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Title: Basic of Neutron NDA

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Intended for: Training Course

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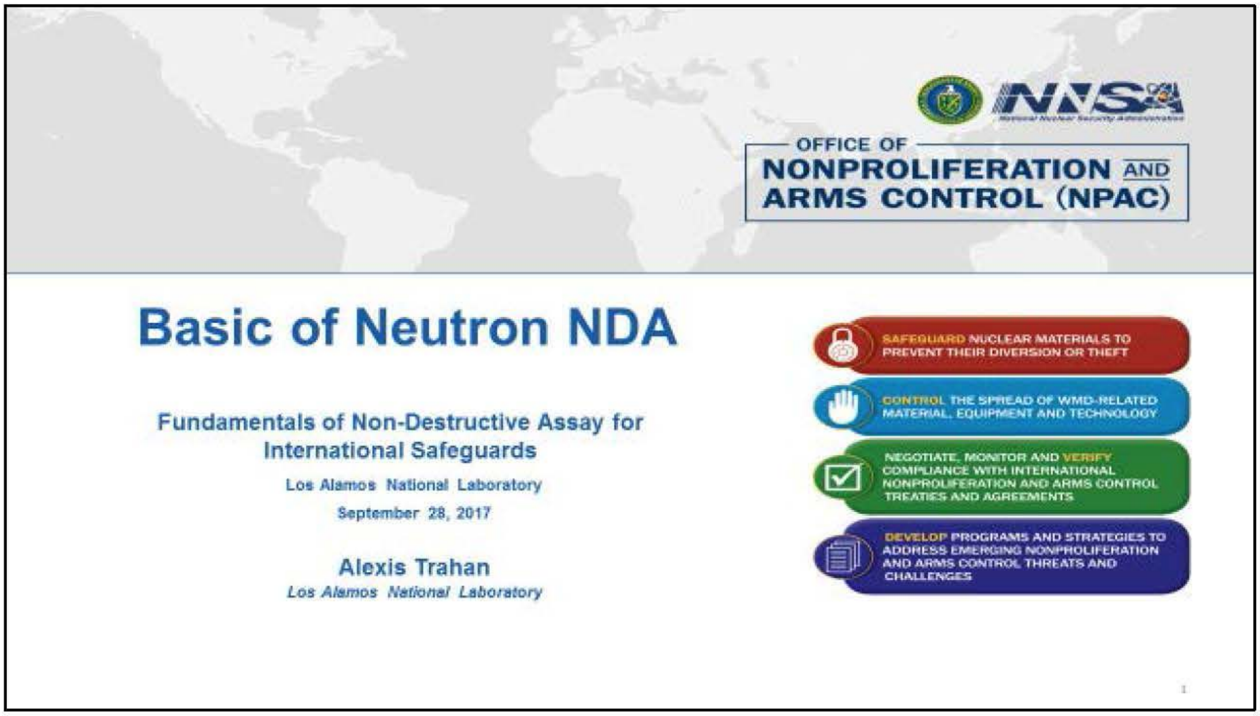
OFFICE OF
NONPROLIFERATION AND
ARMS CONTROL (NPAC)
Basic of Neutron NDA
Fundamentals of Non-Destructive Assay for International Safeguards
Los Alamos National Laboratory
September 28, 2017
Alexis Trahan
Los Alamos National Laboratory
SAFEGUARD NUCLEAR MATERIALS TO PREVENT THEIR DIVERSION OR THEFT
CONTROL THE SPREAD OF WMD-RELATED MATERIAL, EQUIPMENT AND TECHNOLOGY
NEGOTIATE, MONITOR AND VERIFY COMPLIANCE WITH INTERNATIONAL NONPROLIFERATION AND ARMS CONTROL TREATIES AND AGREEMENTS
DEVELOP PROGRAMS AND STRATEGIES TO ADDRESS EMERGING NONPROLIFERATION AND ARMS CONTROL THREATS AND CHALLENGES

Estimated Module Duration: 1 hour

Required Tools and Materials:

1. Projector, screen, laptop with Word and PowerPoint programs
2. Participant guides, with slides and supplemental material

References:

1. [Insert references used to develop the content for the presentation and instructor/student guide, such as an International Atomic Energy Agency (IAEA) service series document. It may be helpful to provide links to where these resources can be found online, if applicable.]
2. […]

Supporting Documents:

1. None

Job Aids:

1. None

Terminal Learning Objectives (TLOs):

- TLO-1: Introduce the basic physics of neutron production, interactions, and detection

Enabling Learning Objectives (ELOs):

- ELO-1: Identify the processes that generate neutrons
- ELO-2: Explain the most common neutron production mechanism: spontaneous and induced fission and (a,n) reactions
- ELO-3: Describe the properties of neutron from different sources
- ELO-4: Recognize advantages of neutron measurements techniques
- ELO-5: Recognize common neutrons interactions
- ELO-6: Explain neutron cross section measurements
- ELO-7: Describe the fundamentals of ^{3}He detector function and designs
- ELO-8: Differentiate between passive and active assay techniques

Additional Information for Students:

Instructor Notes:

