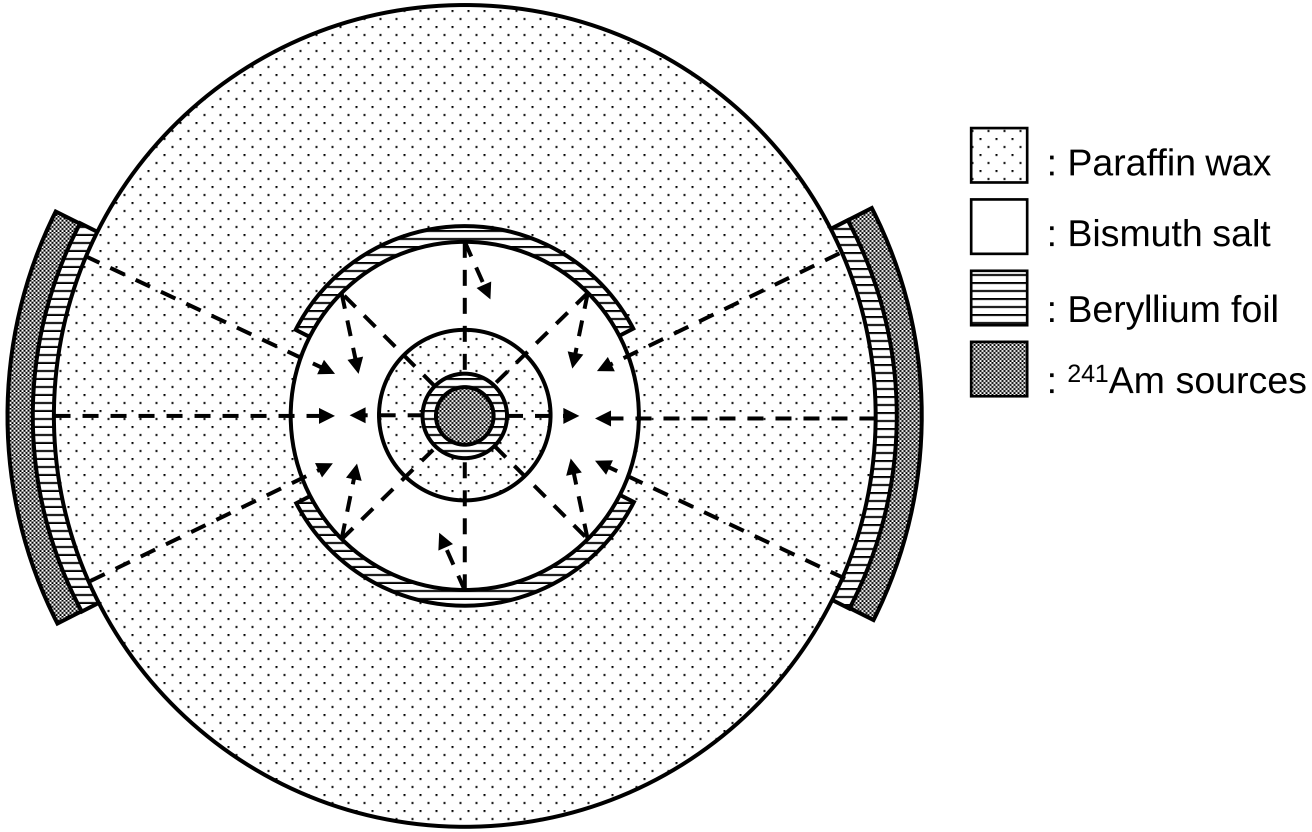
Waheed, A., Ali, N., Baloch, M. A., Qureshi, A. A., Munem, E. A., Rajput, M. A., Jamal, T., & Muhammad, W. (2017). Optimization of moderator assembly for neutron flux measurement: experimental and theoretical approaches. *Nuclear Science and Techniques*, *28*(5). https://doi.org/10.1007/s41365-017-0213-z

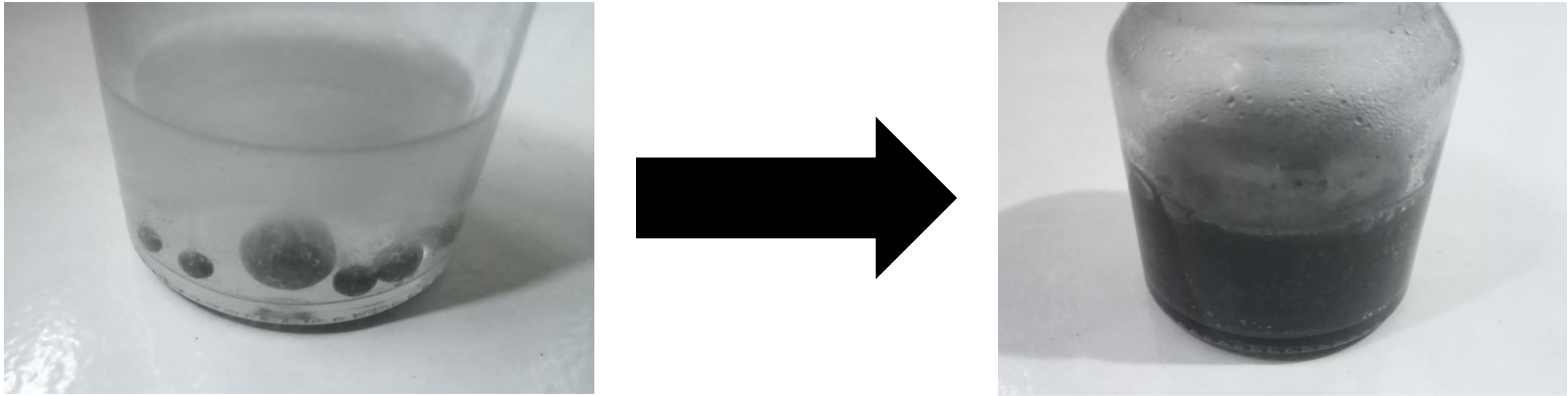
Irradiation Assembly

- ➢Mast source used as central source and plate sources used as peripheral sources
- ➢Beryllium reflectors used to increase neutron flux



