NEUTRON SOURCES

General

General

Neutron Properties

- Composition: two down quarks and one up quark
- Rest Mass: 1.0086649 amu
- Energy equivalent: 939.5656 MeV
- Electric charge: 0
- Half-life: 10.4 minutes (outside the nucleus)
- Decay scheme:

neutron → proton + beta + antineutrino

General

Uses of Neutrons

Reactor start up

Moisture gauges

Activation analysis

Radiography

Triggers for nuclear weapons

Instrument calibration

Density gauges

Well logging

Gemstone colorization

Research (physics, medicine)

General

Neutron Fluence Rate

- The intensity of a neutron source is usually described by the fluence rate

- This is often and incorrectly referred to as the flux

- The neutron fluence rate (ϕ) is the number of neutrons that pass through a specified area per unit time. Commonly employed units for this quantity are n/cm^2/s (i.e., cm^{-2} s^{-1}). The direction of the neutrons is irrelevant.

General

Types of Neutron Sources

- Alpha neutron sources
- Gamma neutron sources
- Spontaneous fission neutron sources
- Fission reactors
- Accelerators

General

Measuring the Neutron Source Strength

- The neutron emission rates for alpha neutron, gamma neutron, and spontaneous fission neutron sources can be determined with the manganese sulfate bath technique.

- The source is positioned in the center of a tank filled with a solution of manganese sulfate (the bath must be large enough to moderate all the neutrons). By quantifying the Mn-56 (2.6 hr) production via gamma spectrometry, the neutron emission rate can be calculated.

General

Measuring the Neutron Source Strength

Image courtesy of NPL.

The manganese solution is inside the spherical tank and the source is lowered through the top.

The white neutron detector on the right side of the tank is used to measure neutron leakage. This value is used to make corrections to the calculated neutron emission rate.

ALPHA NEUTRON SOURCES

Alpha Neutron Sources

General

- Alpha neutron sources are the most commonly encountered type of neutron source.
- An alpha emitter is intimately mixed with a low Z material, usually Be-9.

$$\text{Be-9} + \alpha \rightarrow \text{C-12} + \text{neutron} + 4.44\ \text{MeV}\ \gamma$$

- The source strength is specified by the activity of the alpha emitter. Activities of 0.5 to 40 Ci (18.5 GBq to 1.48 TBq) are common although portable density gauges might employ 10 to 50 mCi (0.37 to 1.85 GBq) sources .

Alpha Neutron Sources

General

- Alpha emitters used in neutron sources include Am-241, Pu-238, Pu-239, Po-210, Ra-226
- The “most important” is Am-241. Plutonium sources are also common.
- One possible concern with these sources is the potential for the build-up of pressure due to helium production.

Alpha Neutron Sources

AmBe Sources

- AmBe ("ambee") sources are a mix of Am-241 and Be-9.
- Yield: ca. 2.0 to 2.4 x 10^6 neutrons/sec. per Ci
  ca. 5.4 to 6.5 x 10^4 neutrons/sec. per GBq
- Half-life: 432.2 years
- Average neutron energy: 4.2 MeV (11 max)
- Neutron dose rate: 2.2-2.7 mrem/hr at 1 m/Ci
  0.59-0.73 uSv/hr at 1m/GBq
- Gamma dose rate: 2.5 mrem/hr at 1 m/Ci
  0.68 uSv/hr at 1m/GBq

Alpha Neutron Sources

PuBe Sources

- PuBe ("pewbee") sources are a mix of Pu-239 or Pu-238 and Be-9.
- Yield: ca. 1.5 to 2.0 x 10^6 neutrons/second per Ci
  ca. 4 to 5.4 x 10^4 neutrons/second per GBq
- Half-life: 24,114 years
- Average neutron energy: 4.2 – 5 MeV (11 max)
- Neutron dose rate: 1.3-2.7 mrem/hr at 1 m/Ci
  0.35-0.73 uSv/hr at 1m/GBq
- Gamma dose rate: 0.1 mrem/hr at 1 m/Ci
  0.027 uSv/hr at 1 m/GBq

Alpha Neutron Sources

RaBe Sources

- RaBe (“raybee”) source, a mix of Ra-226 and Be-9
- Yield: ca. 15 x 10^6 neutrons/sec. per Ci

  ca. 40 x 10^4 neutrons/sec. per GBq
- Half-life: 1,600 years
- Average neutron energy: 3.6 MeV (13.2 MeV max)
- Gamma exposure rates of these sources can be high. There is also the problem of leakage. RaBe sources have been used in moisture gauges sold by Seaman Nuclear - until recently radium has been unregulated by the NRC.