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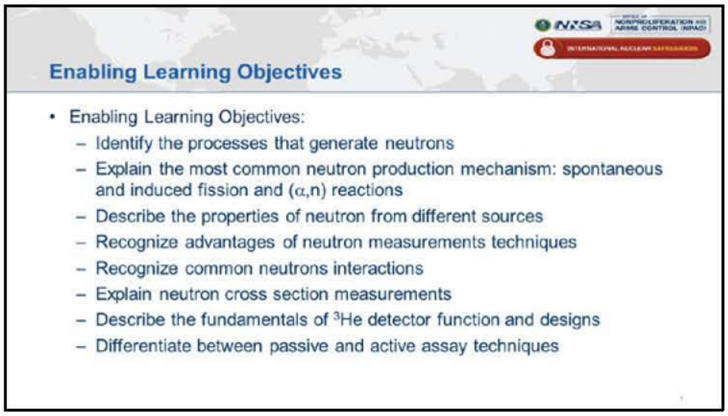

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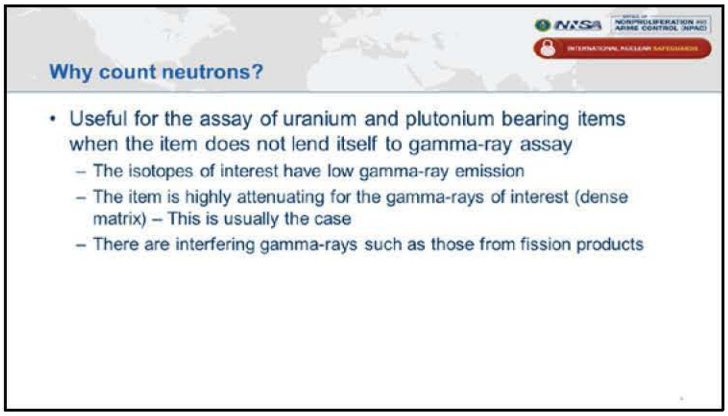

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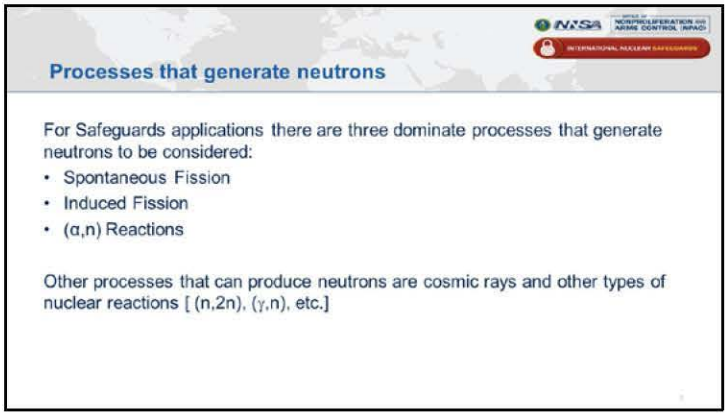

To understand neutron counting techniques, one must first understand the fundamental physics of neutron production and interactions. This module will begin with a discussion of neutron origins. The most well-known process that generates neutrons is fission, which can either be spontaneous or induced. Fission is the primary neutron production mechanism we are concerned with in neutron counting for safeguards and security purposes. However, other neutron production mechanisms can complicate neutron measurements.

(α, n) reactions occur when a nucleus α-decays, meaning an unstable nucleus emits a helium nucleus, or an α particle, composed of two neutrons and two protons. This form of decay is unlikely to occur except in heavy elements, such as uranium, plutonium, and americium. The α particle then interacts with second material, such as oxygen or fluorine, and the resulting nuclear reaction generates a neutron. Neutron count rates can be used to determine the fissile mass in special nuclear materials. In a typical plutonium oxide item, about half the neutrons come from spontaneous fission and half from (α, n) reactions. So it is difficult to measure the plutonium mass by measuring the total neutron emission from an item. We use the timing properties of these different neutron sources to distinguish between them – see later.

Less common reactions include (p, n), (n, 2n), (γ, n), and cosmic ray interactions. As with (α, n) reactions, these processes produce neutrons that can contribute to and possibly complicate neutron assay measurements.

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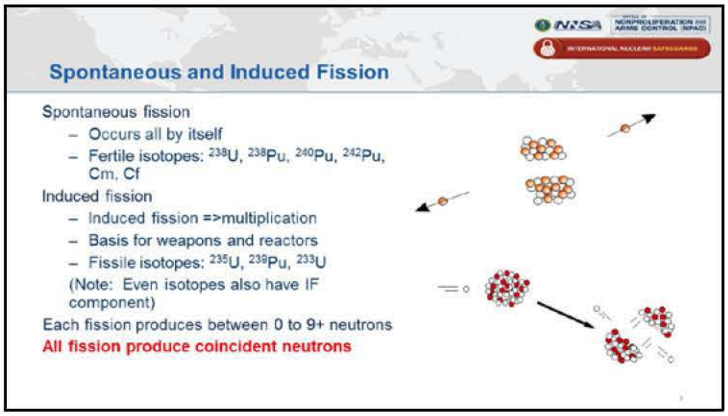

As shown in the slide, spontaneous fission is a random process that occurs as a mode of decay for certain isotopes. The short-range strong nuclear force easily overcomes the repulsive electrostatic forces of protons in light elements. In heavy elements, however, the electrostatic force can overcome the strong nuclear force, causing the isotope to fragment into two new elements. In this process, most of the roughly 200 MeV released in fission are carried in the two fragments. Neutrons and gamma rays are also emitted in the fission event, some immediately (prompt) and some after a few milliseconds or seconds (delayed), which carry some of the energy released in fission. The number of spontaneous fission neutrons emitted is proportional to the mass of the spontaneously fissioning nuclides.