Salt preparation

- Cocrystallisation of bismuth and beryllium acetate from hot peroxyacetic acid solution
- Reduces exposure to beryllium dust



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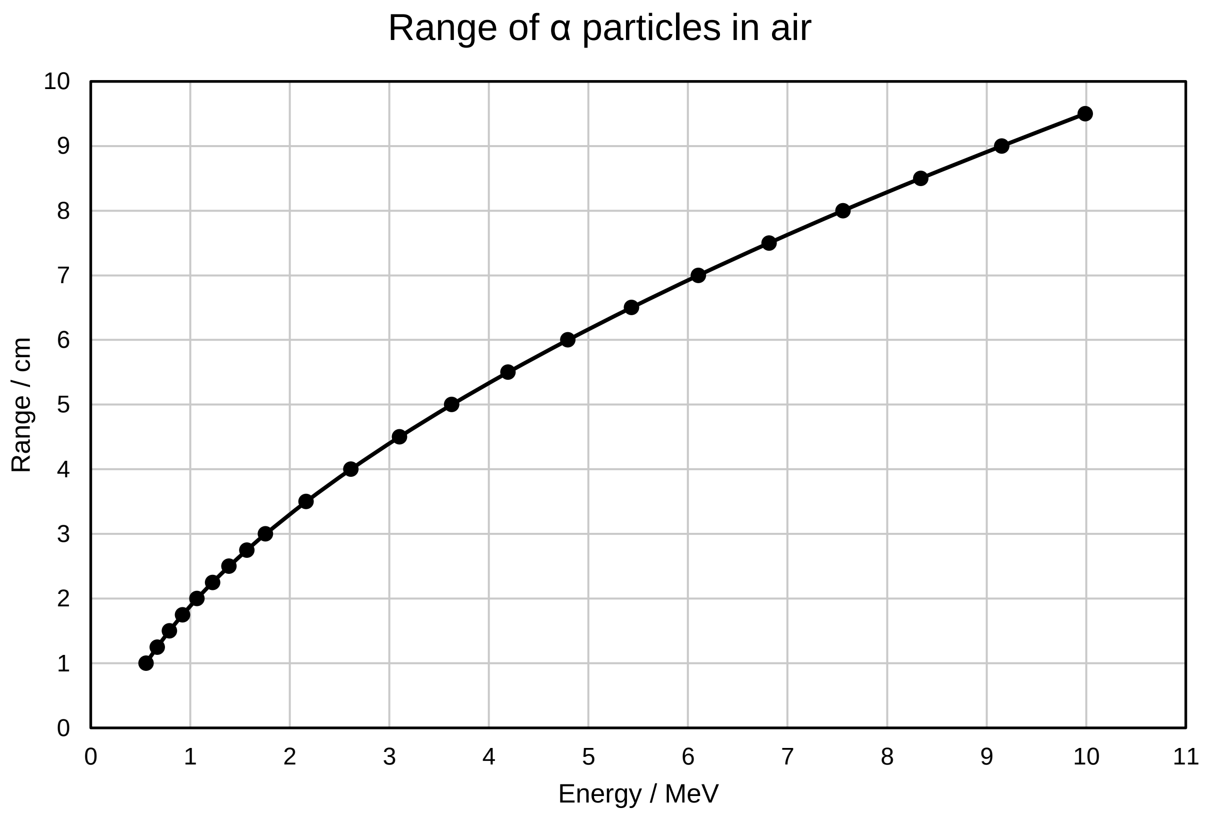
Alpha spectroscopy

- Alpha spectroscopy was used to identify ^{210}Po (characteristic alpha peak at 5.30 MeV)

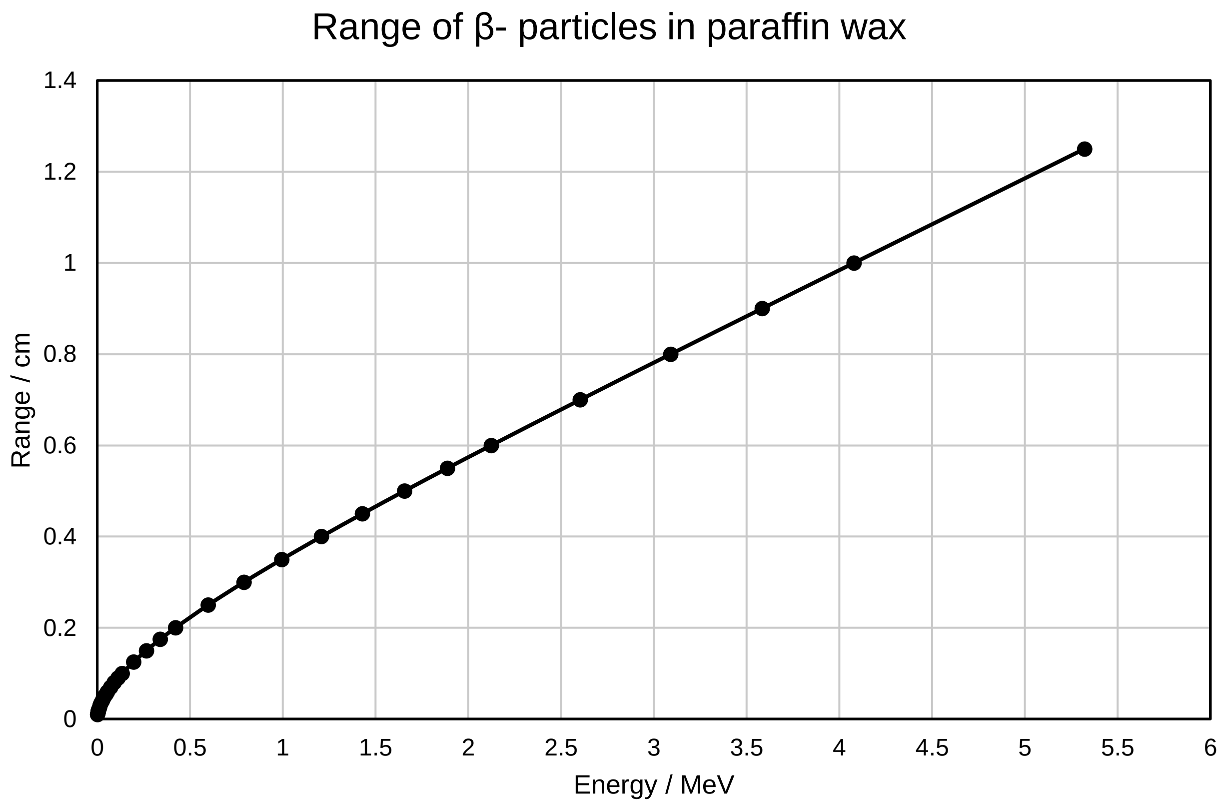
$$R[\text{cm}] = \frac{0.543E[\text{MeV}] - 0.160}{\rho\left[\frac{\text{g}}{\text{cm}^3}\right]}$$



