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Title:	Introduction to neutron sources
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Introduction to neutron sources

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CSU neutron class
Fort Collins, CO
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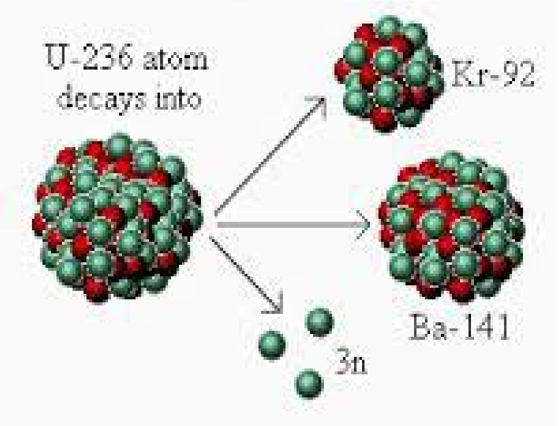
Introduction: talk outline

- Preamble

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

Spontaneous fission sources



About 200 MeV of energy released per fission

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

Spontaneous neutron sources

- Approx. 100 SF sources identified
  - Require 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 ($\lambda_{SF} + \lambda_{alpha} + \lambda \ldots$)

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: $P(E) = C * E^{1/2} * e^{-E/a}$

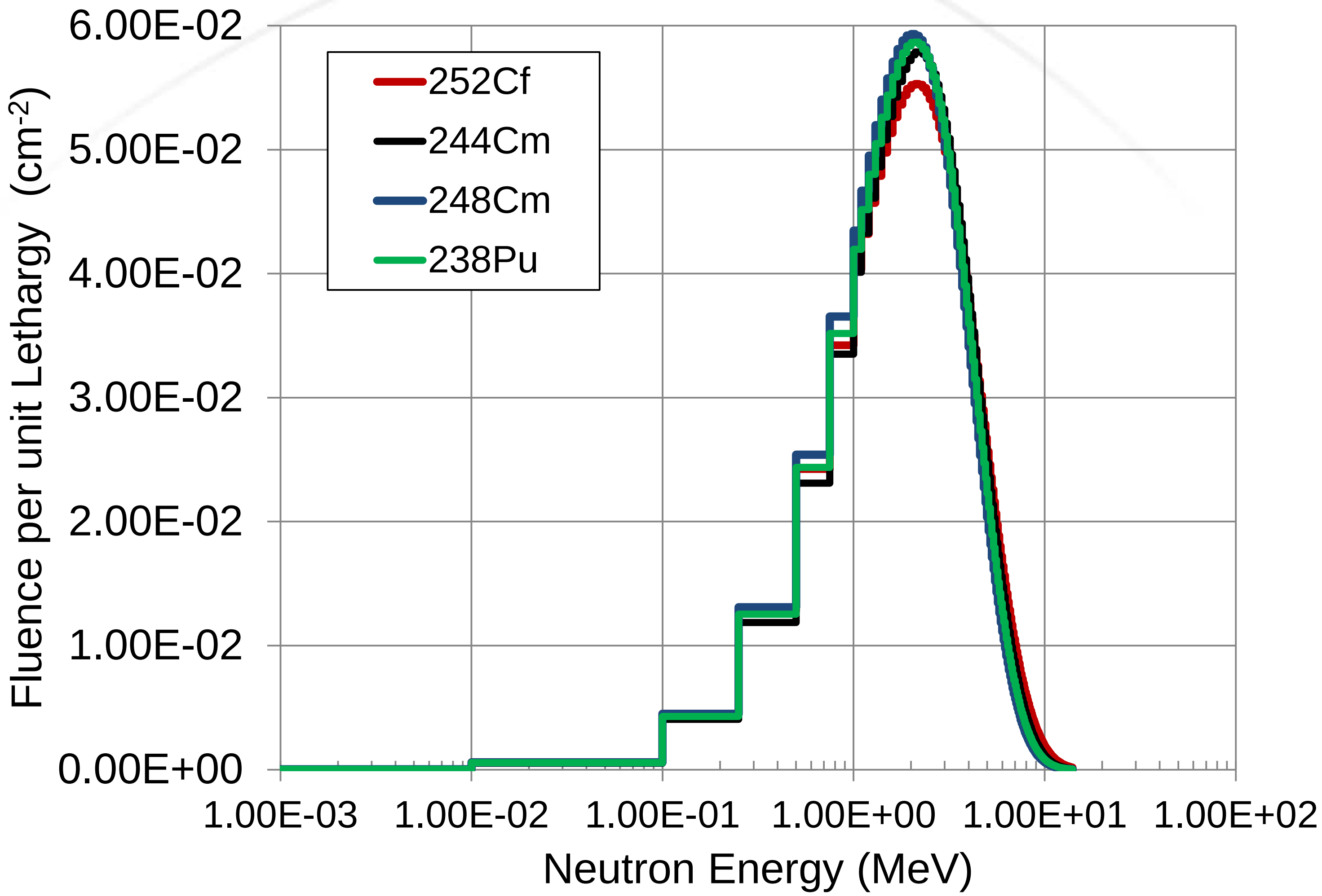
- Where C is the source emission rate (n/s) and “a” and “b” are isotope-specific constants

- Neutron energies as high as 20 MeV are possible but average energies are ~ 2MeV.