Referring back to the slide, the second illustration is of induced fission. Induced fission occurs when heavy isotopes are bombarded with low-energy neutrons, some of which are absorbed. The result is an excited compound nucleus (e.g. $^{235}U + n \rightarrow {}^{236}U^*$) which splits into two fission fragments. As in spontaneous fission, prompt and delated neutrons and gamma rays are also emitted as a result of the fission event. The neutrons emitted in both spontaneous and induced fission can slow down and induce fission in other nuclei, and this process can eventually lead to a fission chain reaction. This chain reaction is the mechanism behind nuclear reactors and weapons. The number of neutrons emitted from induced fission not only depends on the amount of fissile nuclei but also on the shape and density of the material as well as the presence of neutron absorbing materials.

Isotopes with odd neutron numbers (odd-even or odd-odd) that are easily induced to fission by low-energy neutrons are known as "fissile." Fissile isotopes of interest in nuclear safeguards and security include ^{235}U, ^{239}Pu, and ^{233}U. Some even-even isotopes can also be induced to fission, but only with high-energy neutrons. Even-even isotopes that are not easily induced to fission by low-energy neutrons are known as "fertile." Through neutron capture, fertile isotopes can be a source of fissile isotopes. They also have a much higher probability than fissile isotopes of spontaneous fission. Fertile isotopes of interest in nuclear safeguards and security include ^{238}U, ^{238}Pu, ^{240}Pu, ^{242}Pu, ^{242}Cm, ^{244}Cm and ^{252}Cf.

Neutrons from both types of fission are emitted in bursts rather than singly and this can be used to differentiate them from (α, n) neutrons.

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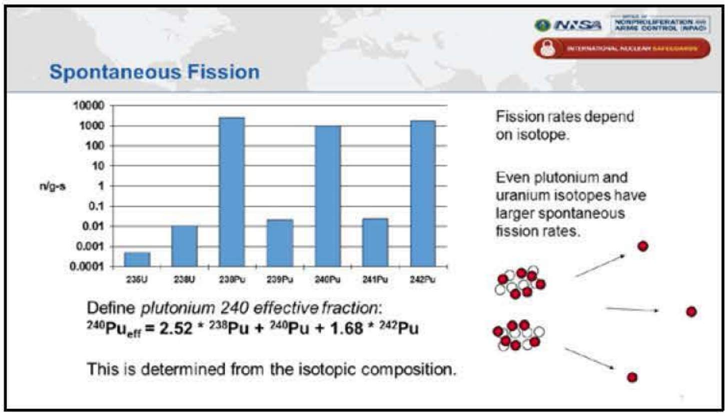

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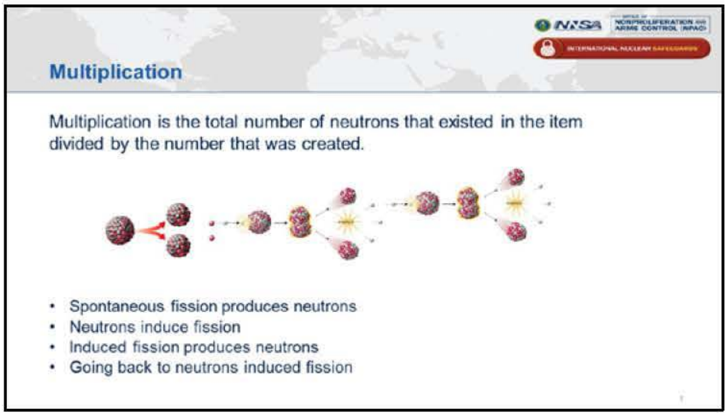

This slide presents an illustration of the multiplication process. A fission (spontaneous or induced) produces neutrons, which induce fission in surrounding nuclei. The induced fissions produce neutrons which also induce fission in surrounding nuclei, and the process continues. The induced fission neutrons are time-correlated to the initial fission or other neutron production event.

Neutron count rates are related to the amount of fissionable material present. In materials with high enough spontaneous fission rates (e.g. plutonium), enough multiplication occurs without outside stimuli that we can use "passive" detection methods to characterize the material. Other materials (e.g. uranium), have very low spontaneous fission rates, and an outside source is required to induce fission within the material and generate a high enough count rate to be statistically significant.

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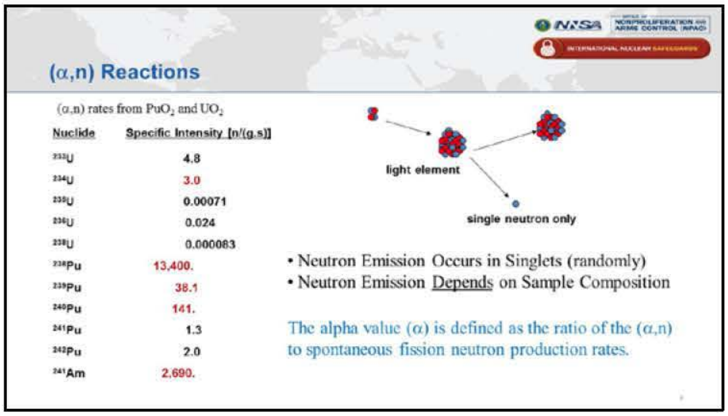

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(α,n) Neutron Yields from Selected Elements

Natural Element	Neutron yield per 10^6 alphas E_α = 5.2 MeV (av. Pu)	Yield Relative to O	Average Neutron Energy (MeV)
Be	65	1102	4.2
B	17.5	297	2.9
F	5.9	100	1.2
Li	1.13	19.2	0.3
Na	1.1	18.6	~0.9
Mg	0.89	15.1	2.7
Al	0.41	6.95	1.0
Si	0.076	1.29	1.2
Cl	0.07	1.19	~0.5
C	0.078	1.32	4.4
O	0.059	1.00	1.9

The number of (α,n) neutrons produced strongly depends on the light elements in the item.