Beta spectroscopy

- Beta spectroscopy was used to identify ^{210}Bi (maximum beta energy of 1.16 MeV)

$$-\frac{dE}{dx} = \frac{4\pi e^4 z^2}{m_0 v^2} NB$$



Mathematical modelling

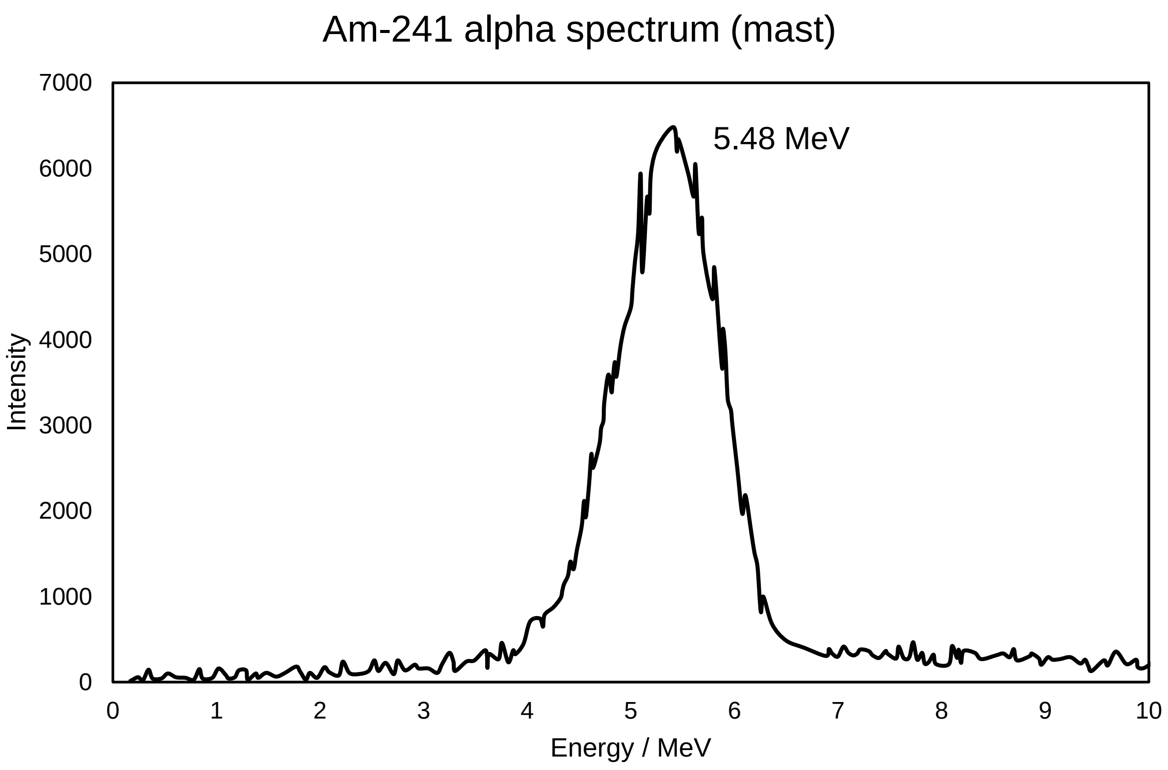
$$N_2 = N_{1(0)} \cdot \frac{\alpha e^{\kappa t}}{1 + \alpha e^{\kappa t}}$$

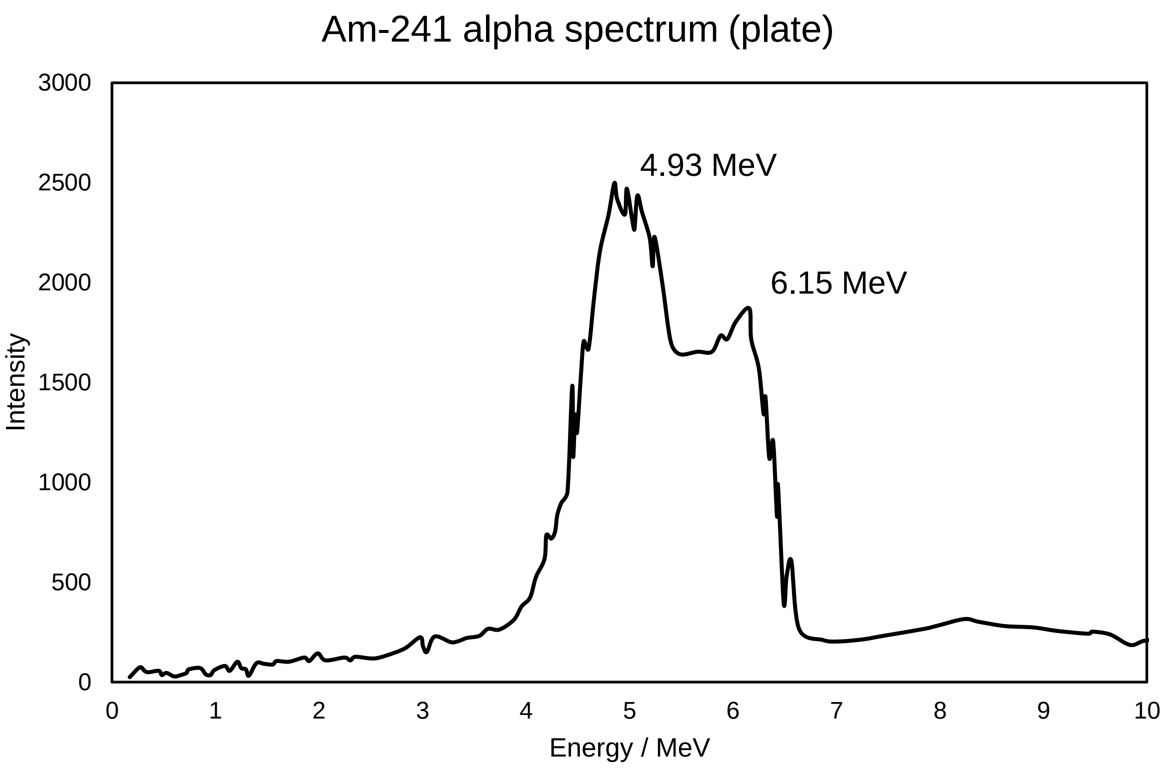
$$\alpha = \frac{\phi \sigma \rho A}{M \varepsilon}$$