Alpha Neutron Sources

Alternatives to Beryllium

- Beryllium is the most common low Z material to be used in alpha-neutron sources because of its relatively high neutron yield.
- Nevertheless, fluorine, lithium and boron have also been used.
- Am-F and Am-Li sources have average neutron energies of 1.5 and 0.5 MeV respectively.

Alpha Neutron Sources

Neutron Yield

- The neutron yield (n/s) of a particular source can only be determined precisely by measurement
- Yield values expressed as n/s/Ci are only estimates.
- The actual yield depends on the source construction and the beryllium - alpha emitter ratio.

Alpha Neutron Sources

Source Construction

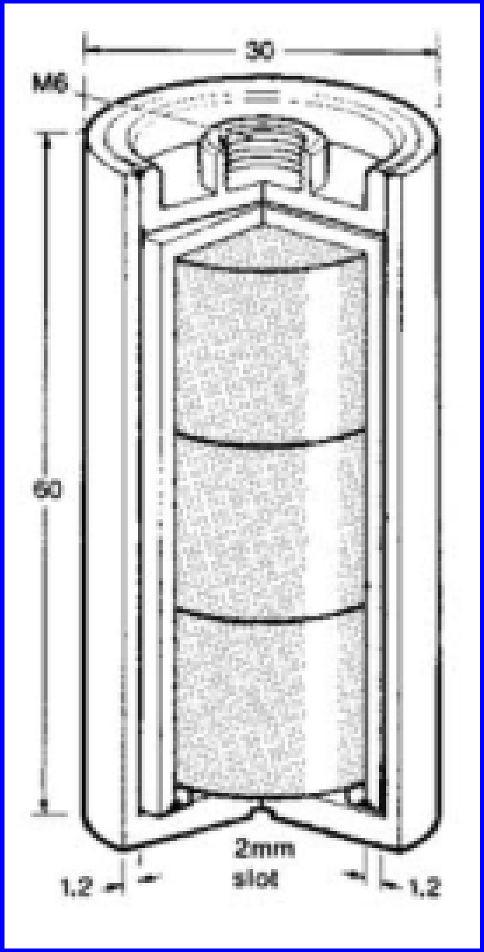
- The alpha emitter and beryllium must be in intimate contact, e.g., by mixing powdered beryllium metal with an oxide of the alpha emitter. This mixture is then compressed into a cylindrical shape for encapsulation. Another approach is to employ a metallic alloy of the beryllium and the alpha emitting actinide.

Typical AmBe sources. Largest pictured is 60 x 30 mm. Image courtesy of NPL..

Alpha Neutron Sources

Source Construction

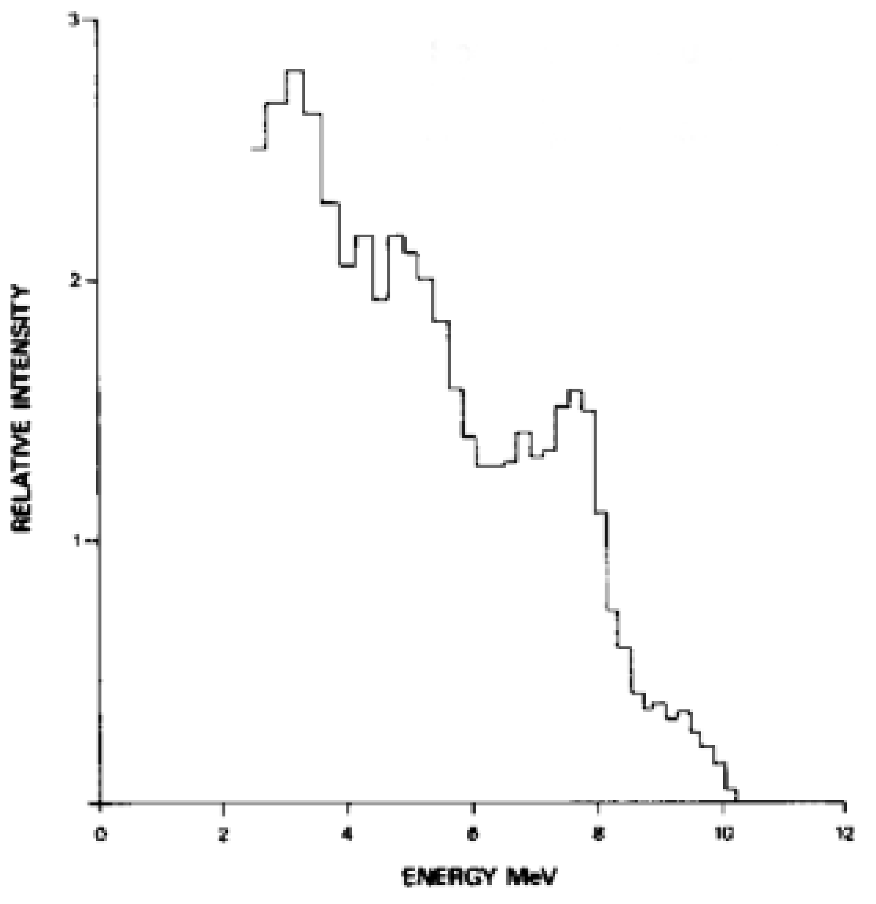
- The source is doubly encapsulated. The inner and outer capsules are usually fabricated of stainless steel (type 304) and the end caps are TIG welded. Space is left within the inner capsule to allow for the gradual buildup of helium that results from the alpha emissions.



