



Introduction to neutron sources

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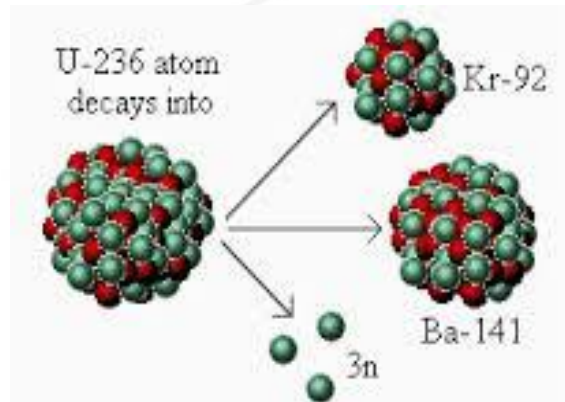
Introduction: talk outline

- Preamble
- Discussion (brief) of neutron source types:
 - Spontaneous fission
 - (α ,n) sources
 - Photoneutron sources
 - Neutron generators
 - Accelerator-based sources
 - Neutrons of cosmic origin

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Slide 2

Spontaneous fission sources



About 200 MeV of energy released per fission

- Spontaneous fission most probable for high Z nuclides of even mass number, A and atomic number, Z ($A = Z + N$)
- Prompt and delayed neutrons produced during fission process
 - On average ~ 3 neutrons per decay but can vary from 1 – 10
 - Each isotope has a unique multiplicity or neutron yield

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Spontaneous neutron sources

- Approx. 100 SF sources identified
 - Most are man-made
 - Requiring up to several months of irradiation of precursors in a reactor to produce
 - Followed by chemical separation
 - Limited availability of most isotopes in quantities required for even a small source
- Typically SF is a minor decay mode (alpha decay usually dominates)
- Activity (and emission rate) follows exponential decay law based on total decay rate ($\lambda_{SF} + \lambda_{\alpha} + \lambda_{\dots}$)

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Spontaneous neutron sources

- Neutron spectrum well described using analytical expressions
 - Watt fission model: $P(E) = C * e^{-E/a} * \sinh(bE)^{1/2}$
 - Maxwell fission model: $P(E) = C * E^{1/2} * e^{-E/a}$
- Where C is the source emission rate (n/s) and “a” and “b” are isotope-specific constants
- Neutron energies greater than 20 MeV are possible but average energies are ~ 2MeV.

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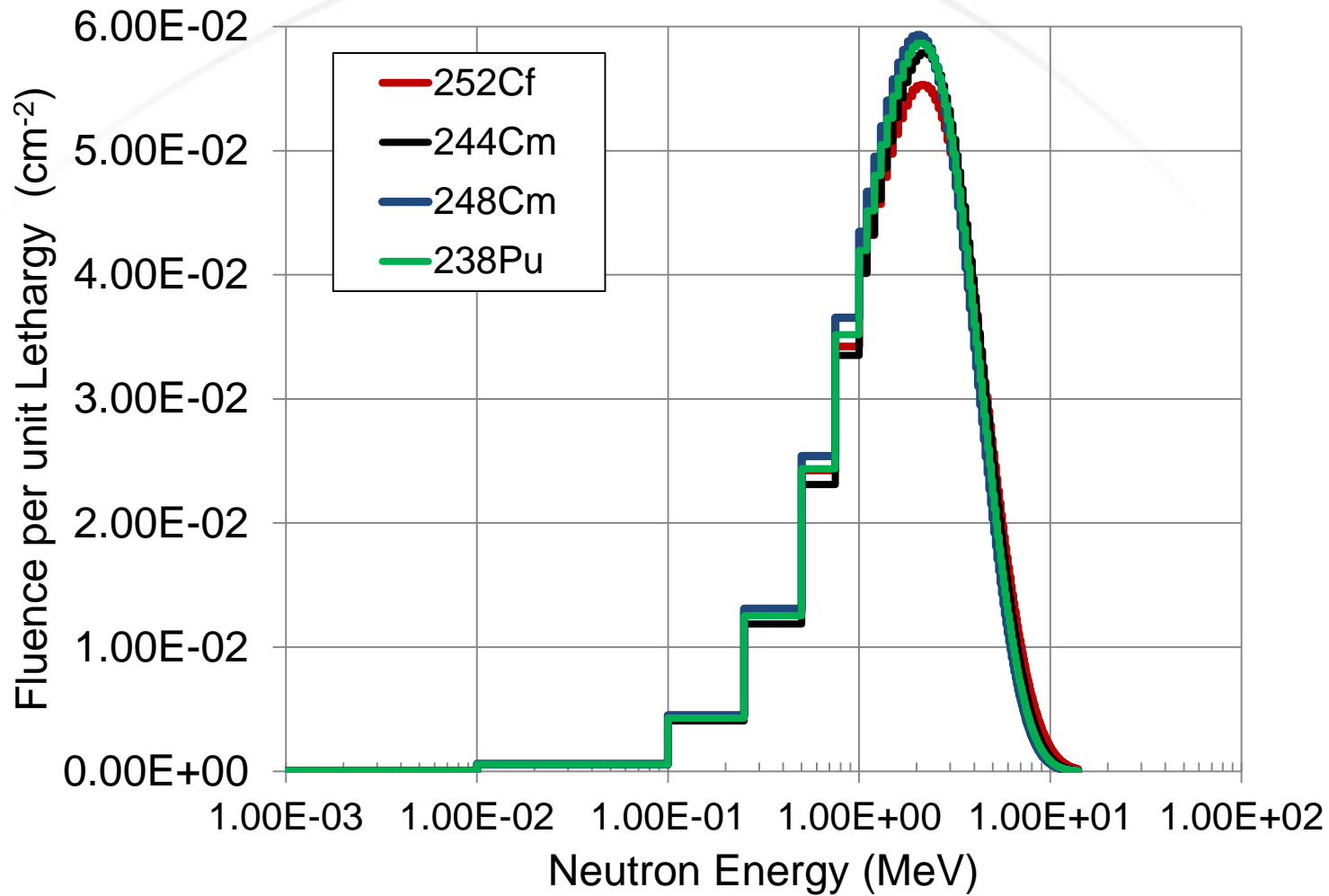
A diversion: Plotting neutron spectra