$$\kappa = \frac{\lambda_1 n}{\lambda_2}$$

- N_2 is the number of ^{210}Po atoms at time *t*
- $N_{1(0)}$ is the number of ^{209}Bi atoms present initially
- ϕ is the neutron flux of the initial neutron source
- σ is the neutron capture cross section of ^{209}Bi
- ρ is the density of ^{209}Bi
- A is Avogadro's number
- M is the molar mass of ^{209}Bi
- ε is the neutron multiplication factor
- λ_1 is the decay constant of ^{210}Bi
- λ_2 is the decay constant of ^{210}Po
- n is the neutron conversion coefficient

Source characterisation (alpha)

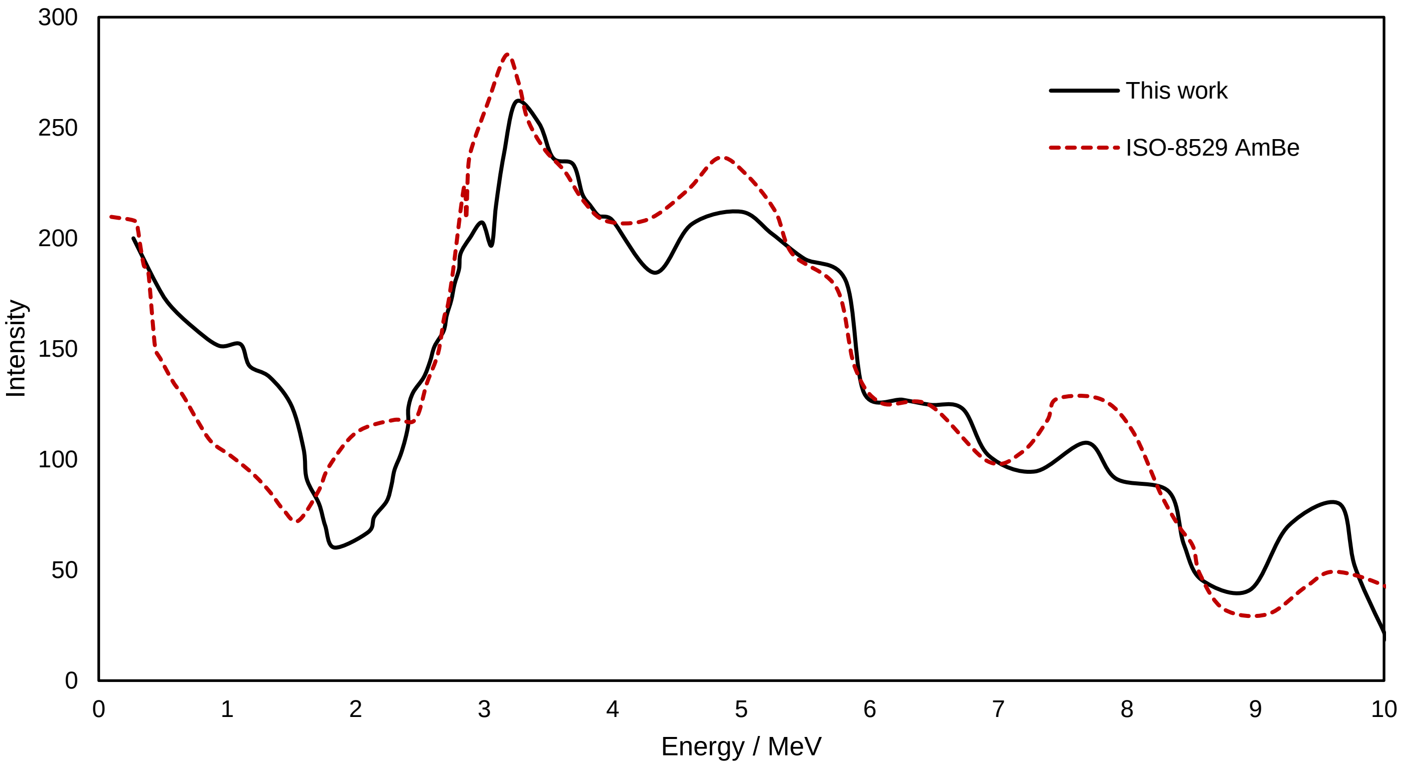




Source characterisation (neutron)