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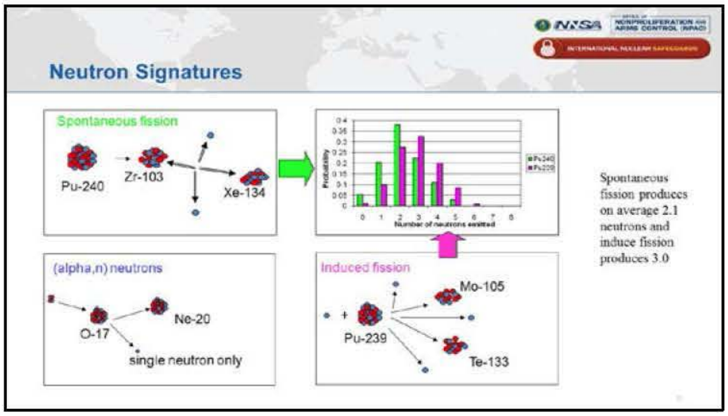

We can verify the amount of fissionable material present by counting the number of neutrons emitted from a sample. The amount of fissionable material is also related to the α-decay rate. Low count rates (as in waste) can be increased by the presence of (α,n) reactions.

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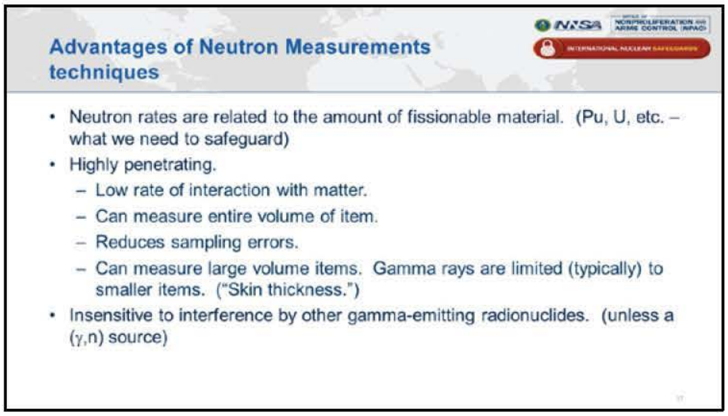

Neutron count rates are related to the amount of fissionable material present. This is an important characteristic to nuclear material safeguards, as it means that we can verify the amount of fissionable material present by counting the number of neutrons emitted from a sample. Neutron measurements allow inspectors to verify the amount of nuclear material within a sample without destroying the sample. Nondestructive safeguards techniques are known as Nondestructive Assay (NDA).

Neutrons have several advantages over gamma rays in safeguards applications. They are highly penetrating because they have low interaction rates with matter. They can be used to measure the entire volume of a sample, as a neutron produced in the center of a sample has a high probability of exiting the sample and being detected.

For destructive analysis a small sample of the whole item is taken and only this part is measured. If the item is not uniform, then the result is not representative of the complete item. This is called sampling error. By measuring neutrons from the entire item we avoid sampling errors. It also means that samples with large volumes can be measured. Gamma rays can only penetrate the outer layer ("skin thickness") of large samples, meaning that they cannot provide a complete picture of the item in question. Therefore, they are typically limited to small items.

Neutron detectors are also insensitive to interference by other gamma-emitting radionuclides that may be present in the sample, except (γ,n) sources. Gamma detectors are sensitive to the signals of all gamma-emitting radionuclides in the vicinity of the detector, which can confuse measurements.

As an example, UF_6 cylinders contain a large amount of fissionable material (^{235}U). Historically measurements of the ^{235}U content of these cylinders have been made using a combination of weighing scales and gamma-ray measurements. The gamma-ray measurements are only able to measure the material closest to the walls of the cylinder, meaning that they may not give a representative value for all of the material in the cylinder. New technological developments have enabled neutron measurements of these cylinders, and thus full-volume verification of the samples.

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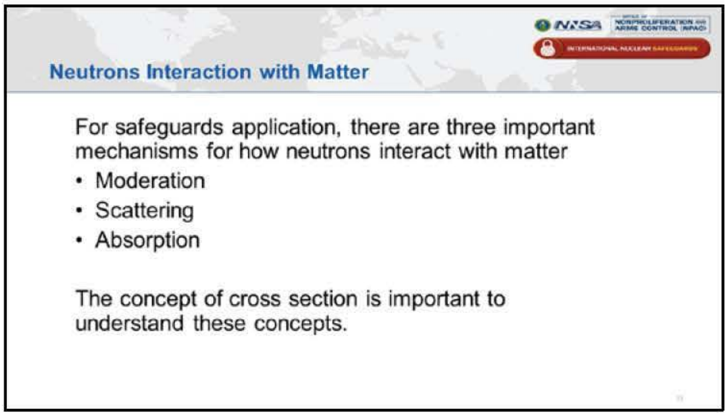

Neutrons interact with matter in several ways. We will discuss two interactions (moderation and absorption) that are important to nuclear safeguards and some of the physics concepts that are necessary to understand neutron interactions over the next few slides.