Alpha Neutron Sources

Neutron Energies

The energies usually range up to 11 MeV with an average energy between 4 and 5 MeV.



GAMMA-NEUTRON SOURCES

Gamma-Neutron Sources

General

- If the nuclei of H-2 or Be-9 are given sufficient excitation energy by a gamma ray, a neutron can be ejected from the nucleus.
- Be-9 + γ → Be-8 + neutron (Q: - 1.67 MeV)
- H-2 + γ → H-1 + neutron (Q: - 2.23 MeV)

Gamma-Neutron Sources

General

- The major advantage of photo-neutron sources is that the emitted neutrons are very close to being monoenergetic.

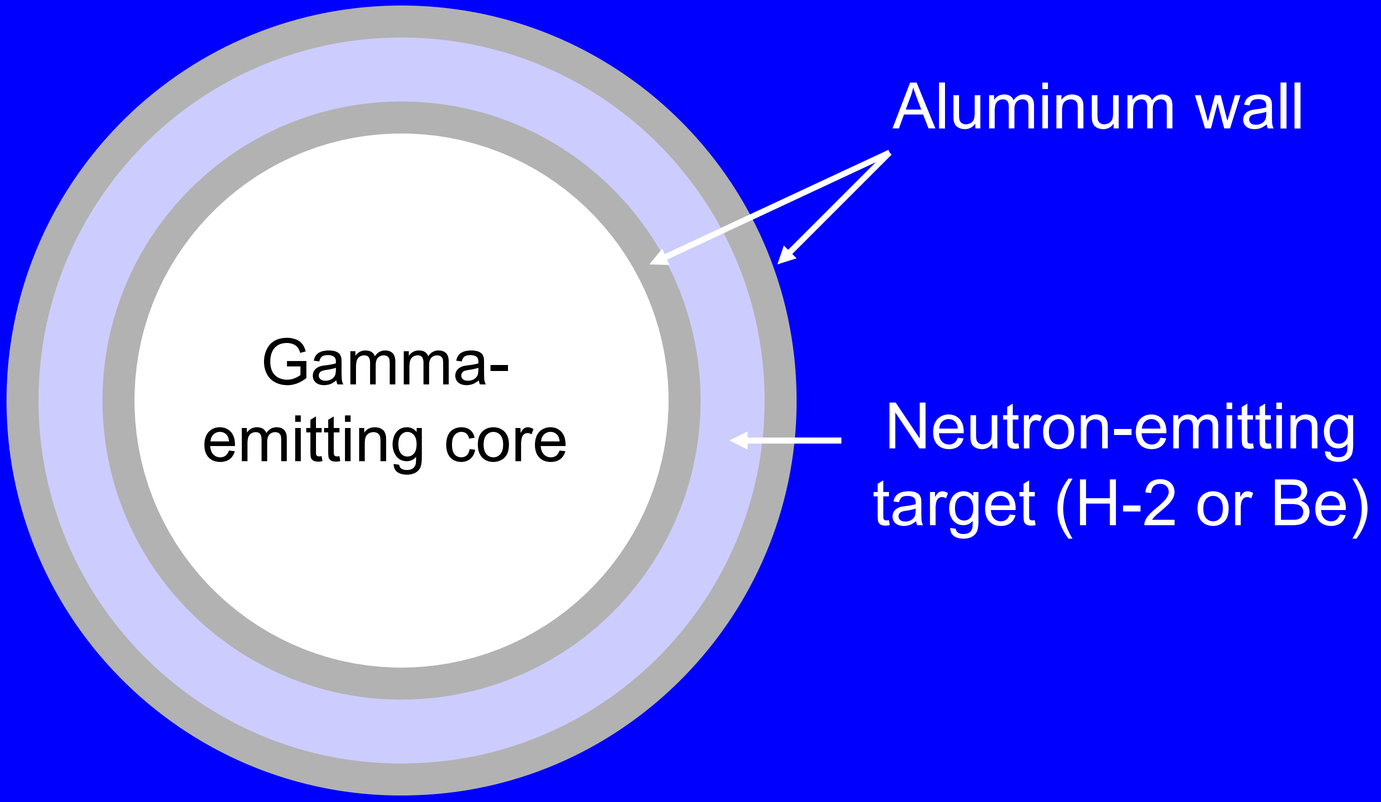
- Their major disadvantage is the very high activity of the gamma source - only one gamma ray in one million (or so) might produce a neutron. The resulting gamma exposure rates can pose a significant radiological hazard.

Gamma-Neutron Sources

Source Construction

- A “typical” photo-neutron source might consist of an inner aluminum-encapsulated gamma-emitting core (e.g., 1 inch diameter) surrounded by an eighth of an inch of the neutron emitting target.
- The overall shape of the source might be cylindrical or spherical.
- In the case of an antimony-beryllium source, the core is antimony that has been activated in a reactor.

Gamma-Neutron Sources



Gamma-Neutron Sources

Sb-Be Source Characteristics

- A mix of Sb-124 and Be-9.
- Yield: ca 0.2-0.3 x 10^6 neutrons/sec. per Ci
  ca. 0.54-0.81 x 10^4 neutrons/sec. per GBq
- Half-life: 60 days
- Gamma energy: 1.69 MeV
- Neutron energy: 0.024 MeV
- Neutron dose rate: 0.18-0.27 mrem/hr at 1 m/Ci
  0.049-0.073 uSv/hr at 1m/GBq
- Gamma dose rate: 1000 mrem/hr at 1 m/Ci
  270 uSv/hr at 1m/GBq

SPONTANEOUS FISSION SOURCES

Spontaneous Fission Sources

General

- A number of high mass even-even alpha emitting radionuclides (e.g., Pu-238, Cm-242, Cm-244, Cf-252) also undergo spontaneous fission.

- Each fission event typically results in the emission of 2 to 4 neutrons.

- Their neutron spectra are similar to that of a fission reactor. In addition, they have a relatively low gamma output.

Spontaneous Fission Sources

Cf-252

- Californium-252 is one of the most important neutron sources. There are two key reasons:
  - its neutron energy spectrum is very similar to that of a reactor fission spectrum
  - its high neutron yield per unit mass permit the construction of physically small neutron sources

Cf-252 → 2 fission products + 3 - 4 neutrons

- Californium-252 sources can contain Cf-250 which has a 13.08 year half-life.

Spontaneous Fission Sources

Cf-252

- Alpha decay (97%), spontaneous fission (3%)
- Effective half-life: 2.645 years
- Produced in high-flux reactors (U.S.A, Russia)
- Specific activity: 532 Ci/g; 19.7 x 10^{12} Bq/g
- Average neutron energy: 2 MeV (10+ MeV max)

Spontaneous Fission Sources

Cf-252

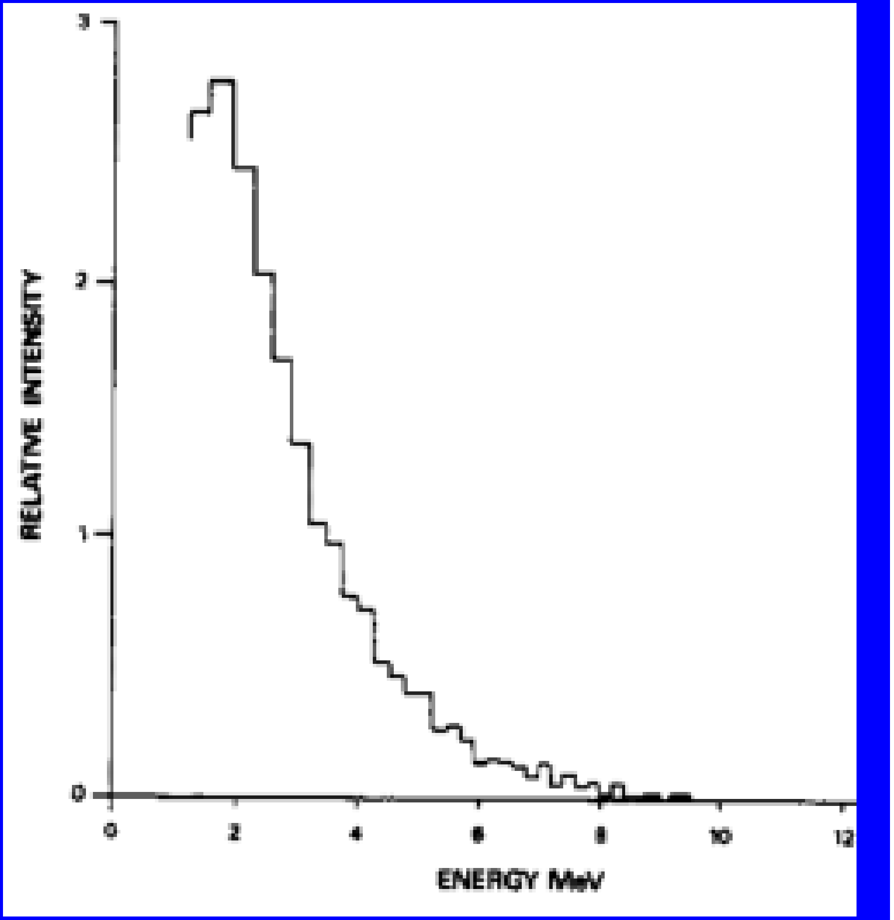
- Neutron yield: 2.3 - 2.4 x 10^{12} n, s^{-1}, g^{-1}
  4.4 x 10^{9} n, s^{-1}, Ci^{-1}
  1.2 x 10^{8} n, s^{-1}, GBq^{-1}
- Neutron dose rate: 2.2 - 2.3 x 10^{3} rem, m^{2}, g^{-1}, h^{-1}
  22 - 23 Sv, m^{2}, g^{-1}, h^{-1}
- Gamma dose rate: 1.6 x 10^{2} rem, m^{2}, g^{-1}, h^{-1}
  1.6 Sv, m^{2}, g^{-1}, h^{-1}

Spontaneous Fission Sources

Cf-252 Neutron Spectrum

- The neutron spectrum is very similar to that of a fission reactor.

- The average neutron energy is 2 MeV.



Spontaneous Fission Sources

Moderated Cf-252

- For instrument calibrations, californium-252 is often moderated with heavy water – this creates a “degraded” neutron spectrum more similar to that in the areas around reactors where dosimeters and survey meters are used.

- When moderated, the Cf-252 is typically centered in a 30 cm diameter steel sphere filled with the heavy water. In general, the steel is covered with a 1 mm cadmium shell.

Spontaneous Fission Sources

Moderated Cf-252

- Heavy water is used as the moderator because it doesn’t absorb neutrons. Only 11.5% of the original neutrons are lost and these are typically the thermal neutrons absorbed in the cadmium.

- A problem with moderated sources is their large size. Among other things, it can be difficult to use shadow cones to account for scatter.

- The average energy of the moderated spectrum is 0.55 MeV)

Spontaneous Fission Sources

The source (californium oxide or a californium-palladium alloy) is usually doubly encapsulated in stainless steel.

Typical Cf-252 sources. Smallest pictured is 10 x 7.8 mm. Image courtesy of NPL.

FISSION REACTORS

Fission Reactors

General

- Very intense sources (e.g., 10^{12} to 10^{15} n cm^{-2} s^{-1}).
- Their neutron yields can usually be changed by several orders of magnitude.
- Research reactors, as opposed to power reactors, incorporate beam ports that allow neutrons to escape the reactor core. These ports also permit samples to be inserted into the core.

Fission Reactors

General

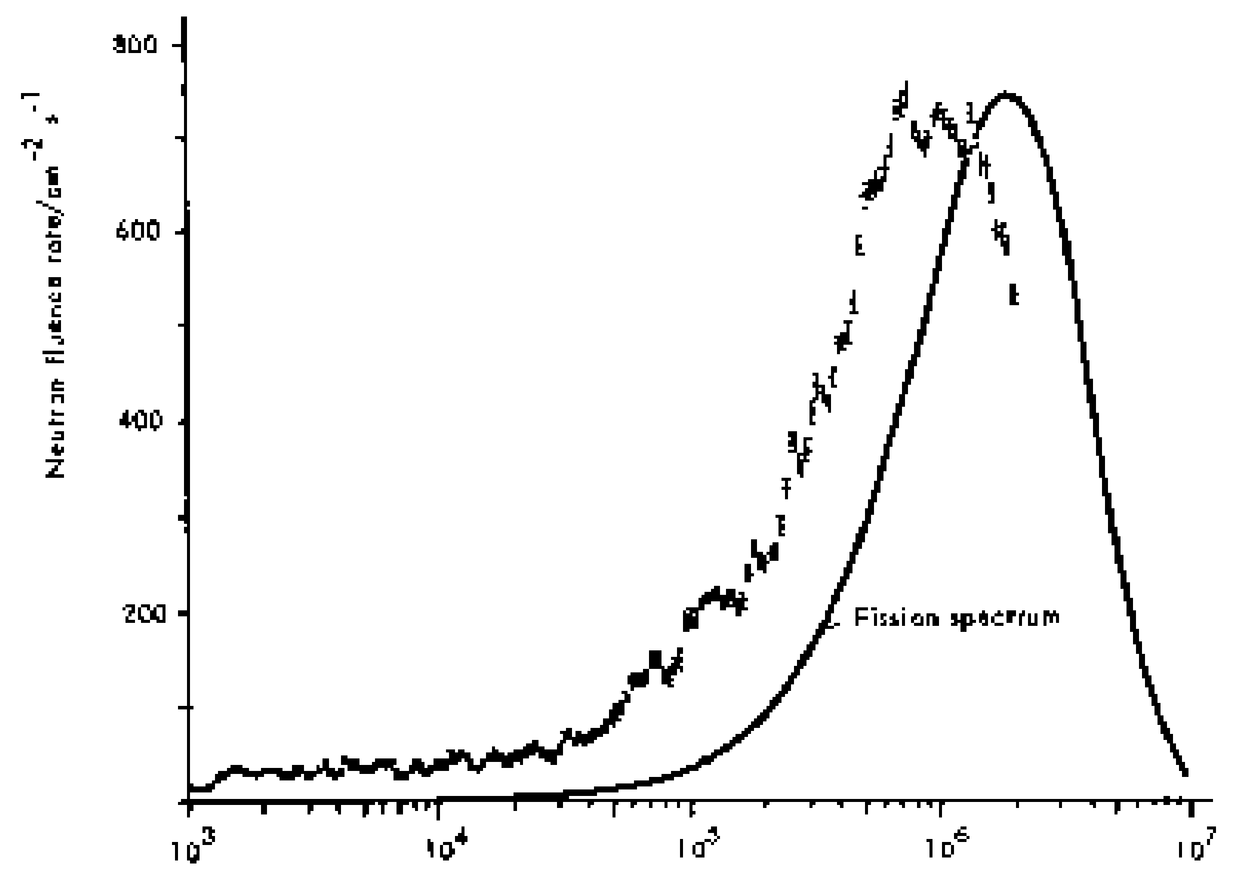
- In general, the neutrons are produced as a result of the fission of U-235. During operation, there is an in-growth of plutonium that will also fission.

$n_{(th)}$ + U-235 → Fission products + 2.4 neutrons (average)

- Neutron yield: 10^{12} n/s per megawatt (MW)
- Average neutron energy: 2.0 MeV
- Most probable energy (mode): thermal for thermal reactors and a few hundred keV for fast reactors

Fission Reactors

Fission Reactor Spectrum



ACCELERATORS

Accelerators

Electron Accelerators

- e.g., betatron, synchrotron and linear accelerators
- produce bremsstrahlung by bombarding high Z targets (e.g., tungsten) with electrons.
- The bremsstrahlung then produces neutrons via the (γ ,n) reaction in beryllium or other material
- Be-9 + bremsstrahlung → Be-8 + neutron

Accelerators

Electron Accelerators

- The higher the energy of the electron beam, the higher the energy of the bremsstrahlung, and the higher the energy of the neutrons. Some neutrons have energies equal to the energy of the bombarding electrons.

- Uranium targets produce neutrons by an additional method: the bremsstrahlung also generates neutrons by photofission (γ ,f).

Accelerators

Electron Accelerators

- Neutrons can be an unwanted byproduct of accelerators that produce high energy x-rays.

- When x-ray energies exceed 8 - 10 MeV, neutrons can be produced by a wide range of materials and the resulting neutron activation of the accelerator components, facility components, the dust and air can present a significant radiological hazard.

Accelerators

Positive Ion Constant Voltage Accelerators

- These devices, often referred to as neutron generators, are frequently used by research facilities and universities.

- By accelerating deuterons, protons, or other particles, into low Z targets, relatively small inexpensive accelerators can produce intense beams of monoenergetic neutrons.

- Constant voltage accelerators, e.g., Van de Graaff and Cockroft Walton accelerators, are often used

Accelerators

Positive Ion Constant Voltage Accelerators

- H-3 + H-2 → He-4 + 14 MeV neutron

  Q = 17.6 MeV

- H-2 + H-2 → He-3 + 2.5 MeV neutron

  Q = 3.26 MeV

Accelerators

Positive Ion Constant Voltage Accelerators

- The D-T reaction, where deuterium ions are accelerated into a tritium target is the most commonly employed reaction in neutron generators.

- The target is a metal halide film, e.g., titanium, scandium or zirconium halide deposited on a copper or molybdenum backing. There are two hydrogen atoms (deuterium or tritium) per atom of metal in the target.