- Plotting of neutron spectra requires special treatment due to the range of neutron energies typically encountered (1E-09 – 20 MeV).
- Energy bin widths must necessarily vary with neutron energy.
- But can't simply normalize by dividing bin fluence ($\Phi(E)$) by width of energy bin (ΔE) in MeV as this results in a distorted view.
- Solution is to plot fluence per unit logarithmic energy interval instead aka fluence per unit lethargy
 - i.e. $\Phi(E) / \ln(\Delta E) = \Phi(E) / \ln(E_{\max}/E_{\min})$
 - where E_{\max} and E_{\min} are the boundaries of the energy bin
 - Plot energy axis on logarithmic scale
 - Plot $\Phi(E) / \ln(E_{\max}/E_{\min})$ on a linear scale
 - Area between any two energies is then proportional to the contained fluence

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Spontaneous fission source spectra



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Selected properties of some spontaneous fission sources

Isotope	Half-life (y)	SF probability	Avr. Energy (MeV)	Avr. neutrons per fission	n/s per g
²⁵² Cf	2.645	0.0392	2.13	3.7655	2.31E12
²⁵⁰ Cm	7400	0.86	1.83	3.31	2.03E10
²⁵⁰ Cf	13.08	7.7E-04		3.53	1.10E10
²⁴⁸ Cm	3.48E05	0.0839	1.95	3.11	4.00E07
²⁴² Cm	0.446	6.37E-08	2.10	2.52	1.97E07
²⁴⁴ Cm	18.1	1.37E-06	2.11	2.75	1.13E07
²³⁶ Pu	2.85	1.37E-09	2.24	2.13	5.73E04
²³⁸ Pu	87.74	1.85E-09	2.02	2.22	2.60E03

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Spontaneous neutron sources

- Example calculation of neutron emission rate per gram
- ^{252}Cf (Z=98, N=154, A=252)
 - SF probability : 0.03092 spontaneous fissions per decay
 - Multiplicity : 3.7655 neutrons per spontaneous fission on average
 - Isotope mass: 252.082 g/mole
 - Avogadro's # : $6.022\text{E}23$ atoms/mole
 - Atoms per gram: $2.3889\text{E}21$ atoms/g of ^{252}Cf
 - Half-life : 2.645 y
 - Decay constant :
 $= \ln(2)/(2.645 \text{ y} * 365.25 \text{ day/y} * 24 \text{ h/day} * 3600 \text{ s/h})$
 $= 8.304\text{E}-09 \text{ s}^{-1}$
 - Activity per gram :
 $A(\text{Bq}) = \lambda N = 8.304\text{E}-09 \text{ s}^{-1} * 2.3889\text{E}21 \text{ atoms/g}$
 $= 1.9837\text{E}13 \text{ Bq/g or (dis/s)/g}$
 - n/s per gram :
 $= 1.9837\text{E}13 \text{ (dis/s)/g} * 0.03092 \text{ SF/dis} * 3.7655 \text{ n/SF}$
 $= \mathbf{2.3097\text{E}12} \text{ n/s per g of } ^{252}\text{Cf}$

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Spontaneous neutron sources

- ^{252}Cf is most widely used SF source
 - Relatively easy to produce and isolate
 - High specific yield (2.31E12 n/s per gram)
 - Therefore no concerns with thermal heating due to alpha decay even at high neutron emission rates.
 - Relatively free of other Cf isotopes and other interferences
 - Therefore emission rate predictable with time
 - Relatively low gamma component
 - Widely used in calibrating neutron instrumentation
- Only major drawback is its 2.64y half-life

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(α ,n) sources

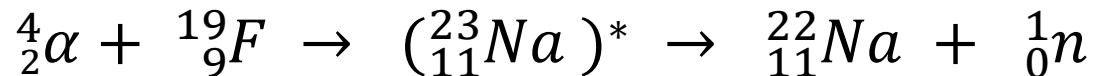
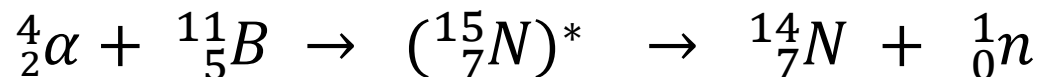
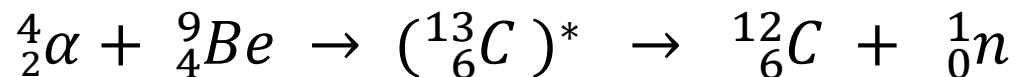
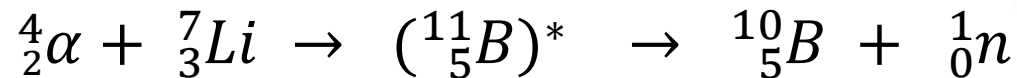
- Homogenous mixture or alloy of alpha emitter and target nucleus
- Alpha particle overcomes coulomb barrier to form a compound nucleus
 - Therefore a threshold alpha energy exists
- A neutron is emitted to form product nucleus
- A high alpha energy is desirable but must be cognizant of half-life consequences. A compromise is $E_{\alpha} \sim 6$ MeV
- This constraint, in turn, limits target nuclei to low Z (<14) elements due to rapidly rising coulombic barrier energies
 - Practically, the limit is $Z=3,9$ (Li to F)

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(α ,n) sources

- Example (α ,n) source reactions



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(α ,n) sources: alpha emitters