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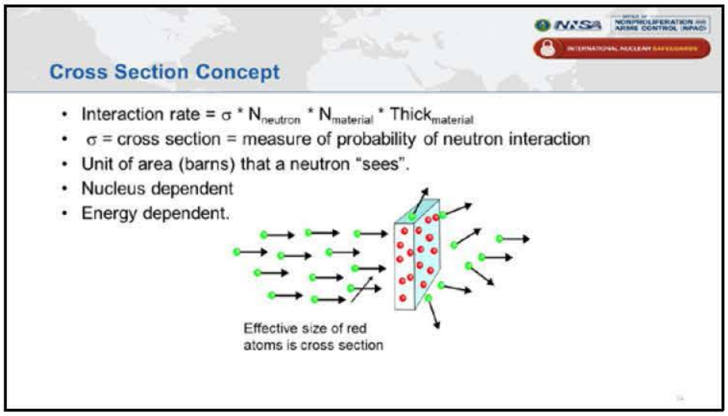

Neutron cross sections are a measure of the probability that a neutron will interact with a certain material. Look at the image on the slide and imagine the green dots are neutrons. They intercept the material, which has some thickness, and they interact in different ways with the material. Some are absorbed, some are scattered, and some pass through without interacting at all. The probability of a particular interaction can be considered to be the "effective size" of the red atoms that compose the material. This effective size is measured in a unit of area called a "barn," which can also be thought of as the area that the neutron "sees." A barn is 10^{-24} cm^2.

The interaction rate of neutrons passing through a material is calculated by multiplying the cross section in barns by the thickness of the material, the number density of neutrons and the number density of the material. The unit analysis is as follows: [interactions/cm^3·s] = [cm^2]x[neutrons/cm^3]x[atoms material/cm^3]*[cm].

Cross sections are dependent on the particular nuclei involved in the interactions and on the energy of the incoming neutron. For example, ^{3}He, which is used as the detection medium for most neutron detectors, has a large absorption cross section for thermal neutrons. However, it has a very low absorption cross section for fast neutrons. The dependence of cross sections on energy will be illustrated in an upcoming slide. In contrast, interactions between gamma and materials vary much more uniformly as a function of material mass and gamma energy.

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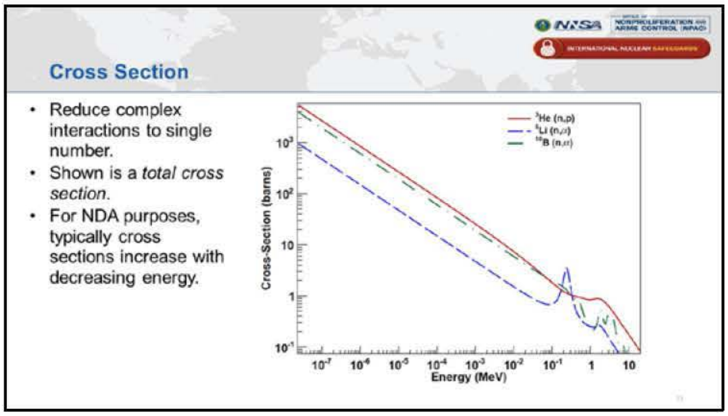

As mentioned in the previous slides, neutron cross sections for different materials are dependent on the energy of the incoming neutron. This slide provides an illustration of this effect. One can see that the (n,α) or (n,p) cross sections of boron-10, lithium-6, and helium-3 increase by several orders of magnitude as the incoming neutron energy decreases from 1 MeV (fast) to 0.025 eV (thermal). The increase in cross section with decreasing energy is the reason moderating materials are used in detector systems. Moderation significantly increases the probability of interaction within the detector.

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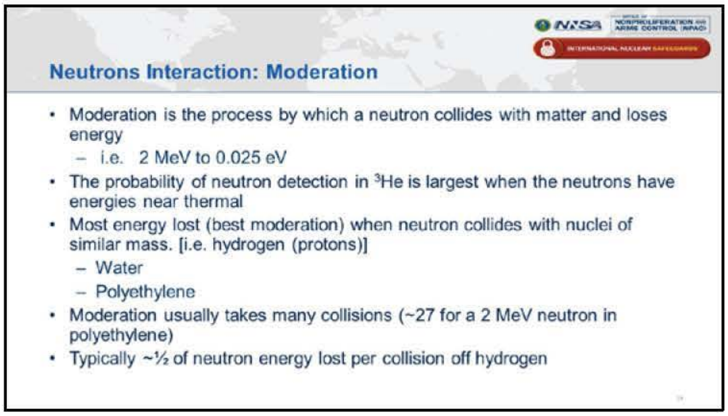

Moderation is the process by which neutrons collide with matter and lose energy as they pass through different materials. For example, if a 2 MeV neutron is emitted from a radioactive source and bounces around in a material it loses energy with each collision event, eventually reaching "thermal" energy, 0.025 eV. Depending on the material, this energy loss happens at different rates. Moderation is important in safeguards because the probability of neutron detection in ^{3}He, the most common neutron detection medium in nuclear safeguards, is highest when neutrons have energies near thermal.

The best moderating materials for neutrons are those with nuclei of similar mass, like hydrogen, which consists only of a single proton and an electron. Hydrogenous materials, like water and polyethylene, therefore make the best moderators. In polyethylene, a 2 MeV neutron requires about 27 collisions to reach thermal energy. The collisions required to moderate neutrons usually take only 2-5 µs. In a heavy material like lead, the neutron requires many more collisions to reach thermal energy, which allows neutrons to be much more highly penetrating than gamma rays in certain materials, like metals.