80μCi AmBe source

AmBe neutron source spectrum



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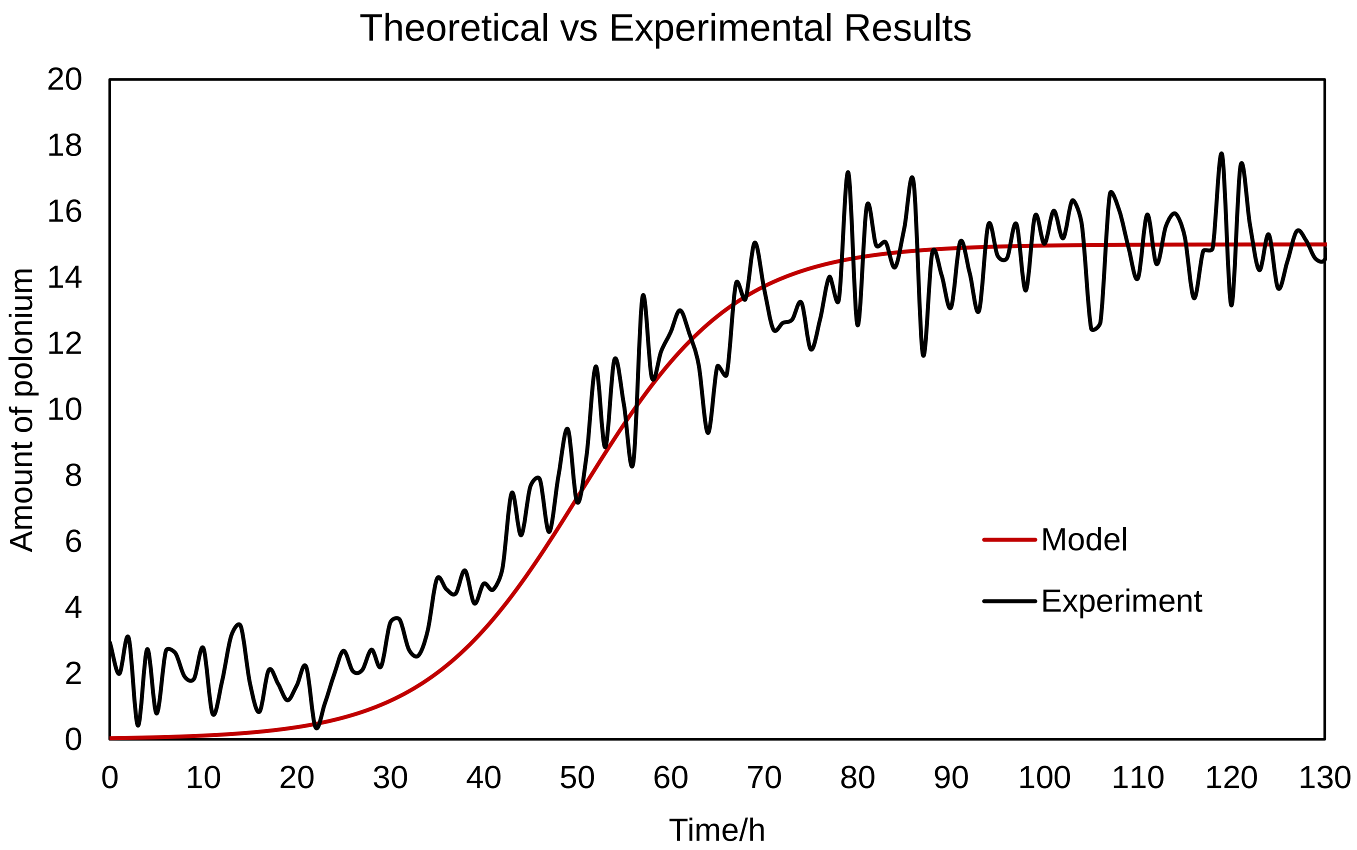
Chain reaction propagation



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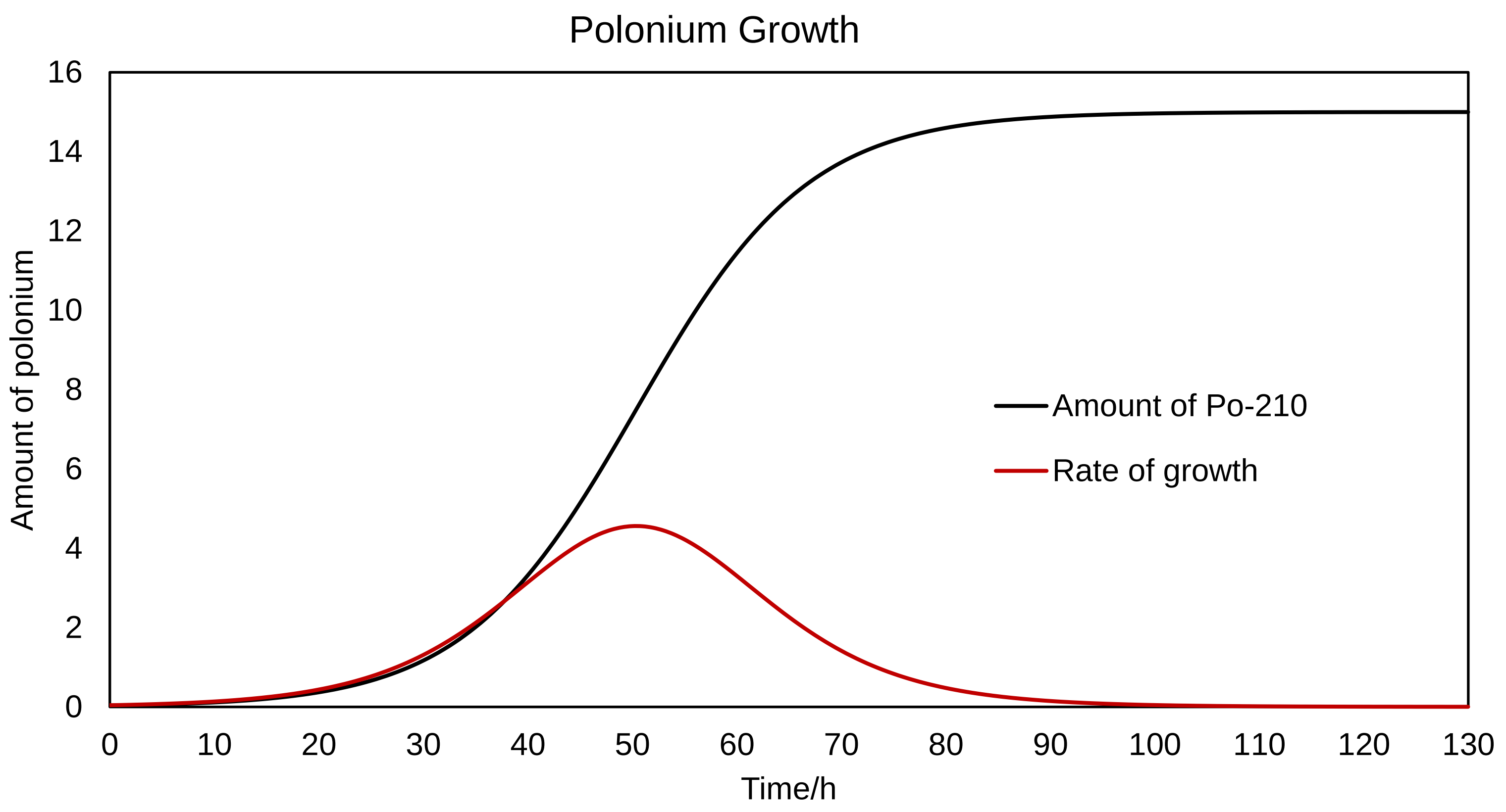
Rate of polonium growth