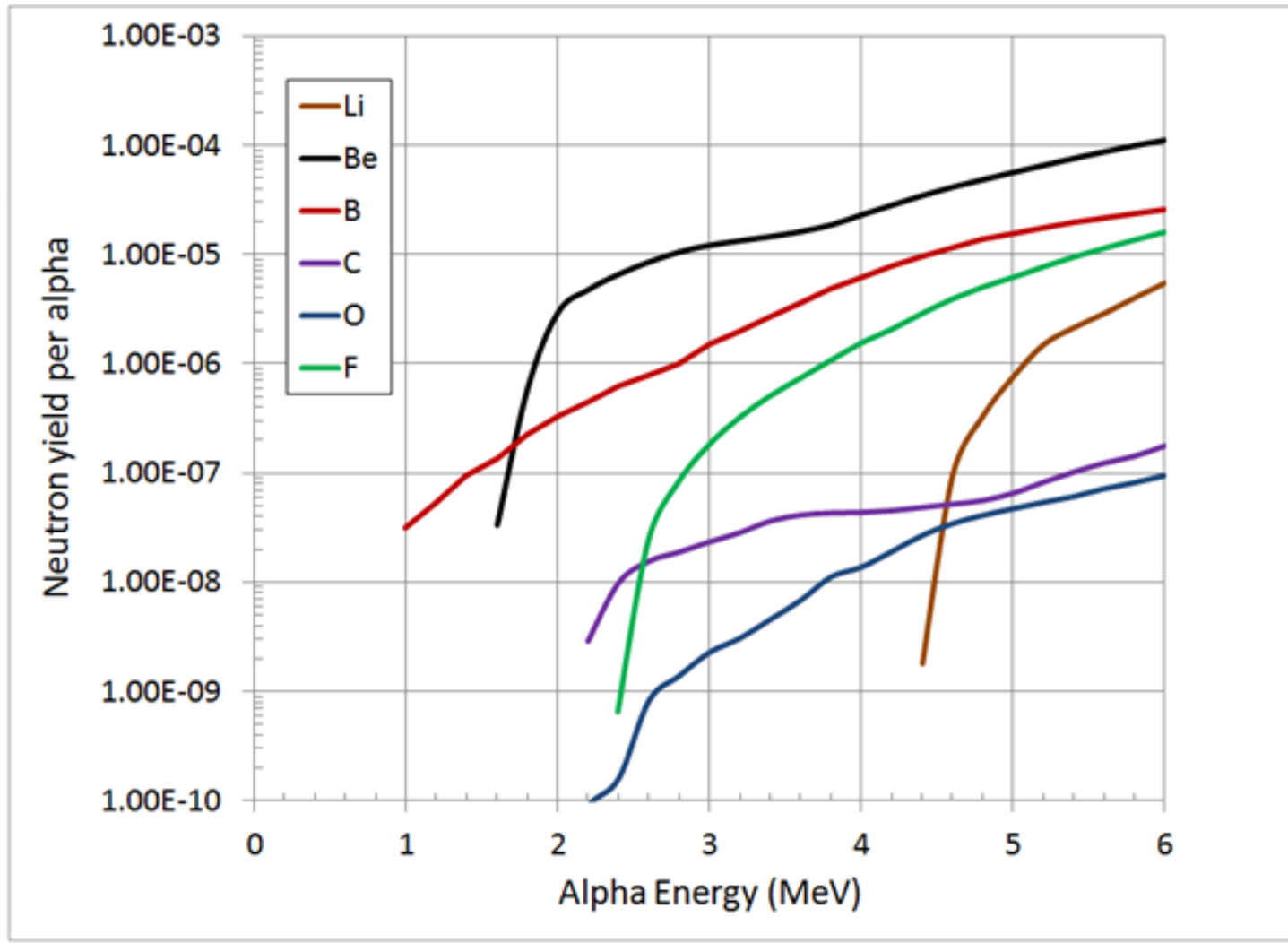
- Alpha emitters of practical interest include:

Isotope	Half-life (y)	Specific activity (Bq/g)	Alpha energies (MeV) and abundances
^{241}Am	433.6	1.27E11	5.486(85.2%), 5.443(12.8%), 5.388(1.4%)
^{238}Pu	87.74	6.33e11	5.499(71.6%), 5.456(31.7%)
^{239}Pu	2.41e04	2.30E09	5.156(73.2%), 5.143(15.1%), 5.105(10.6%)
^{242}Cm	0.446	1.23E14	6.113(74%), 6.070(25%)
^{244}Cm	18.1	2.99E11	5.805(76.4%), 5.763(23.6%)
^{226}Ra	1600	3.66E10	4.784(94.5%), 4.601(5.6%) + progeny
^{210}Po	0.379	1.66E14	5.305(100%)

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(α ,n) sources: neutron yield

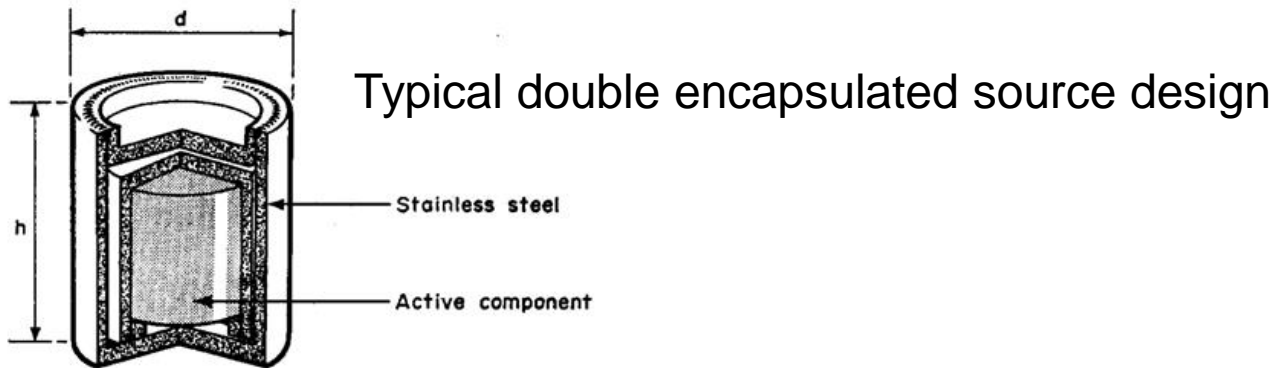


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(α ,n) sources

- Very low efficiency for neutron production.
 - ~ 1 neutron per $10^4 - 10^6$ alpha decays is a reasonable expectation

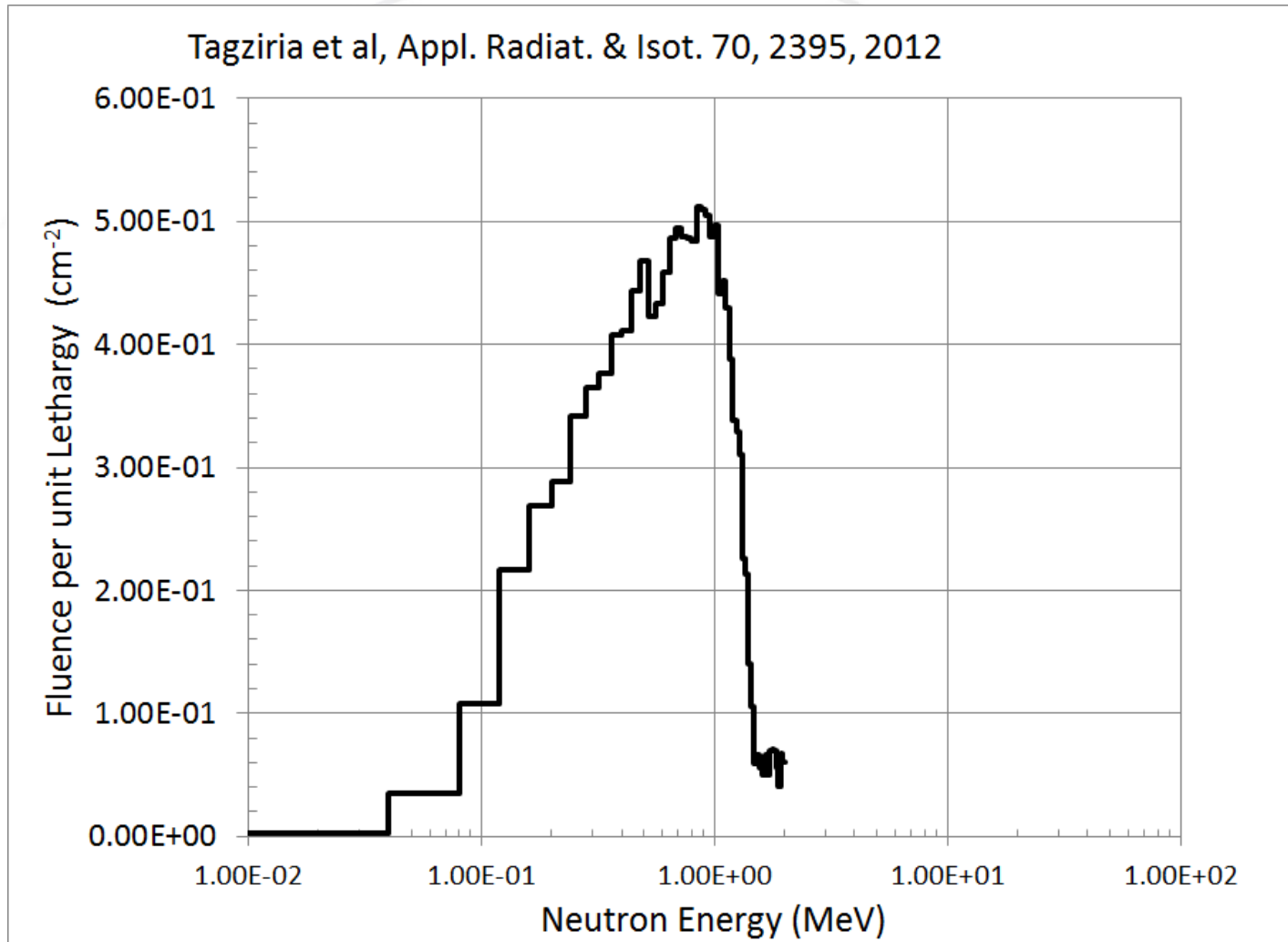


- Neutron yield and spectrum are functions of:
 - Proximity of alpha particle to target isotope
 - Alpha energy
 - Target isotope

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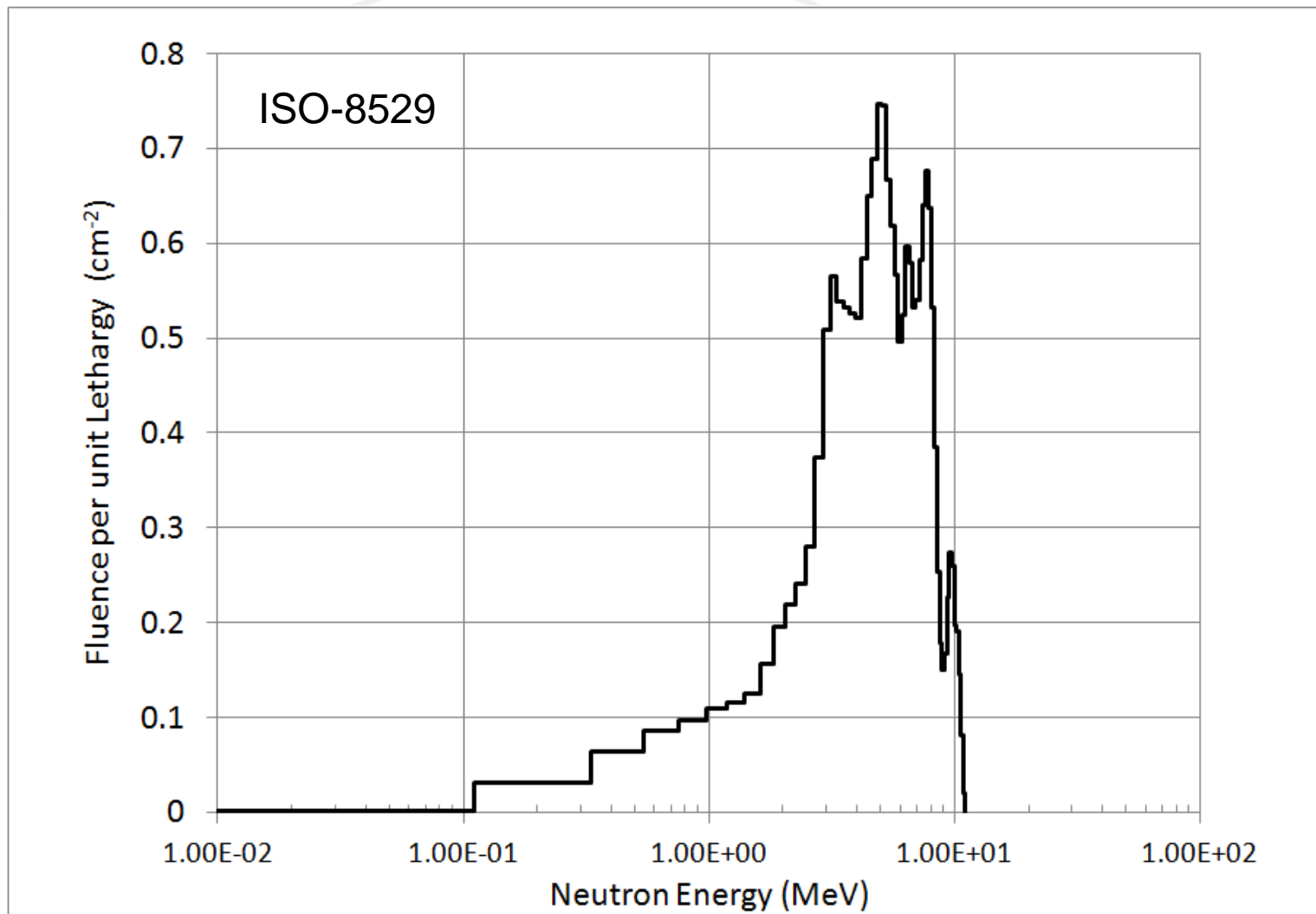
$^{241}\text{AmLi}$



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Slide 16

$^{241}\text{AmBe}$



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Slide 17

(α ,n) sources

- Spectra and emission rates can be predicted using SOURCES4c
 - A LANL-developed code
 - Based on a homogeneous composition specified by user
 - Also applicable to SF sources
 - Available from RSICC (www.rsicc.org)
- Most common (α ,n) source is AmBe
 - Produces highest energy neutrons
 - Relatively high neutron yield
 - Source emission rates up to 2E07 n/s available
 - ~ 10Ci or 2.4 g of ^{241}Am required

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Properties of selected (α ,n) sources

Neutron source	Typical yield (n/s per Bq)	Average energy (MeV)	Maximum neutron energy (MeV)
$^{241}\text{AmBe}$	6.6E-05	4.4	12
^{241}AmB	1.6E-05	2.7	6
$^{241}\text{AmLi}$	1.2E-06	0.45	1.5
$^{238}\text{PuO}_2$	2.2E-08	2	5
$^{238}\text{PuF}_4$	6E-06	1.2	4
$^{244}\text{Cm}^{13}\text{C}$	8E-08	4.4	8

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Slide 19

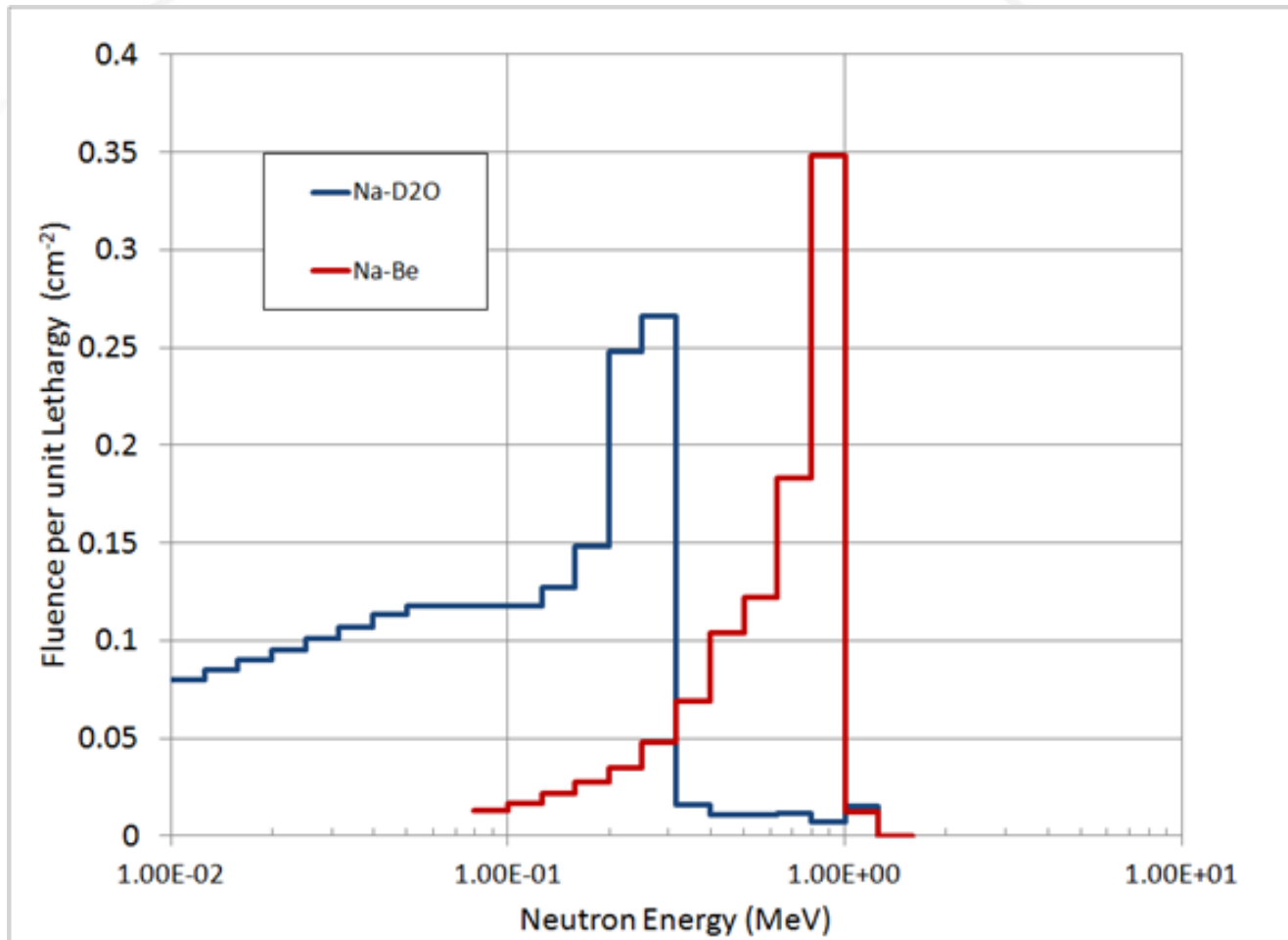
Photoneutron sources

- Gamma-emitter core surrounded by target element
- Only ^2H and Be have low enough thresholds for typical gamma sources (i.e. $E_\gamma < 3 \text{ MeV}$)
- Common gamma sources include ^{24}Na and ^{226}Ra (and progeny)
- Low efficiency, therefore high gamma-to-neutron ratio
 - Low neutron energies ($< 1 \text{ MeV}$) too
 - However nearly monoenergetic if single photon energy used
- These sources have fallen out of favor since wide availability of (α, n) and some SF sources

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Slide 20

Photoneutron sources based on ^{24}Na



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Slide 21

Neutron generators

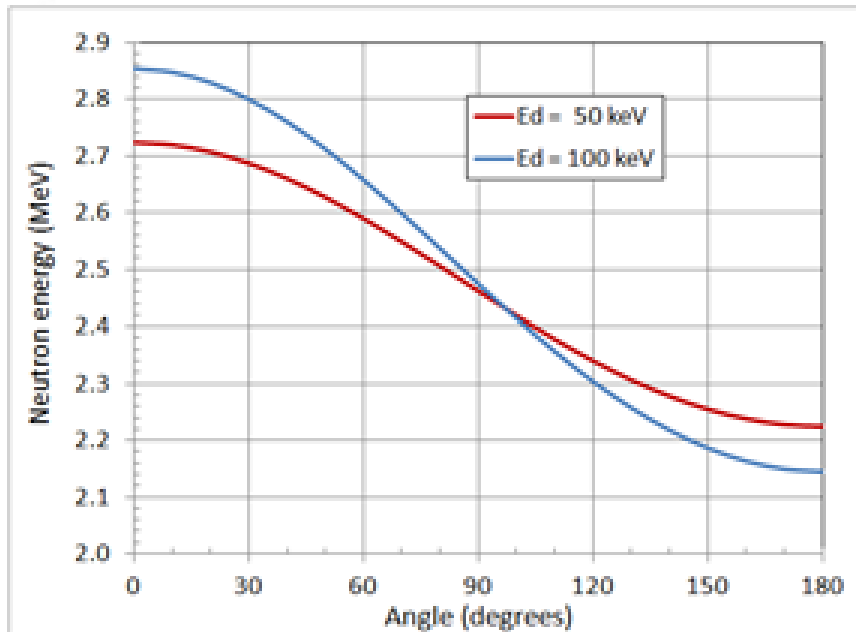
- Based on fusion reactions
 - Where low energy deuteron beam accelerated toward target
 - 50 - 150 keV
- ${}^2\text{H} + {}^2\text{H} \rightarrow {}^3\text{He} + n + 3.27 \text{ MeV}$ (DD reaction)
 - 2.45 MeV neutron (highly monoenergetic) produced ~ isotropically
- ${}^2\text{H} + {}^3\text{H} \rightarrow {}^3\text{He} + n + 17.2 \text{ MeV}$ (DT reaction)
 - 14.2 MeV neutron (highly monoenergetic) produced ~ isotropically
- The DT cross-section is ~ 100x higher over the range of deuteron energies used

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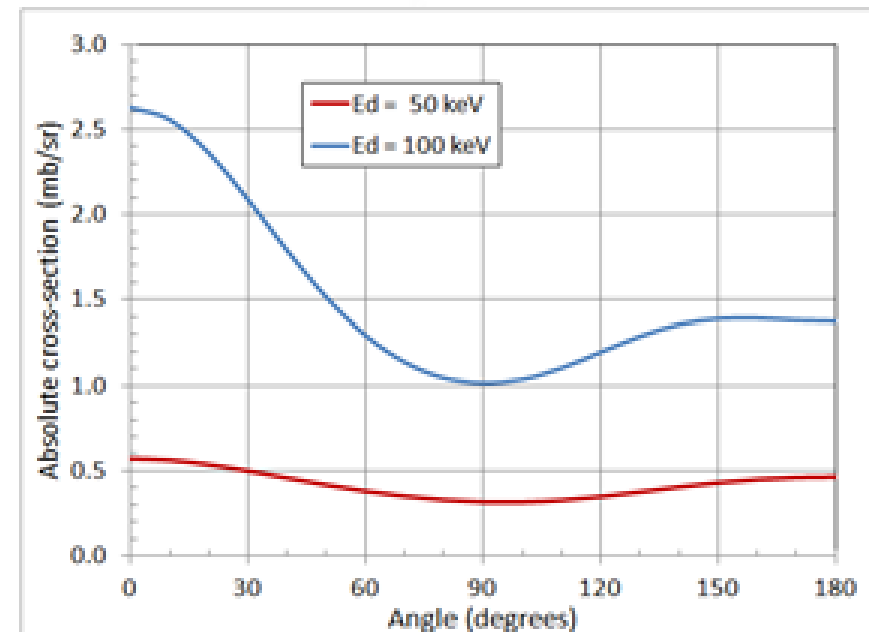
Slide 22

DD neutron generator data

Neutron energy dependence on angle of emission and E_d



Probability of neutron line of flight as function of E_d

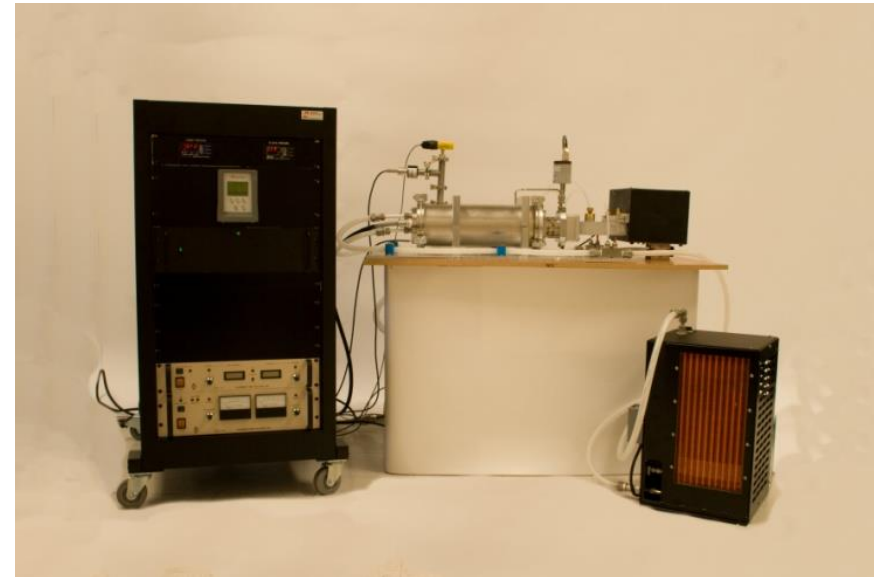


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Neutron generators

- Typical generators are costly (~\$100k) and heavy
 - Advantage: Can be turned on/off
 - Disadvantage: Require more maintenance and neutron output not as predictable as other sources
 - Pulsed or steady state operation
 - DD outputs up to 10^9 n/s
 - DT outputs up to 10^{12} n/s
 - Many DHS applications

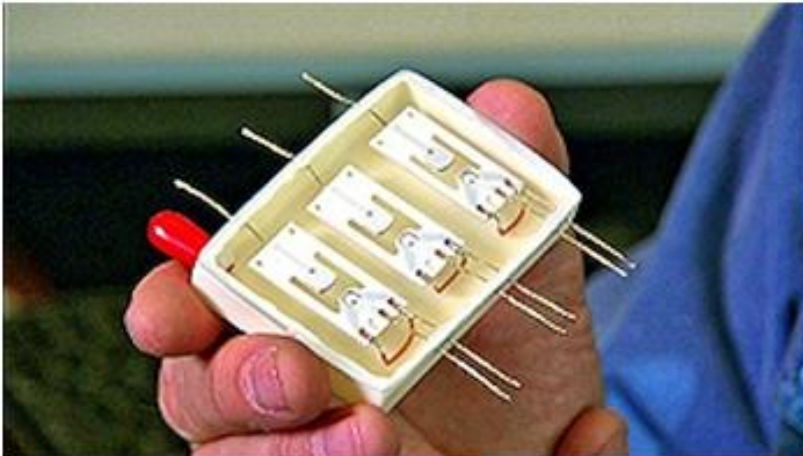


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Neutron generators

- But compact affordable generators are being developed
 - E.g. LBNL and Sandia designs
 - Have replaced some ^{252}Cf sources and used in medical applications too



Sandia's "Neutrister" device

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Neutron accelerators

- Similar to neutron generators but operate at higher particle energies
- Various designs
 - Van de Graaff, linear accelerator (linac) and cyclotron
 - Basic configuration
 - Ion source
 - A means of accelerating the ions
 - High vacuum beam line to transport ions to target
 - A means of steering and focusing the ion beam
 - High voltage supplies
 - A means of selecting the ion energy of interest
 - A suitable target and a method of cooling same
 - An external beam monitor to determine neutron fluence

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Neutron accelerators

- Monoenergetic neutrons can be produced up to 20 MeV using well-known reactions

ion	Target isotope	Target material	Range of ion energies (MeV)	Range of neutron energies (MeV)
protons	${}^7\text{Li}$	LiF	1.95 - 6.0	0.005 - 4.3
protons	${}^3\text{H}$	Tritiated metal	1.2 - 9.5	0.005 - 8.7
deuterons	${}^2\text{H}$	Deuterated metal	0.5 - 3.5	1.6 - 6.8
deuterons	${}^3\text{H}$	Tritiated metal	0.5 - 3.5	12 - 20

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Slide 27

Neutron accelerators

- Neutron energy a function of ion energy and target material and also emission angle with respect to target.
- Highest energies in forward direction and lowest in backward direction.
- Monoenergetic neutrons very useful to characterize instrument performance at specific energies.
- Full set of measurements defines the instrument energy response (example to follow).
- Monoenergetic data also useful in benchmarking Monte Carlo calculations

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Slide 28

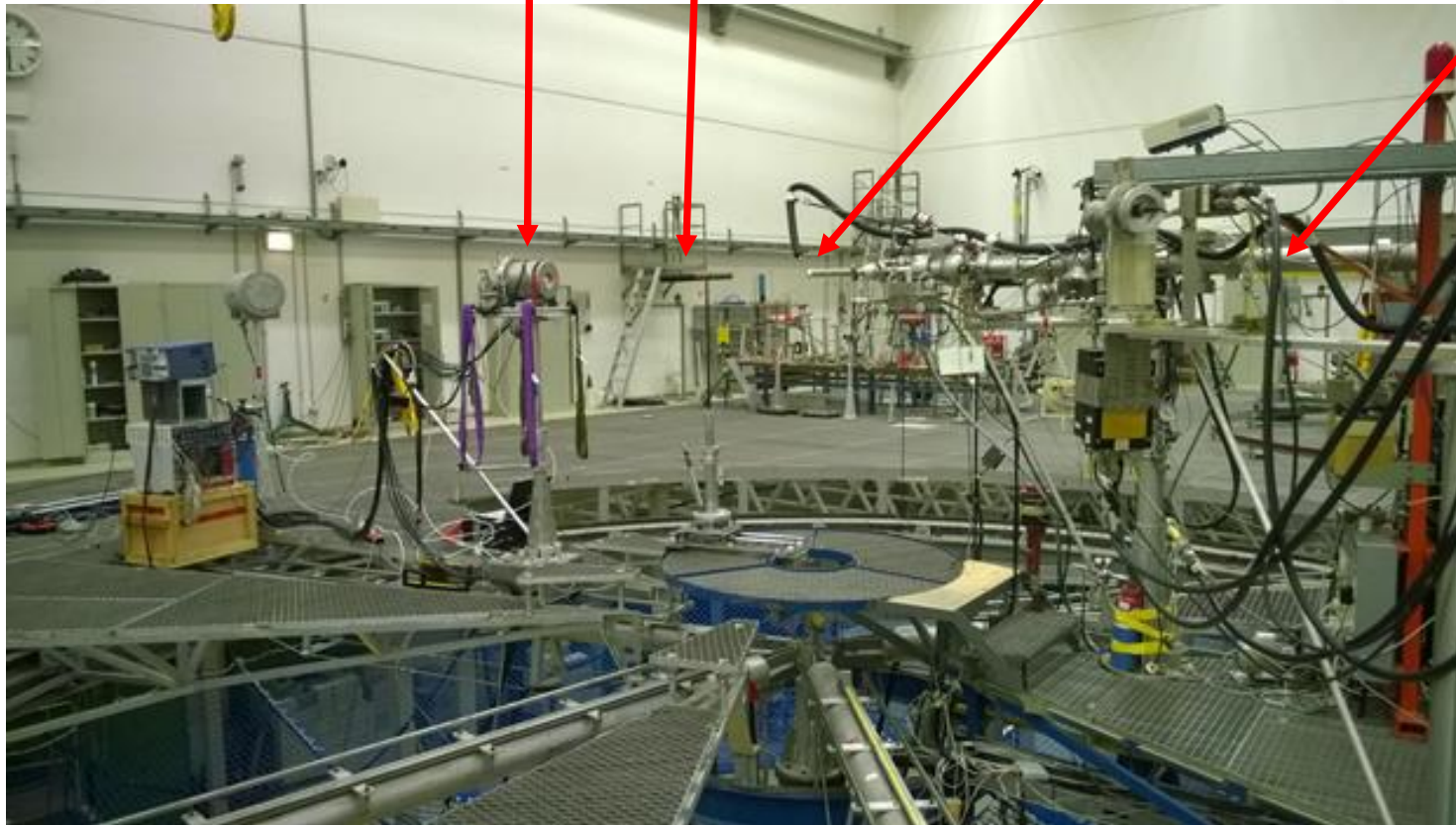
PTB Neutron calibration facility

Instrument
under test

Shadow cone

Target

Beam line

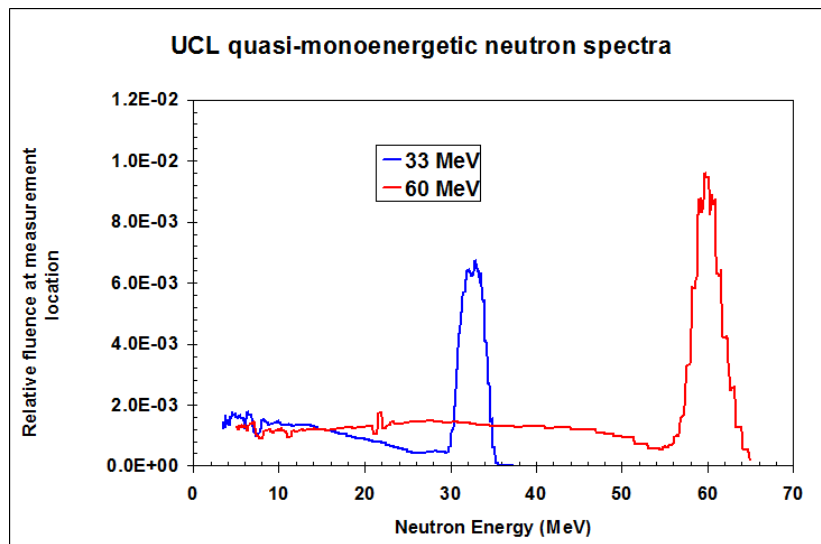


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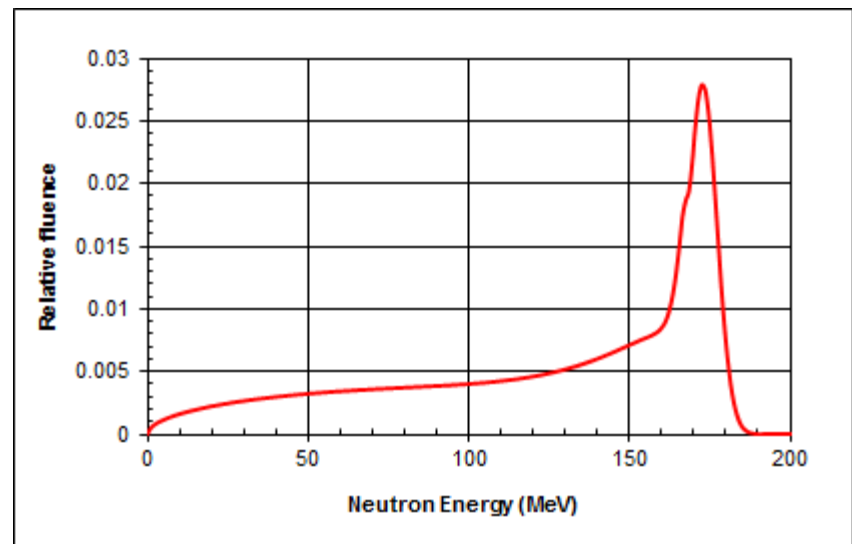
Slide 29

Neutron accelerators

- As particle (ion) energies increase, the neutron output becomes less monoenergetic.



UCL 33 and 60 MeV



TSL 173MeV

- (p,Li) rxn used at both accelerators

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Neutron accelerators

- Spallation neutron sources
 - E.g. LANSCE-WNR (LANL) and SNS (Oak Ridge)
 - ~ 1 GeV protons collide with target (W or Hg)
 - Protons fragment target nuclide to produce many neutrons (>10) per incident proton
 - Neutron energy distributions broad and dependent on angle wrt target.
 - Neutron energies up to proton energy and average energies of ~ 350 MeV at 0°.

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Other accelerators

- Accelerators not designed to produce neutrons often do nonetheless
- Including:
 - High-energy X-ray machines that produce neutrons via photoneutron production (threshold ~ 8 MeV for many materials)
 - Proton therapy accelerators ($E_p \sim 250$ MeV) generate neutrons from interactions with patient and surroundings
 - Neutrons are frequently the main health physics concern outside the biological shielding that surrounds accelerators

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Neutrons of cosmic origin

- Neutrons produced by interaction of cosmic particles with upper layers of atmosphere.
- Neutron fluence strong function of altitude
 - Some commercial air crews in Europe are badged as radiation workers
- Many literature reports on neutron measurements on mountain peaks
- But at sea level neutron fluence reduced to $< 2E02 \text{ m}^{-2} \text{ s}^{-1}$
 - Dose rates $< 5 \text{ } \mu\text{rem/h}$

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Slide 33

Neutron sources

Questions ?

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