Moderation is also known as inelastic scattering, meaning that in a scattering event, some amount of energy is deposited in the impacted nucleus. Inelastic neutron scattering interactions are commonly]

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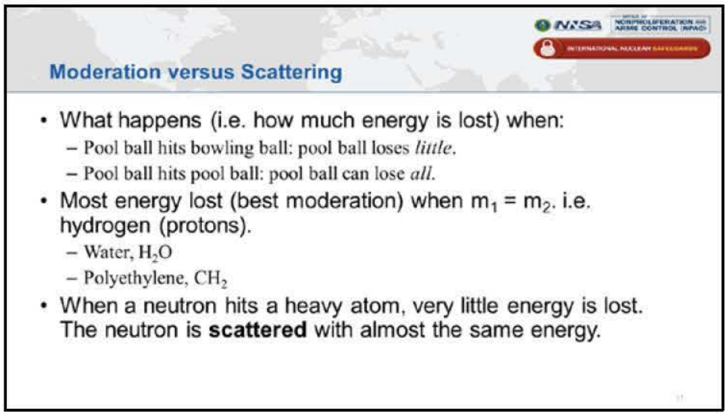

Consider the collision of two equal mass balls. When one ball hits another ball, the energy from the first ball transferred to the second ball in the collision depends on the angle of the outgoing ball. The energy of the first ball after the collision can vary between its incoming energy and zero. This is because the two balls have an equivalent mass. Now consider a billiard ball hitting a bowling ball. In this collision, the billiard ball retains most of its initial energy (whatever the angle) and bounces off the bowling ball, and the bowling ball hardly moves, because the mass of the bowling ball is much greater than that of the billiard ball.

This example illustrates the reason that the best moderation occurs when the mass of the moderator is similar or equal to the mass of the neutron, as in hydrogenous materials. Water consists of two hydrogen atoms and one relatively light atom of oxygen. Polyethylene also consists of two hydrogen atoms and one relatively light atom, in this case, carbon. Water is commonly used as a moderator in nuclear reactors, because it serves the additional purpose of cooling the reactor fuel. It is not practical, however, to carry water-based detection systems around, so polyethylene is the most common moderator used in safeguards.

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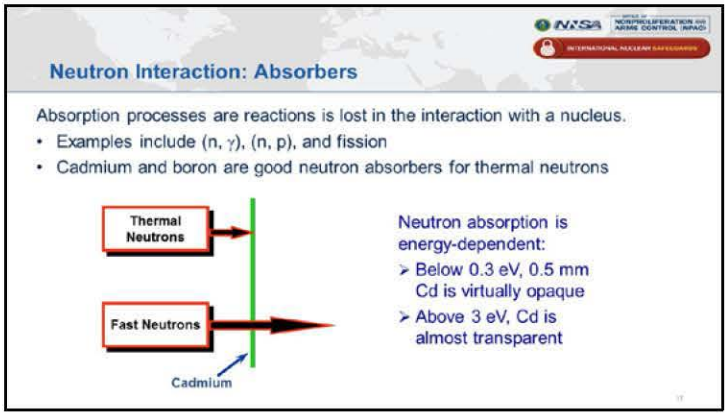

Neutrons can also be absorbed, rather than simply slowed down, when they interact with certain nuclei. The absorption yields an excited nucleus, which de-excites through the release of something else, like protons or gamma rays. Examples of these sorts of interactions include (n,γ), (n,p), and fission reactions.

Neutron absorbers are very important in nuclear safeguards. They can impair measurements, improve the statistical uncertainty in measurements, and, in the case of fission reactions, form the entire basis of measurements.

An example in which neutron absorbers impair measurements is in the case of gadolinium (Gd), which is commonly added as a neutron poison to increase the lifetime of nuclear fuel. Measurements made by the Uranium Neutron Coincidence Collar (UNCL), which we will study in the final module of this course, must be corrected for the presence of Gd in fuel, because it reduces the number of neutrons emitted from the fuel and obscures the true amount of fissionable material present in a sample. Boron is also occasionally used as a neutron poison in nuclear fuel, and in some cases as a detection medium in neutron detectors.

An example in which neutron absorbers improve the statistical uncertainty of measurements is the case of cadmium liners. These liners capture thermal neutrons, but allow “fast” (high energy) neutrons to pass through. Certain detectors only count fast neutrons because they can provide more information about the sample than thermal neutrons, for which all information about the energy of the neutrons when they are emitted from the sample is lost to the moderation process.

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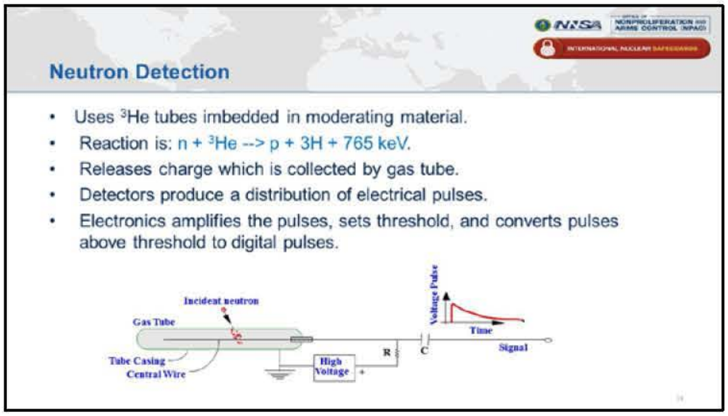

Now that you know the fundamental physics of neutron detection, we can discuss how ^{3}He detectors work. All of the detectors we will be using in this course for neutron counting are ^{3}He-based.