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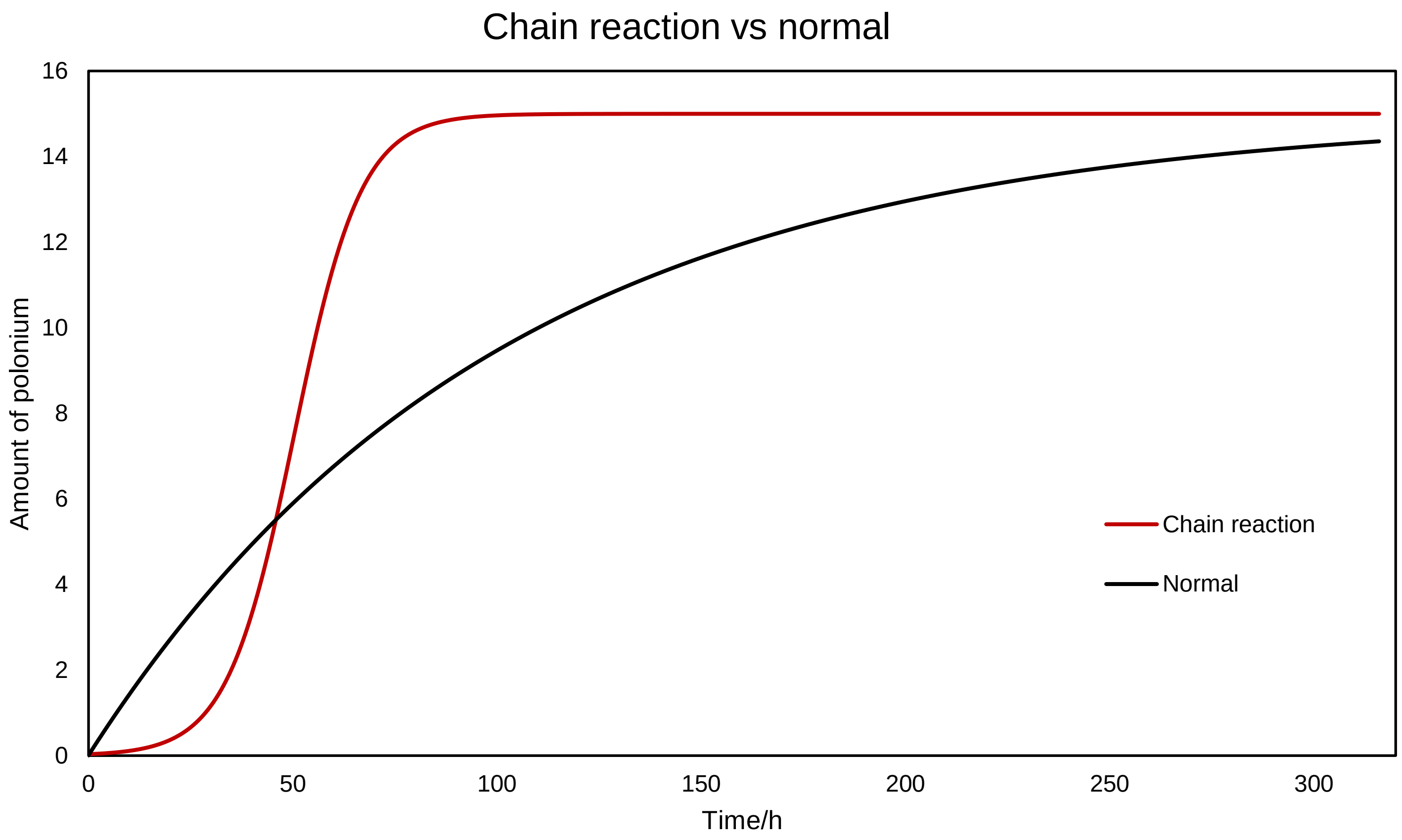
Comparison with normal reaction