Accelerators

Positive Ion Constant Voltage Accelerators

Accelerators

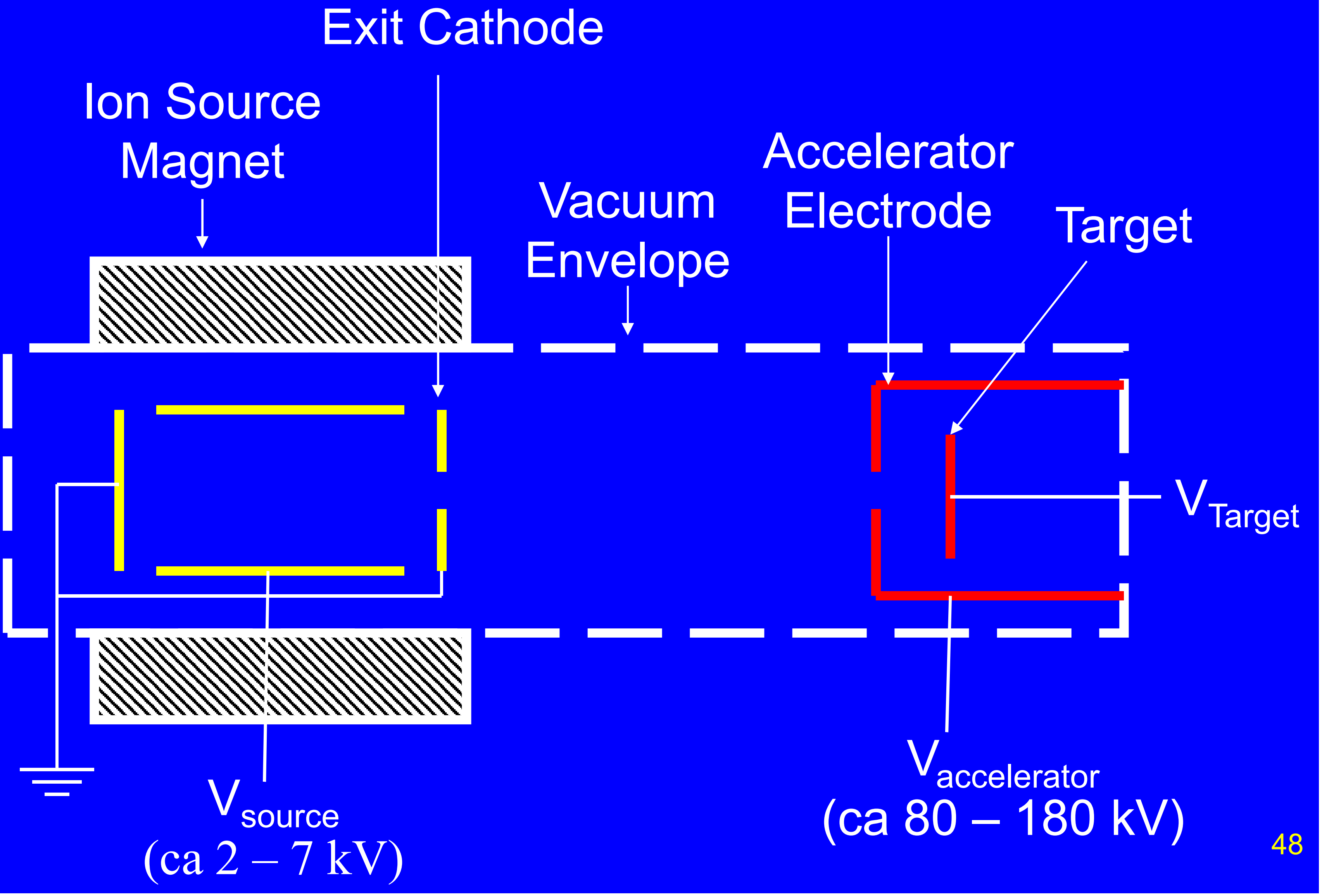
Positive Ion Constant Voltage Accelerators

- A typical neutron generator has three components: the accelerator itself, a high voltage power supply, and a control console

  Unlike alpha-neutron or spontaneous fission neutron sources, these neutron generators can be turned off.

Accelerators

Positive Ion Constant Voltage Accelerators



Accelerators

Positive Ion High Frequency Accelerators

- High frequency positive ion accelerators (e.g., cyclotron, synchrocyclotron, proton synchrotron and heavy ion linear accelerator) produce pulsed beams of ions.
- Unfortunately, any neutron production associated with these accelerators is also pulsed and many neutron detectors cannot function properly in pulsed beams.

Accelerators

Positive Ion High Frequency Accelerators

- Common reactions used to produce neutrons :

Be-9 + H-2 → B-10 + neutron

Q: 4.36 MeV

Li-7 + p → Be-7 + neutron

Q: - 1.65 MeV

Accelerators

Positive Ion High Frequency Accelerators

- The higher the energy of the ion beam, the greater the neutron yield and the wider the range of neutron energies

- The neutrons produced by such accelerators are often an unwanted byproduct of their operation. Proton beams above 10 MeV produce neutrons when they strike almost any type of material.

ESTIMATING NEUTRON DOSE EQUIVALENT RATES

Estimating Neutron Dose Equivalent Rates

General

We will consider two approaches for estimating the neutron dose equivalent rate:

1. Using the source activity and the neutron dose constant.
2. Using the neutron fluence rate and a flux to dose factor.

Estimating Neutron Dose Equivalent Rates

1. Using the Source Activity and a Neutron Dose Constant

The dose equivalent rate is calculated with the following formula

$$\dot{H} = \frac{A \text{ x } N}{d^2}$$

A is the source activity (e.g., Ci, GBq) or mass (e.g., g)
N is the neutron dose rate constant (e.g., mrem, m^2, Ci^{-1}, h^{-1})
d is the distance (e.g., m) from the source to the point at which the dose equivalent rate is calculated

Estimating Neutron Dose Equivalent Rates

1. Using the Source Activity and a Neutron Dose Constant

This method might be used with an alpha-beryllium, a photo-neutron or a Cf-252 source. It would not work if the neutron source is an accelerator or reactor.

As an example, we will calculate the dose equivalent rate at 2 meters from a 50 GBq AmBe source using a conservative dose factor.

Estimating Neutron Dose Equivalent Rates

1. **Using the Source Activity and a Neutron Dose Constant**

$$\dot{H} = \frac{A\,N}{d^2}$$

$$= \frac{50\ x\ 0.73}{(2)^2}$$

$$= 9.125\ uSv/hr$$

Estimating Neutron Dose Equivalent Rates

2. Using the Neutron Fluence Rate

This method can be used if the neutron fluence rate has been measured or calculated.

If the neutrons are produced by an alpha-beryllium, photo-neutron or Cf-252 source, we can calculate the neutron fluence rate with the formula on the following page.

Estimating Neutron Dose Equivalent Rates

2. Using the Neutron Fluence Rate

$$\phi = \frac{S}{4\pi d^2}$$

ϕ is the neutron fluence rate (n/cm^2/s)

S is the neutron emission rate (n/s)

d is the distance from the source at which the fluence rate is calculated (cm).

Estimating Neutron Dose Equivalent Rates

2. Using the Neutron Fluence Rate

Example: calculate the fluence rate at 2 meters from a 50 GBq neutron source.

First we calculate the neutron emission rate:

$S = A \times 6.5 \times 10^4$ neutrons/sec. per GBq

$= 50$ GBq $\times 6.5 \times 10^4$ neutrons/sec. per GBq

$= 3.25 \times 10^6$ n/s

Estimating Neutron Dose Equivalent Rates

2. Using the Neutron Fluence Rate

Then we calculate the fluence rate as follows:

$$\phi = \frac{S}{4\pi d^2}$$

$$= \frac{3.25 \ x \ 10^6}{4\pi (200)^2}$$

$$= 6.47 \, n / cm^2 / s$$

Estimating Neutron Dose Equivalent Rates

2. Using the Neutron Fluence Rate

Once we have the neutron fluence rate, the neutron dose equivalent rate can be estimated as follows:

$$\dot{H} = 3.6 \, x \, 10^3 \, \frac{\phi}{F}$$

F is a factor that indicates the neutron fluence per unit dose equivalent (n/cm^2/rem) .

3.6 x 10^3 converts the number of neutrons per cm^2 per second into neutrons per cm^2 per hour.

Estimating Neutron Dose Equivalent Rates

2. Using the Neutron Fluence Rate

There are various sources for the neutron fluence per unit dose equivalent (e.g., n/cm^2/rem) factors, e.g., they can be obtained from table 1004(B).2 in 10 CFR 20.

One source of uncertainty: these factors are for monoenergetic neutrons whereas neutron exposures inevitably involve neutrons with a range of energies.

One acceptable approach might be to use the factor for the average neutron energy.

Estimating Neutron Dose Equivalent Rates

2. Using the Neutron Fluence Rate

In our example, the average neutron energy for an AmBe source is approximately 4.2 MeV.

Table 1004(B).2 in 10 CFR 20 indicates that the fluence per unit dose equivalent for 5 MeV (the closest energy listed to 4.2 MeV) neutrons is 23×10^{6} neutrons cm^{-2} rem^{-1}.

Estimating Neutron Dose Equivalent Rates

2. Using the Neutron Fluence Rate

$$\begin{aligned}
\dot{H} &= 3.6\ x\ 10^{3}\ \frac{\phi}{F} \\
&= 3.6\ x\ 10^{3}\ \frac{6.47}{23\ x\ 10^{6}} \\
&= 1\ x 10^{-3}\ rem / hr \\
&= 1\ mrem / hr \\
&= 0.01 mSv / hr \\
&= 10 uSv / hr
\end{aligned}$$