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 width must necessarily vary with neutron energy.
- But can't simply normalize by dividing bin fluence (Φ(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

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

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
  - Avogardo's # : 6.022E23 atoms/mole
  - Atoms per gram: 2.3889E21 atoms/g of ^{252}Cf
  - Half-life : 2.645 y
  - Decay constant : = ln(2)/(2.645 y *365.25 day/y * 24 h/day * 3600 s/h)
    = 8.304E-09 s^{-1}
  - Activity per gram : A(Bq) = λN = 8.304E-09 s^{-1} * 2.3889 atoms
    = 1.9837E13 Bq/g or (dis/s)/g
  - n/s per gram : = 1.9837E13 (dis/s)/g * 0.03092 SF/dis * 3.7655 n/SF
    = **2.3097E12** n/s per g of ^{252}Cf

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

(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 a stable product nucleus
- A high alpha energy is desirable but must be cognizant of half-life consequences. A compromise is E_α~ 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)

(α,n) sources

- Example (α,n) source reactions

$$^{4}_{2}\alpha + {}^{7}_{3}Li \rightarrow ({}^{11}_{5}B)^{*} \rightarrow {}^{10}_{5}B + {}^{1}_{0}n$$

$$^{4}_{2}\alpha + {}^{9}_{4}Be \rightarrow ({}^{13}_{6}C)^{*} \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$$

$$^{4}_{2}\alpha + {}^{11}_{5}B \rightarrow ({}^{15}_{7}N)^{*} \rightarrow {}^{14}_{7}N + {}^{1}_{0}n$$

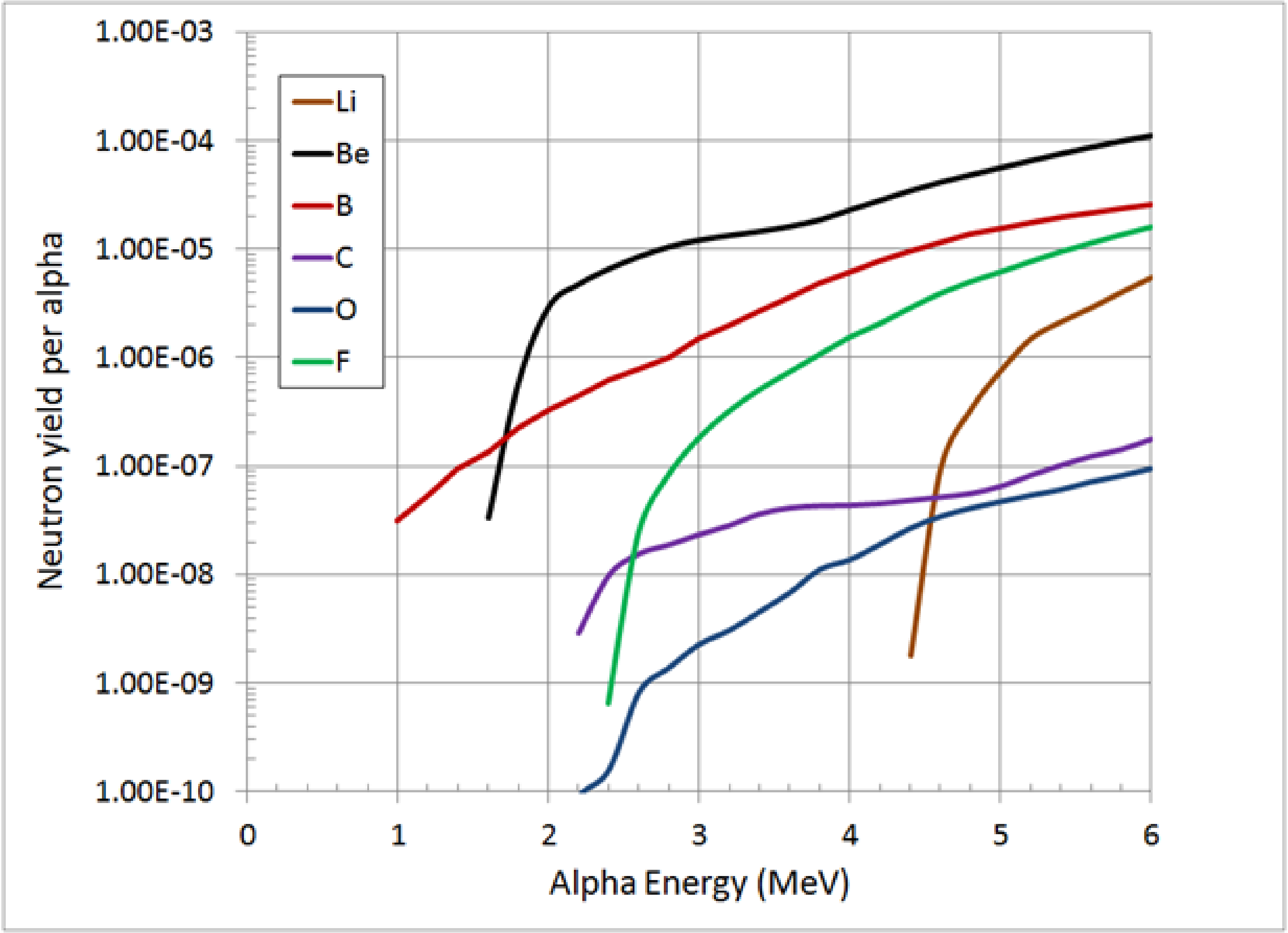
$$^{4}_{2}\alpha + {}^{19}_{9}F \rightarrow ({}^{23}_{11}Na)^{*} \rightarrow {}^{22}_{11}Na + {}^{1}_{0}n$$