The image in the slide illustrates a typical ^{3}He detector design. Most ^{3}He detectors consist of some number of aluminum tubes filled with ^{3}He gas. These tubes are embedded in a moderating material, such as polyethylene. As you may recall from the previous slide, ^{3}He has the highest cross section for incoming neutrons near thermal energies. When a thermalized neutron enters a ^{3}He tube, it reacts with the ^{3}He, generating a proton (^{1}H) and a triton (^{3}H), which share 765 keV of energy (plus the initial neutron energy).

^{3}He detectors fall in the category of detectors known as proportional counters, and they rely on gas multiplication to amplify the signal generated in the neutron/gas reaction. A high voltage is applied across the tubes, creating an electric field within the tubes. Electrons generated in the reaction are accelerated in the electric field. If they are sufficiently accelerated by the field, when they collide with the gas molecules, they can create electron-ion pairs. The resulting electrons are accelerated and also react, eventually causing a chain reaction called an *avalanche*. A positively charged anode wire runs through the center of the negatively charged tube casing. The anode wire collects the free electrons, generating a voltage pulse which is measured by the detector electronics. The avalanche ends when all of the free electrons have been collected.

If one (or both) of the charged particles hits the detector wall, there is less energy deposited in the gas and fewer ion pairs are created. This does not change the counting rate (or detection efficiency) of the detector as long as the electronic threshold is set sufficiently low.

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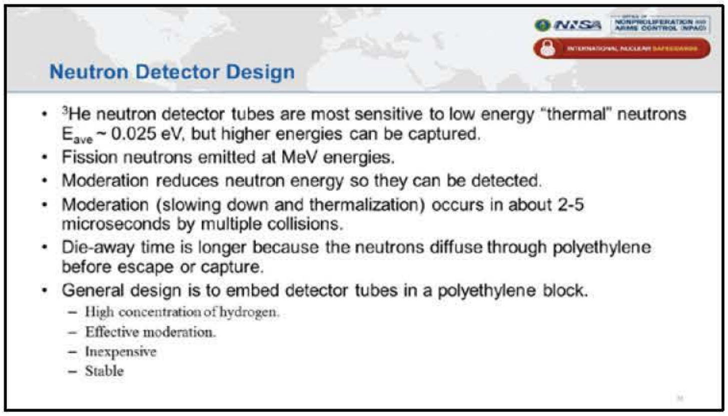

This slide summarizes the most important lessons learned about detector design. First, ^{3}He detector tubes are most sensitive to low energy "thermal" neutrons, which have an average energy of about 0.025 eV, but neutrons with higher energies can be captured. Fission neutrons are emitted at high energies, in the MeV range, so moderators must be used to reduce the neutron energies and allow them to be detected. The collisions required to sufficiently moderate neutrons usually require only 2-5 µs. Die-away times are longer than moderation times because the neutrons diffuse through the system before they either escape or are captured. The general design basis for most neutron detectors is to embed several ^{3}He tubes in a polyethylene block, which has a high concentration of hydrogen and thus is an effective moderator.

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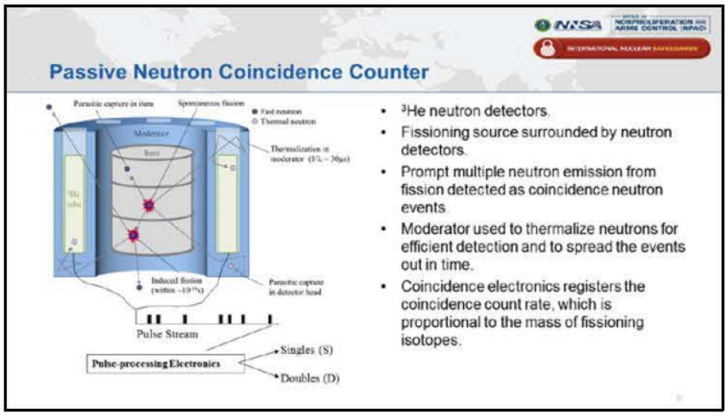

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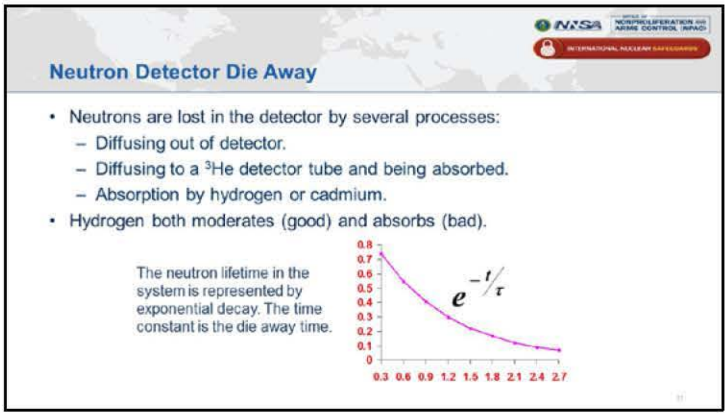

Neutrons are lost within neutron detection systems by several processes. They can diffuse out of the detector, they can be absorbed within the detector tube and thus be counted, or they can be absorbed by either hydrogen or cadmium. While hydrogen is a useful moderator, it can absorb thermal neutrons and thus reduce the neutron count rate. Cadmium is frequently used between the sample and the moderator when trying filter out neutrons that have been thermalized within the sample in question, and only measure neutrons that are emitted at fast or epithermal energies.