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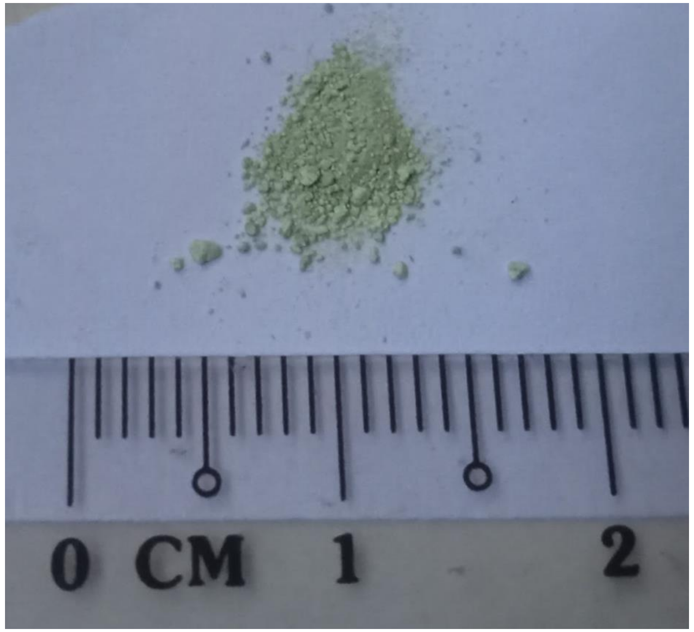
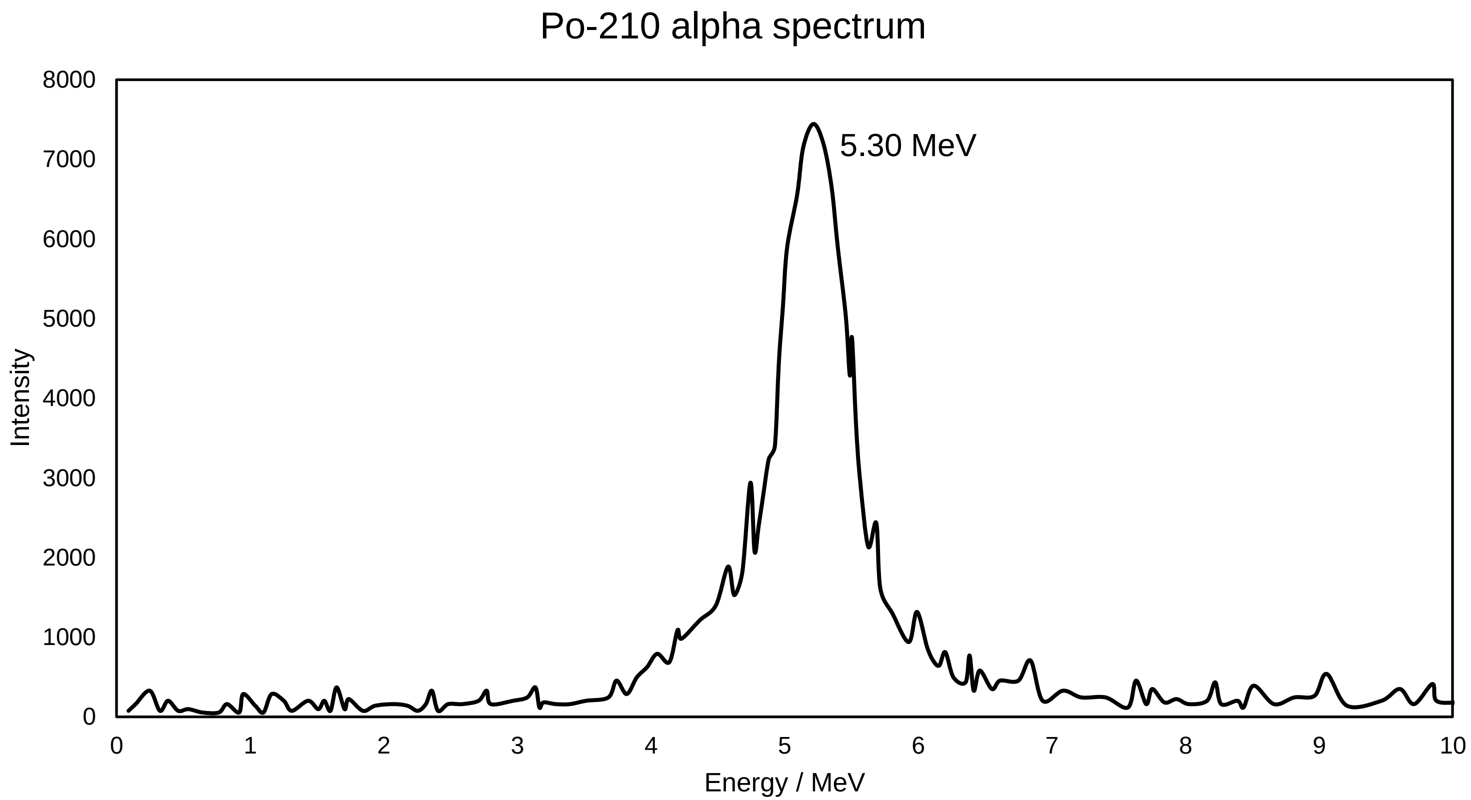
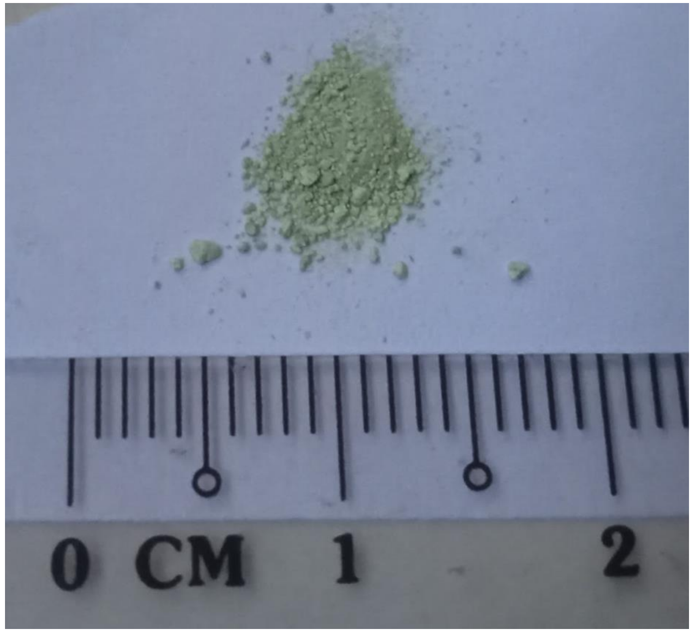
Alpha spectrum (^{210}Po)



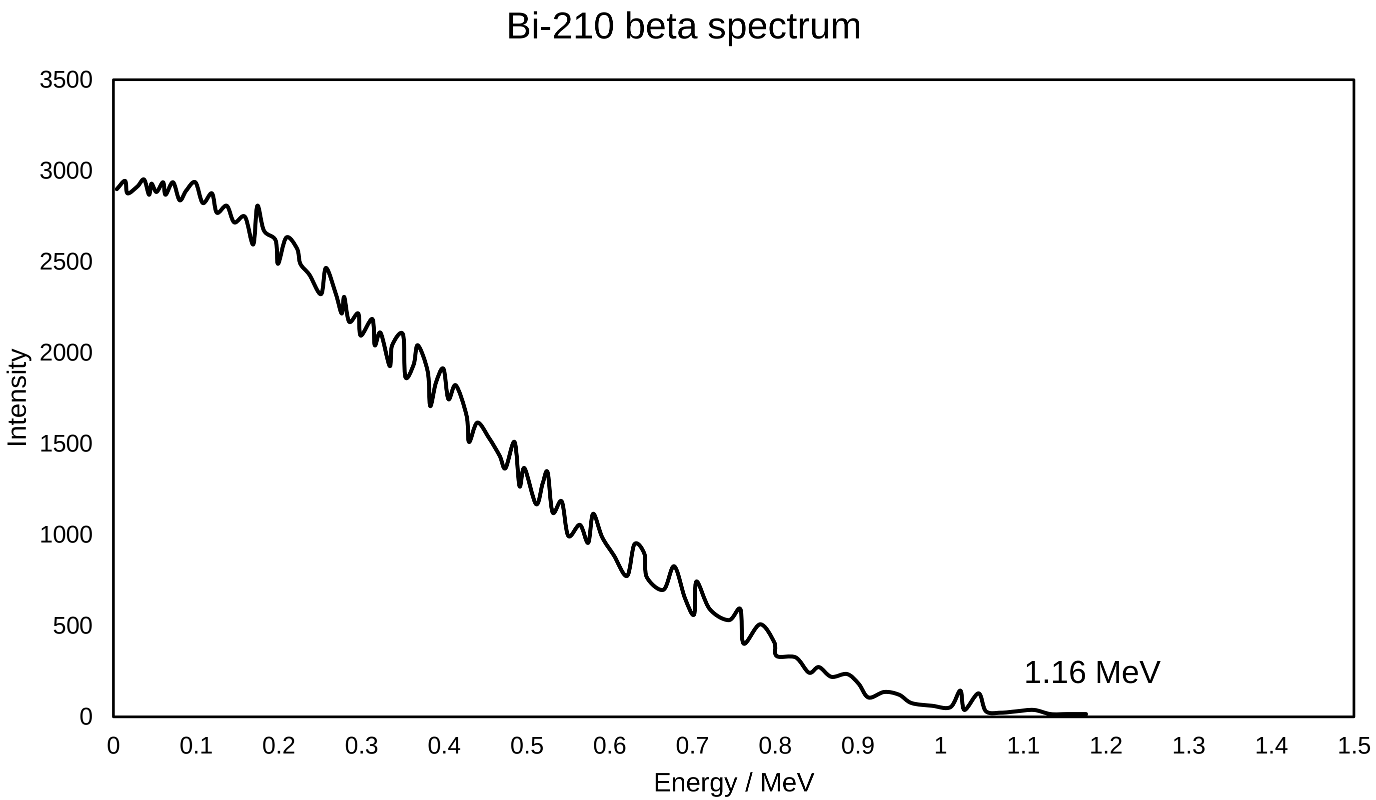
Reaction mixture



Beta spectrum (^{210}Bi)



Reaction mixture



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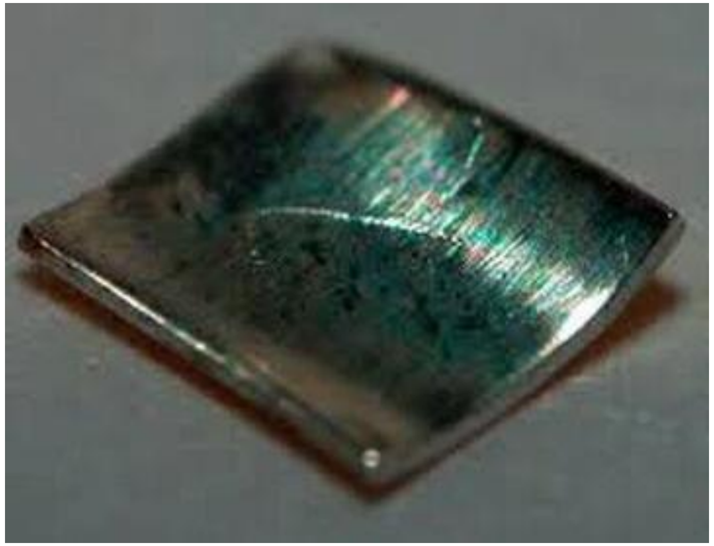
Conclusions

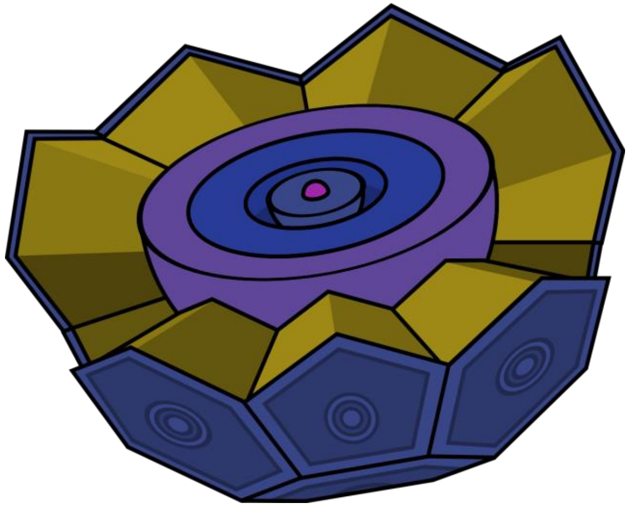
- Novel chain reaction has been proposed and characterised in bismuth beryllium acetate
- Formation of polonium in larger quantities achievable through normal methods has been confirmed

Future Work

Mobile polonium-210 generators



Purification of polonium-210



Gaseous neutron sources

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References

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