(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%)
^{210}Po	0.379	1.66E14	5.305(100%)

(α,n) sources: neutron yield



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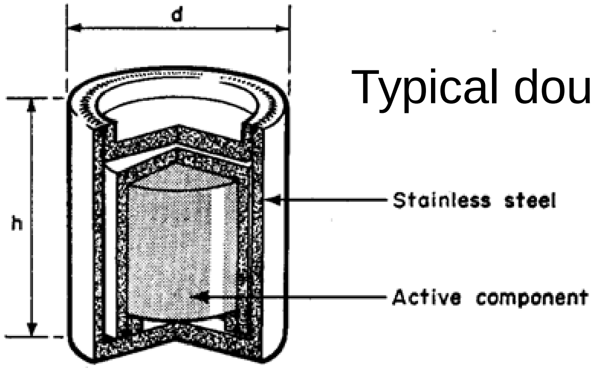
(α,n) sources

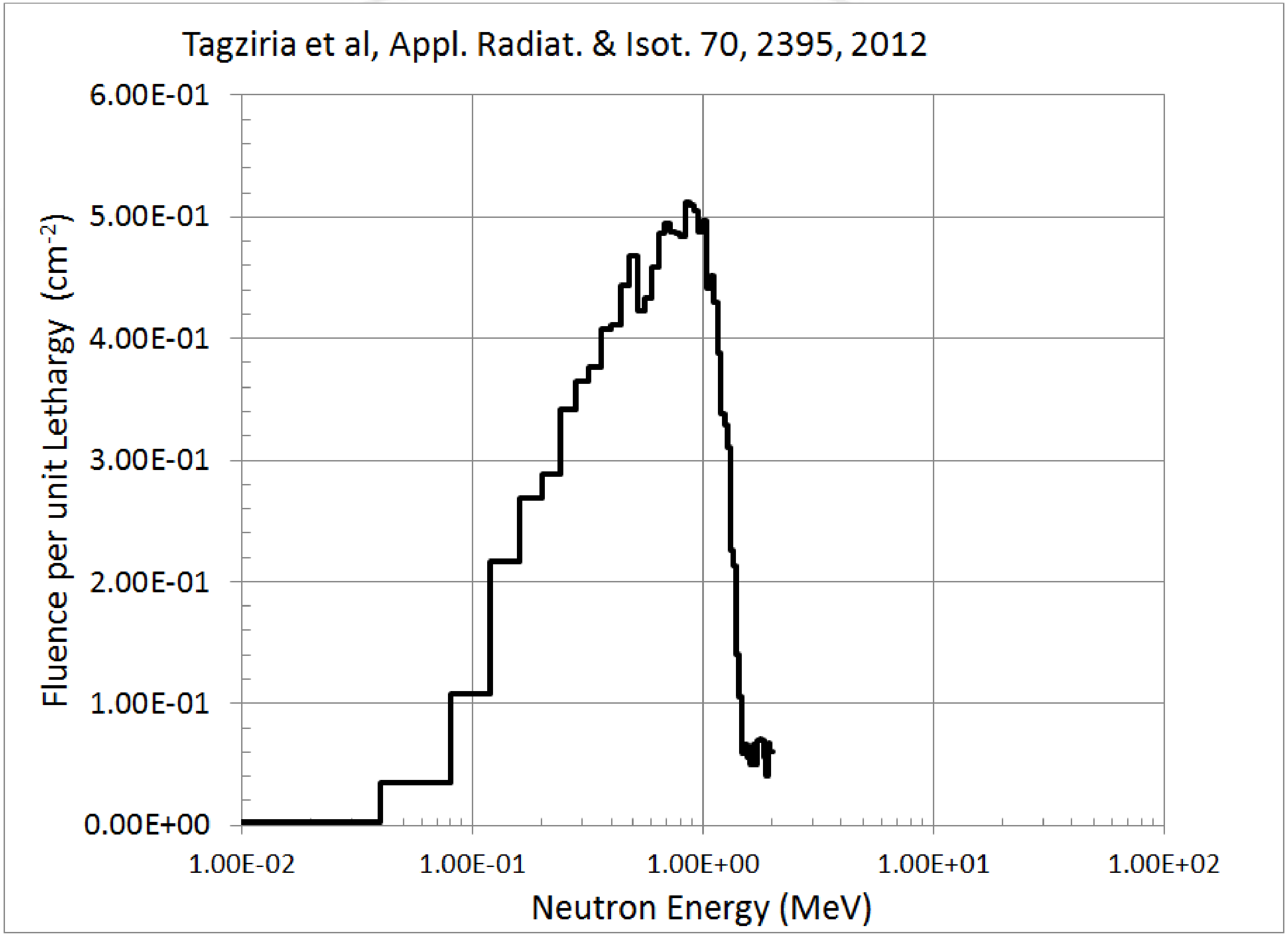
- Very low efficiency for neutron production.
  - ~ 1 neutron per 10^4 - 10^6 alpha decays is a reasonable expectation



Typical double encapsulated source design

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

^{241}AmLi



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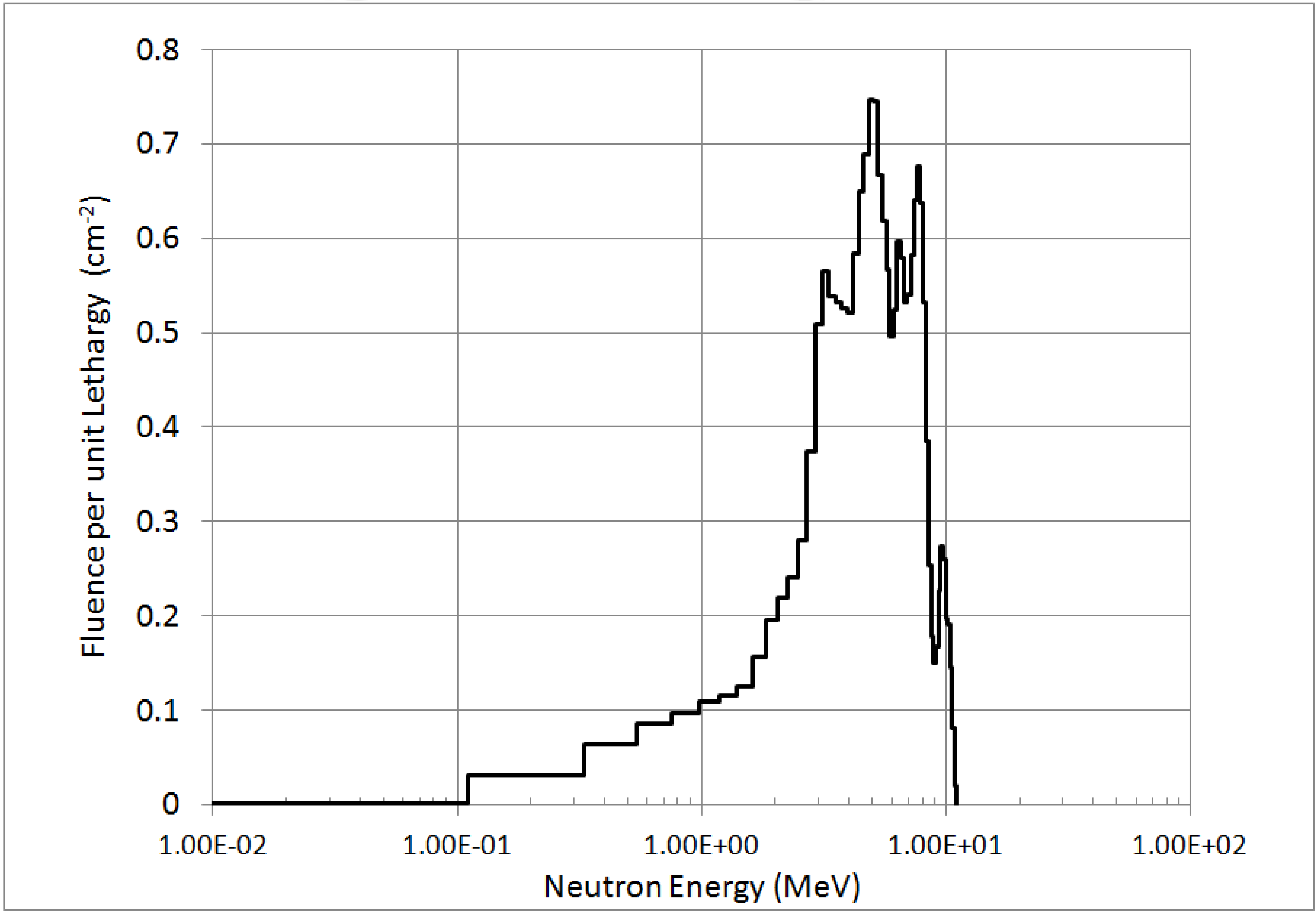
^{241}AmBe



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(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

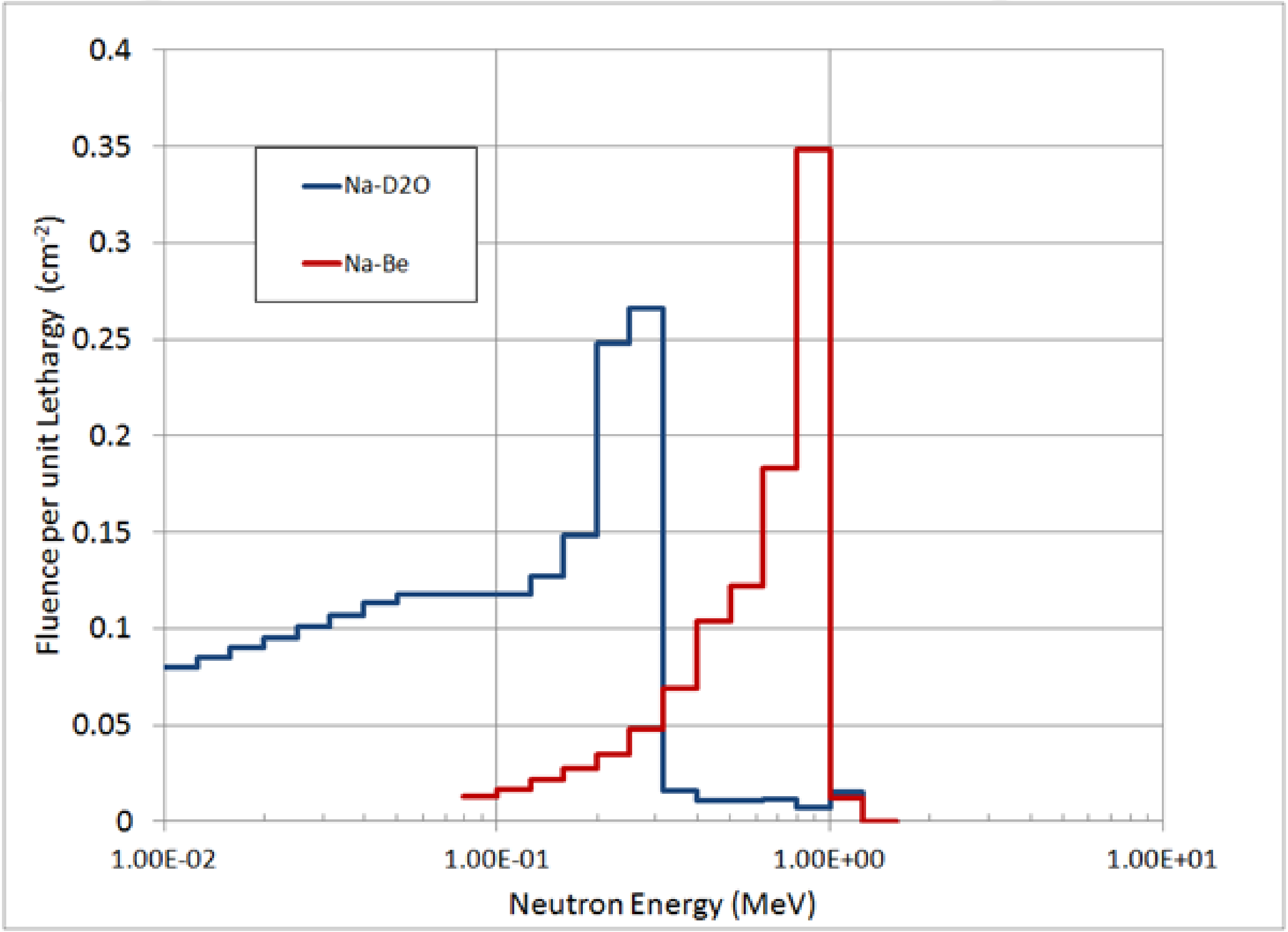
Properties of selected (α,n) sources

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

Photoneutron sources

- Gamma-emitter core surrounded by target element
- Only ^{2}H and Be have low enough thresholds for typical gamma sources (i.e. $E\gamma < 3$ MeV)
- Common gamma sources include ^{24}Na and ^{226}Ra (and progeny)
- Low efficiency, therefore high gamma-to-neutron ratio
  - Low neutron energies (<1MeV) 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

Photoneutron sources based on ^{24}Na



Neutron generators

- Based on fusion reactions
  - Where low energy deuteron beam accelerated toward target
    - 50 - 150 keV

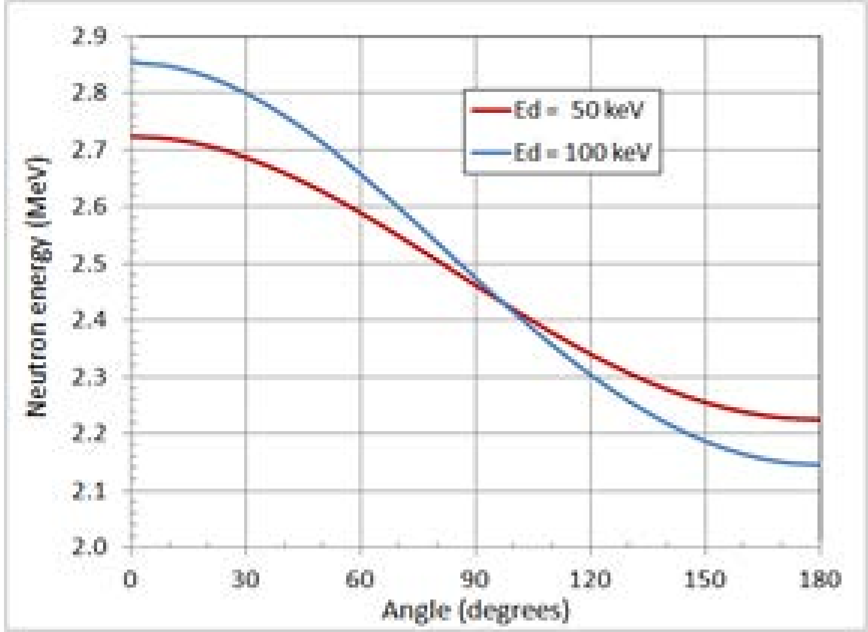
- $^{2}H + ^{2}H \rightarrow ^{3}He + n + 3.27\ MeV$ (DD reaction)
  - 2.45 MeV neutron (highly monoenergetic) produced ~ isotropically

- $^{2}H + ^{3}H \rightarrow ^{3}He + n + 17.2\ MeV$ (DT reaction)
  - 14.2 MeV neutron (highly monoenergetic) produced ~ isotropically

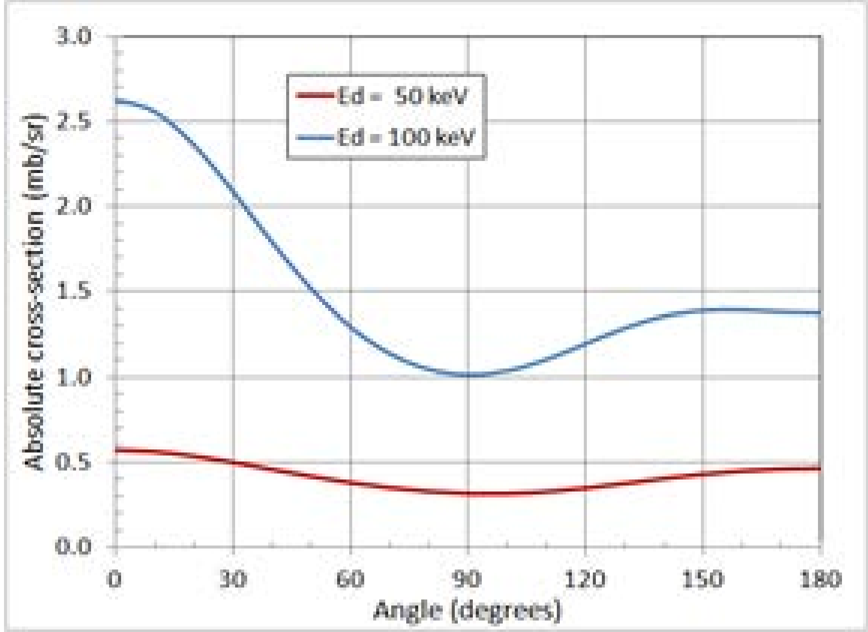
- The DT cross-section is ~ 100x higher over the range of deuteron energies used

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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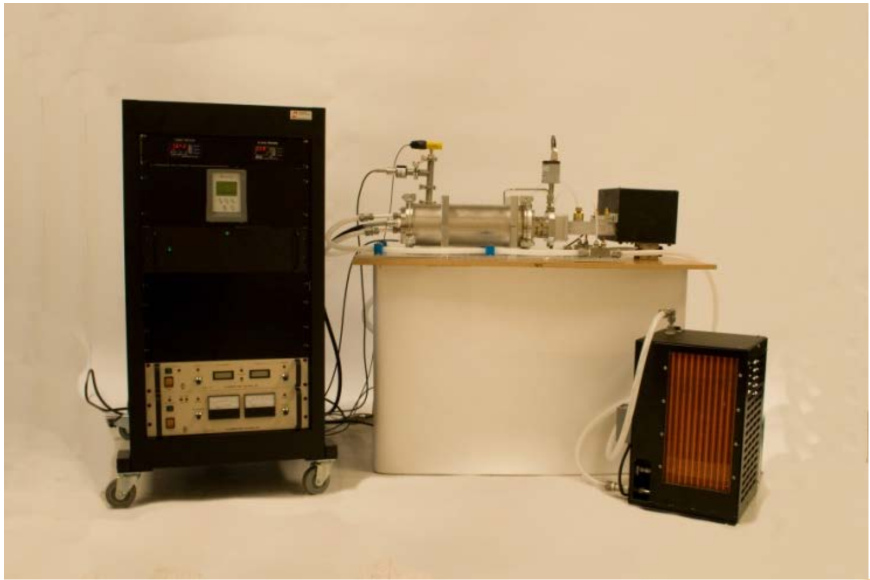
Neutron generators

- 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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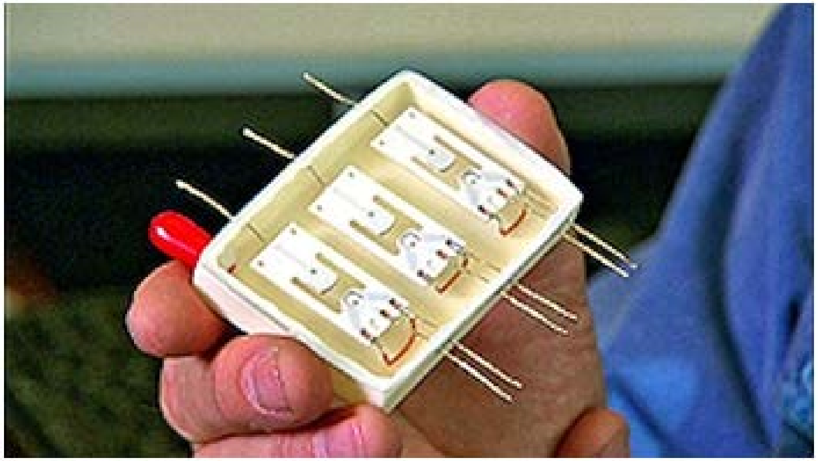
Neutron generators

- 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

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

Neutron accelerators

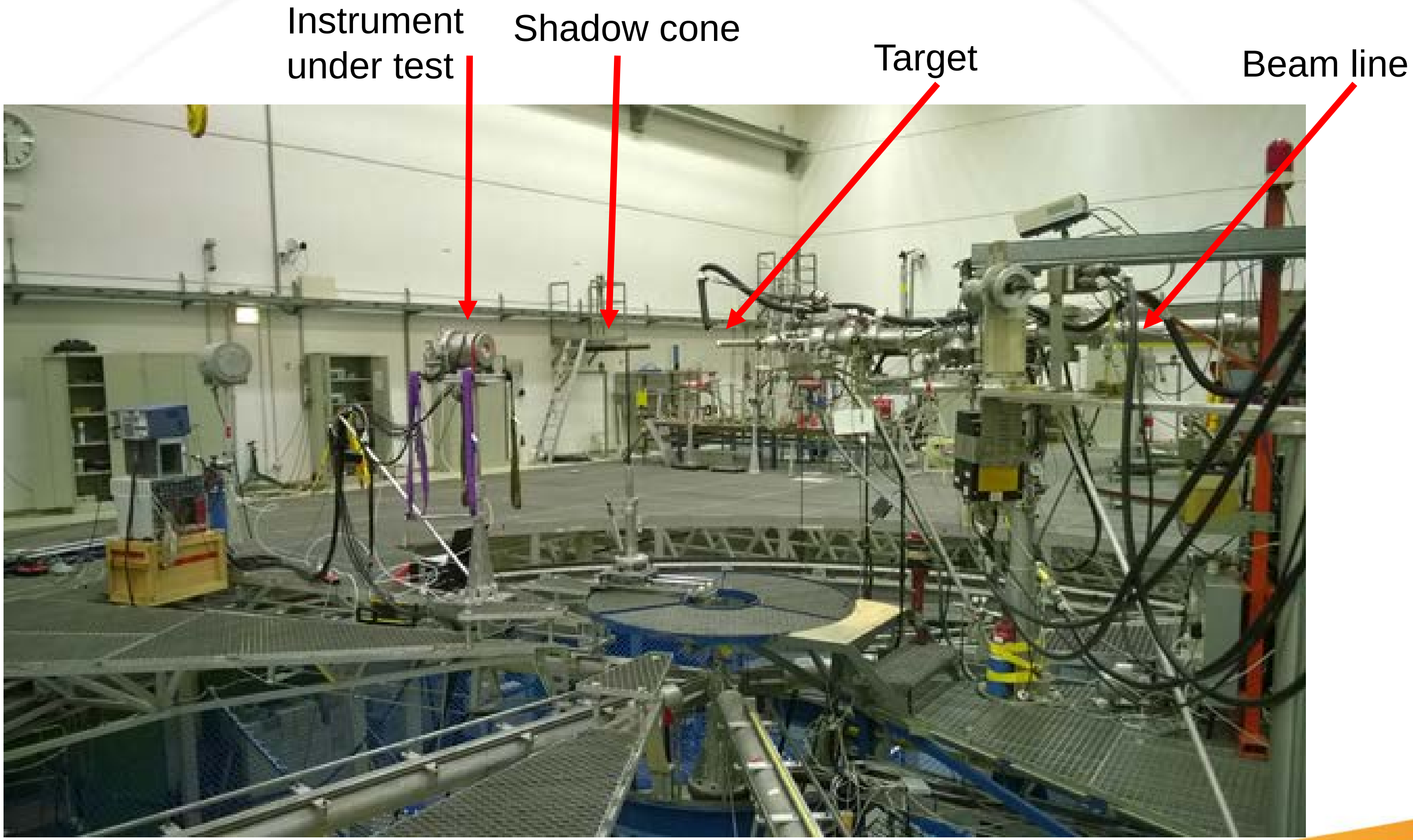
- Monoenergetic neutrons can be produced up to 20 MeV using well-known reactions

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

Neutron accelerators

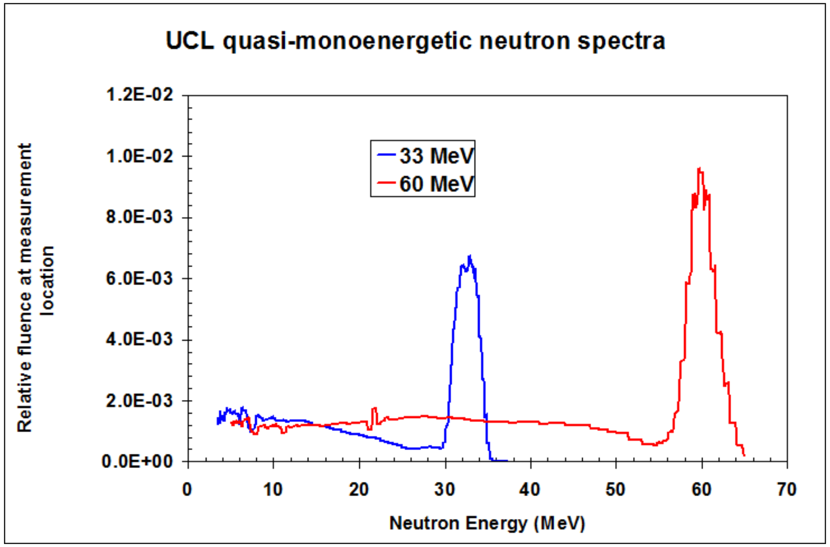
- Neutron energy a function of ion energy and target material and also angle with respect to target.
- Highest energies in forward direction and lowest in backward direction.
- Monoenergetic neutrons very useful to characterize instrument performance at specific energies.
- Full set of measurements defines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

PTB Neutron calibration facility

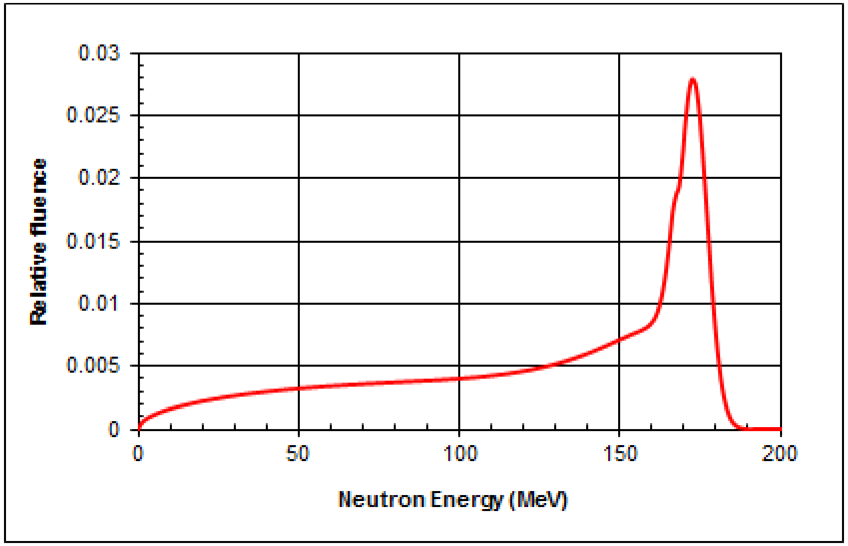


Neutron accelerators

- 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

Neutron accelerators

- Spallation neutron sources
  - E.g. LANSCE-WNR (LANL) and SNS (Oak Ridge)
  - ~ 1GeV MeV 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°.

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 ~ 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

Neutrons of cosmic origin

- Neutrons produced by interaction of cosmic particles with upper layers of atmosphere.
- Neutron fluence strong function of altitude
  - 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 m^{-2} s^{-1}
  - Dose rates < 5 μrem/h

Neutron sources

Questions ?