The time that passes between neutron generation and loss is known as the neutron lifetime. The neutron lifetime is represented by exponential decay, $e^{\frac{-t}{\tau}}$, where the time constant τ is the die-away time. The die-away time is detector-specific. Most die-away times fall within 20-60 μs.

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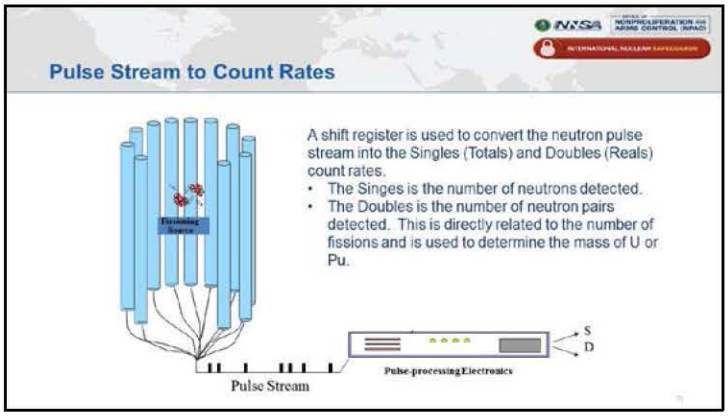

The image on the slide above shows a typical neutron detector schematic for safeguards applications. A number of ^{3}He tubes embedded in a moderating material surround a fissioning source. As described in the slide above, the neutrons are detected indirectly by reacting with the ^{3}He gas, which generates a voltage pulse that is measured by the counting electronics. Because the incoming neutrons are moderated, all information about their initial energies is lost. Therefore, we do not consider the size of the pulse (except to filter out background noise as any pulses falling below a particular threshold.) Rather, we consider the number of pulses that are counted. The procession of incoming pulses is known as the *pulse stream*. This stream is analyzed by pulse-processing electronics, as will be described in future lessons, to produce *Singles (Totals)* and *Doubles (Reals)* count rates, which can be used to obtain information about the fissioning sample in question.

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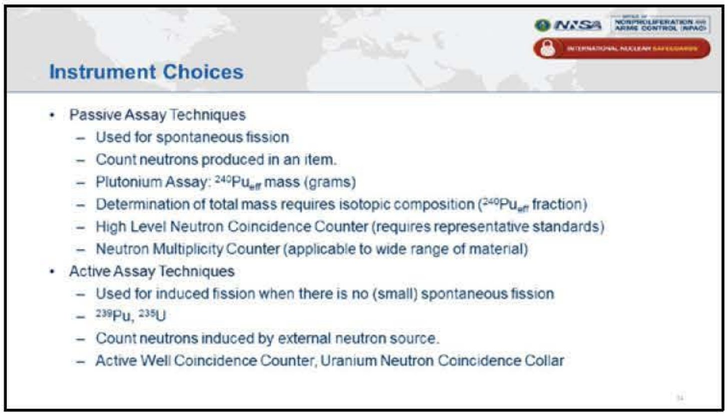

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Active measurements are used to assay uranium samples. It consists of 42 ^{3}He tubes that are pressurized to 4 atm and arranged in two circular rings around the sample space and embedded in polyethylene. It has an efficiency of 26% (far lower than that of the ENMC) and requires one or two ^{252}Cf sources in the top and bottom end plugs to induce fission within the sample. By selective use of Cd shielding, the detector can be configured to use fast or thermal neutrons to induce fission in the uranium items.

The Uranium Neutron Coincidence Collar (UNCL) is used to verify fresh fuel assemblies in fuel fabrication facilities. It consists of 16 ^{3}He tubes that are pressurized to 4 atm and embedded in polyethylene blocks on three sides. The fourth side is a polyethylene block with a source holder for the AmLi source. The source induces fission within a fuel assembly and the resulting neutrons are counted by the ^{3}He tubes. The count rate is analyzed to verify the mass and enrichment of uranium in the assembly.

You will have the opportunity to use both of these detectors during the laboratory sections of this course.

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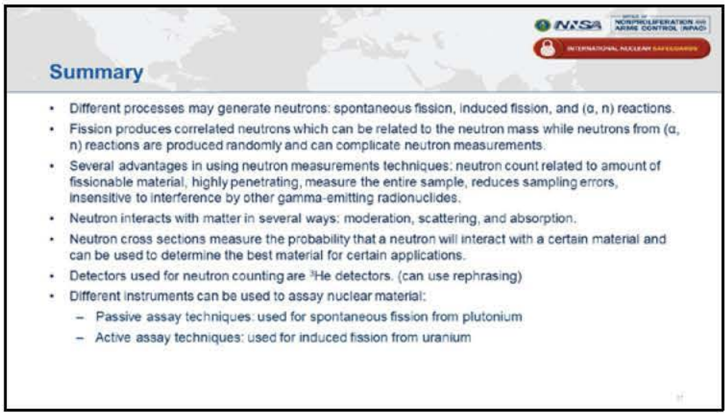
You will have the opportunity to use both of these detectors during the laboratory sections of this course.

Additional Information for Students:



Instructor Notes: