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Spallation Physics - An Overview

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ABSTRACT

Most of you know that LANSCE uses 800-MeV protons (from LAMPF) to produce neutrons for scattering experiments. But do you know how we do it? This article explains the basics of spallation and compares it to fission, and discusses some basic target neutronics.

I. WHAT IS SPALLATION?

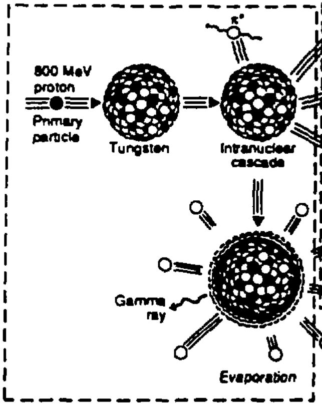
Spallation refers to nuclear reactions that occur when energetic particles (for example, protons, neutrons, or pions) interact with an atomic nucleus. At LANSCE, energetic (800 MeV) protons hit a tungsten target; at 100 μA, this amounts to 6.24×10^{14} protons per second striking the target. However, to illustrate the spallation process, we will describe the reactions that follow when only one 800-MeV proton, a primary particle, hits a target nucleus.

As shown in Fig. 1, spallation can be thought of as a two-stage process. In the first stage, the primary particle reacts with nucleons--neutrons and protons--inside the nucleus. The reactions that follow create an *intranuclear cascade* of high-energy (greater than 20 MeV) protons, neutrons, and pions within the nucleus. During the intranuclear cascade, some of these energetic *hadrons* escape as secondary particles. Others deposit their kinetic energy in the nucleus leaving it in an excited state. In the second stage (nuclear de-excitation), evaporation takes place when the excited nucleus relaxes by emitting low-energy (less than 20 MeV) neutrons, protons, alpha particles, etc., with the majority of the particles being neutrons. The low-energy neutrons produced during nuclear de-excitation are important in a spallation source because they can be moderated (reduced) to even lower energies for use as research probes. After evaporation, the nucleus that remains may be radioactive and may emit gamma rays.

Secondary high-energy particles produced during the intranuclear cascade move roughly in the same direction as that of the incident proton and can collide with other nuclei in the target. The reactions that follow are a series of secondary spallation reactions (see Fig. 2) that generate more secondary particles and low-energy neutrons. The so-called *hadronic cascade* is the accumulation of all reactions caused by primary and secondary particles in a target.

If the target is very heavy (for example, depleted uranium or lead), high-energy fission can compete with evaporation during nuclear de-excitation (see Fig. 3). Even more fission events can occur in fissile targets such as ^{235}U or ^{238}U.

Hadronic cascade



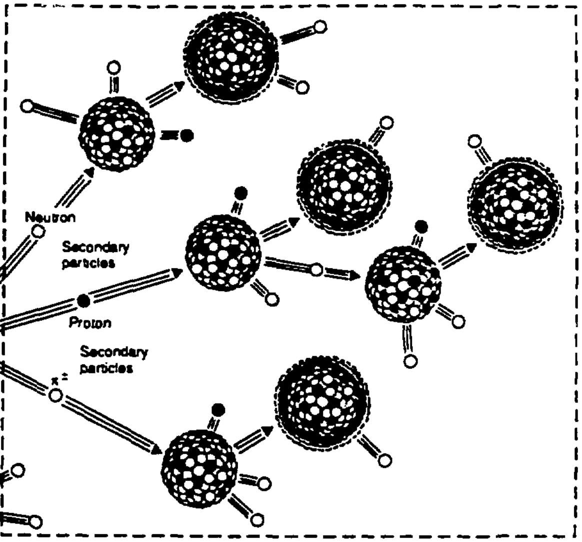


Figure 2. Secondary particles (neutrons, protons, and pions) from the intranuclear cascade go on to induce further spallation reactions. The hadronic cascade is the accumulation of reactions caused by primary plus secondary particles.

Figure 1. The primary particle (800- MeV proton) hits the tungsten nucleus, inducing spallation (the intranuclear cascade and evaporation).

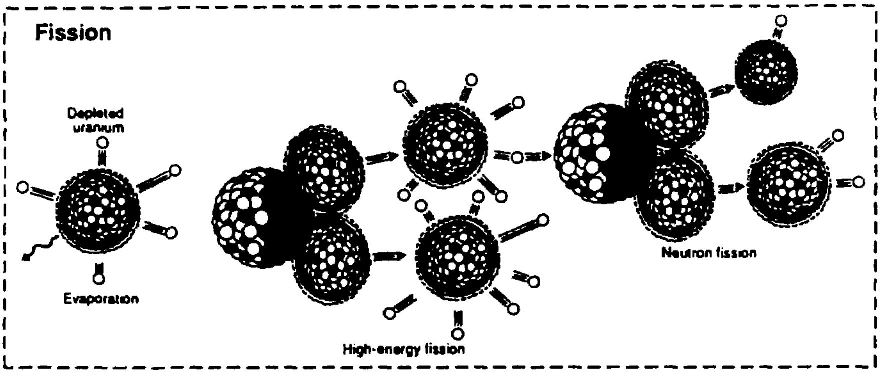


Figure 3. When a depleted uranium target is bombarded by 800-MeV protons, high-energy fission competes with evaporation during nuclear de-excitation. More neutrons are emitted from high-energy fission than from evaporation. The neutrons emitted from high-energy fission and evaporation can go on to induce more fission events.

II. HOW DOES SPALLATION DIFFER FROM FISSION?

Spallation and fission differ in several ways. One difference is in the nuclear debris remaining after the reactions. Predicted yields of spallation products from a 10-cm-diameter by 30-cm-long machineable tungsten target, bombarded on axis by 800 MeV protons, are depicted in Fig. 4. Note in Fig. 4 the more-or-less continuous distribution of spallation products down to mass number 120, the symmetric high-energy fission products in the mass range 60 to 120, and the spallation and high-energy fission products below mass 60. Spallation products below mass 60 come from the iron and nickel in machineable tungsten. Machineable tungsten used for the LANSCE targets has a density of 18.3 gm/cm^3, and is composed of 97.0 w% tungsten, 2.1 w% nickel, and 0.9 w% iron. In fission, the nucleus divides into two, producing a variety of fission products (see Fig. 3).

Another difference between spallation and fission is in the number of neutrons released. The overall number of neutrons released per fission event (about 2.5) is considerably less than that released per spallation event; about 13 neutrons for each incident proton are released from the LANSCE target (See Fig. 5). Furthermore, at least one of the 2.5 neutrons produced by fission is useless for neutron scattering--it is needed to sustain the fission reaction.

Spallation and fission also differ in other ways:

- *in the amount of energy deposited per neutron produced*

For fission, about 180 MeV of energy is deposited as heat for each neutron produced; for spallation in tungsten, the corresponding number is about 32 MeV. Although there is less heat generated with spallation, the intensity of the proton beam at a high-power spallation source can lead to cooling problems--equivalent to those of a high-power reactor source--in windows and targets, unless special care is taken.

- *in the amount of gamma-ray energy produced*

At LANSCE, about 2 MeV of gamma-ray energy is emitted for each neutron produced; about 12 MeV is released per fission event. Because spallation neutron sources do not produce as much gamma-ray energy as equivalent reactor sources, gamma-ray heating and contamination of neutron beams are less problematic.

- *in the energy distribution of the emitted neutrons*

Spallation neutrons have higher energies than fission neutrons (see Fig. 6). In a spallation source, high-energy cascade neutrons approach the energy of the incident proton (800 MeV at LANSCE). High-energy neutrons are extremely penetrating as well as being useless for neutron scattering. Well-designed shielding is needed to prevent high-energy neutrons from causing unwanted background in experiments.

III. HOW DOES SPALLATION TARGET DESIGN AFFECT NEUTRON YIELD?

The objective in designing a spallation target is to increase the leakage of low-energy neutrons and to decrease the leakage of high-energy neutrons from the target. Low-energy neutrons that leak from the target are potentially useful because suitable materials can reduce their speed (by factors of 10^1 to 10^{10}) to produce pulsed neutron beams useful for research in materials science and nuclear physics. Fortunately, low-energy neutrons from the hadronic cascade outnumber the high-energy neutrons (see Fig. 7).

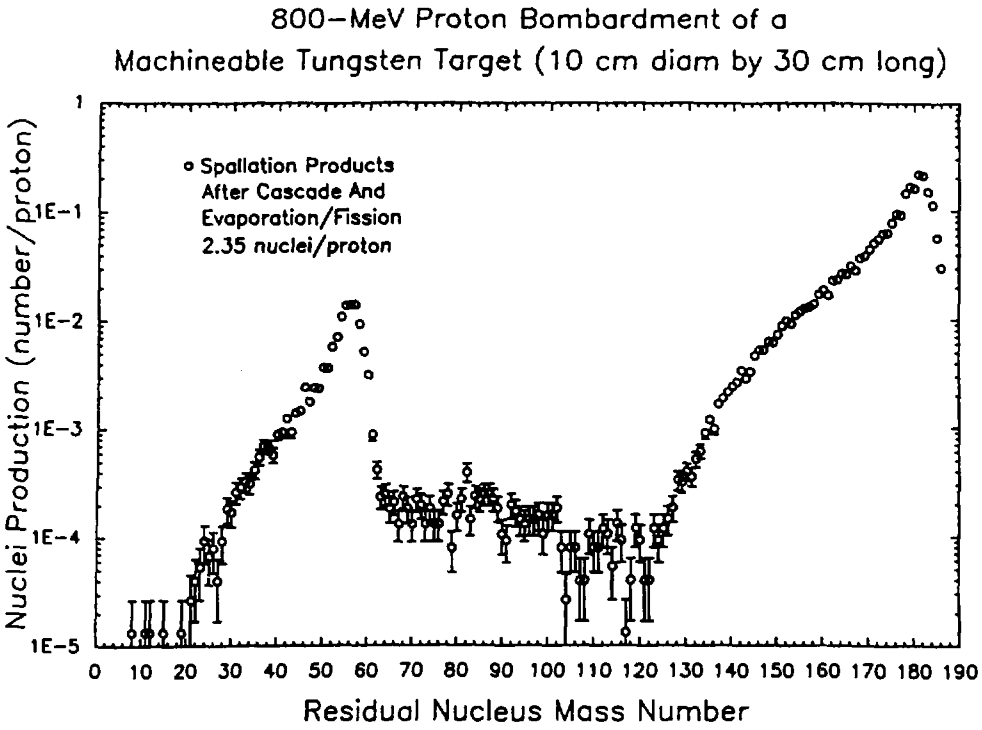


Figure 4. Calculated spallation product yields for 800-MeV protons on machineable tungsten.

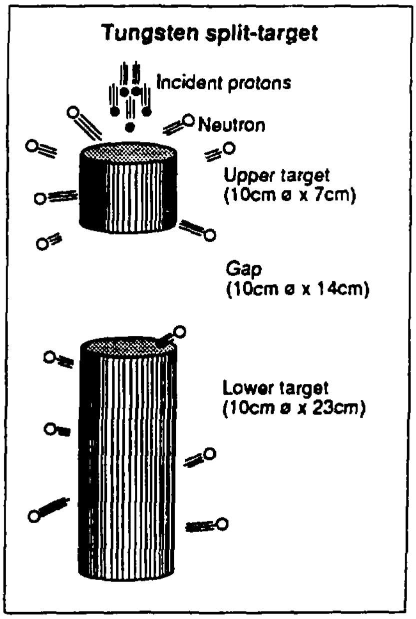


Figure 5. Illustration of the LANSCE split-target.

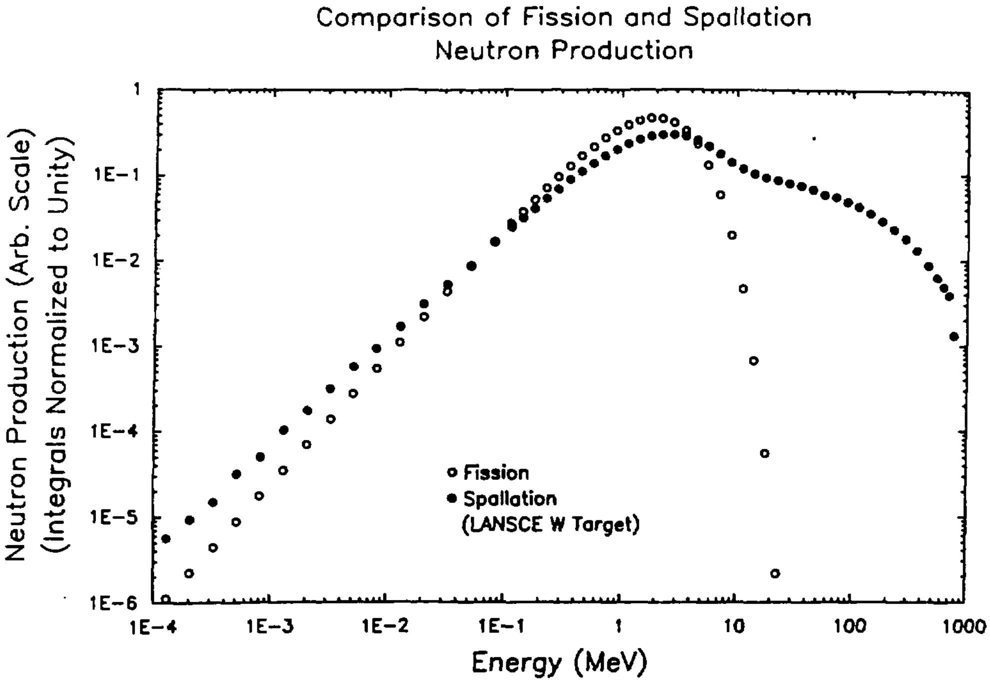


Figure 6. Neutron production from fission (○) and from spallation (●).

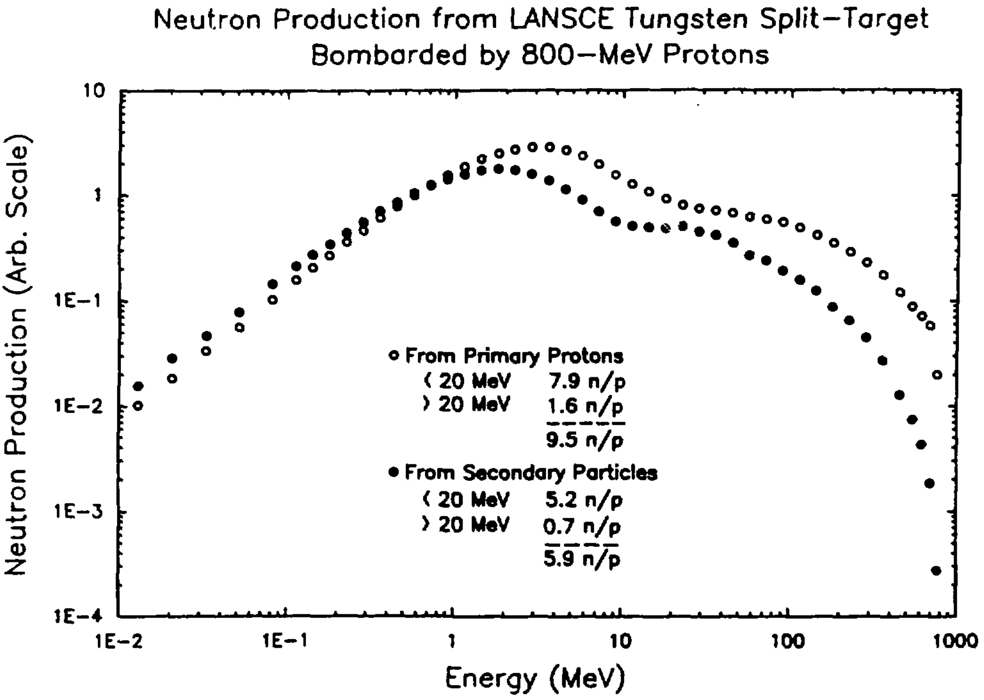


Figure 7. Neutron production from reactions caused by the primary proton (○) and the secondary particles (●) in LANSCE tungsten-target nuclei. About 85% of the total neutrons produced are low energy, and about 60% of the low-energy neutrons are produced by primary protons.

**n/p=neutrons/incident proton*

Three primary variables can affect the number of low-energy neutrons produced by a target:
- the energy of incident protons,
- the target material, and
- the target geometry.

Energy of incident protons

As the energy of protons incident on a spallation target increases, the number and energy of neutrons produced increase. Figure 8 illustrates this effect.

Target material

For spallation neutron sources, practical target materials are lead, tantalum, tungsten, depleted uranium, and lead/bismuth. The calculated low-energy neutron leakages for most of these target materials having the same dimensions of the LANSCE target are as follows:

lead	*11.9*
tantalum	*12.7*
tungsten	*13.1*
depleted uranium (dilute)	*19.4*
depleted uranium (solid)	*21.4*

Compared to tungsten, a depleted uranium target designed to operate at 100 μA of 800-MeV protons must be clad to contain fission products and must be segmented more to affect target cooling. Cladding and coolant materials make the target dilute and do not produce as many neutrons as the target itself; therefore, the number of neutrons for the dilute depleted uranium target is lower than the solid depleted uranium target.

Neutrons leaking from solid split-targets of tungsten and depleted uranium are compared in Fig. 9. Neutrons emerging from a tungsten target are biased towards lower energies; these neutrons can be moderated more effectively for neutron scattering experiments.

The total neutron yield of a pulsed spallation source is not the only feature of the source that interests neutron scatterers. For accurate experiments, short pulses and low backgrounds between pulses are also important. Therefore, depending on the application, a fissile target (which produces more delayed fission neutrons between pulses than say tungsten) may not be the best choice.

Target geometry

The number of low-energy neutrons produced depends on the size of the spallation target. For example, in Fig. 10, the number of low-energy neutrons increases with target diameter and reaches an asymptotic value of about 20 neutrons/incident proton (n/p) at a diameter of about 50 cm for a 30-cm-long tungsten target bombarded with 800-MeV protons. Neutron leakage from the same target reaches a maximum value of about 15 to 16 n/p at a 20-cm diameter.

Varying the target size also changes the energy and time distribution of neutrons that leak from a target. Small targets yield more high-energy neutrons than large targets, and the change in time distribution is important in some applications (for example, nuclear physics research) in which very short neutron pulses are required.

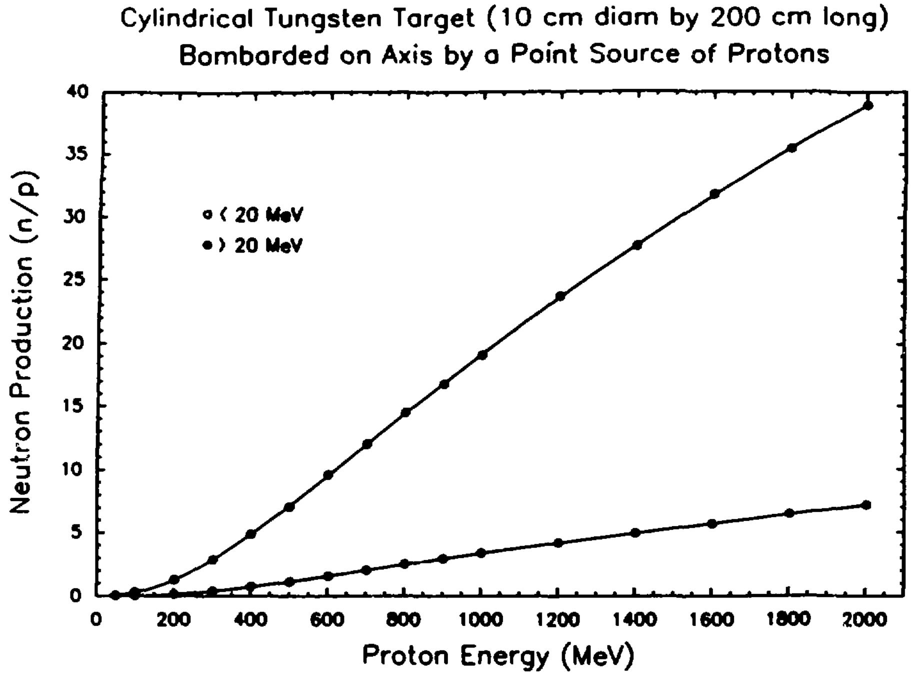


Figure 8. Production of low-energy (○) and high-energy (●) neutrons for a cylindrical tungsten target (10-cm diam by 200-cm length). The length of 200 cm was arbitrarily chosen and was long enough to range out 2000-MeV protons.

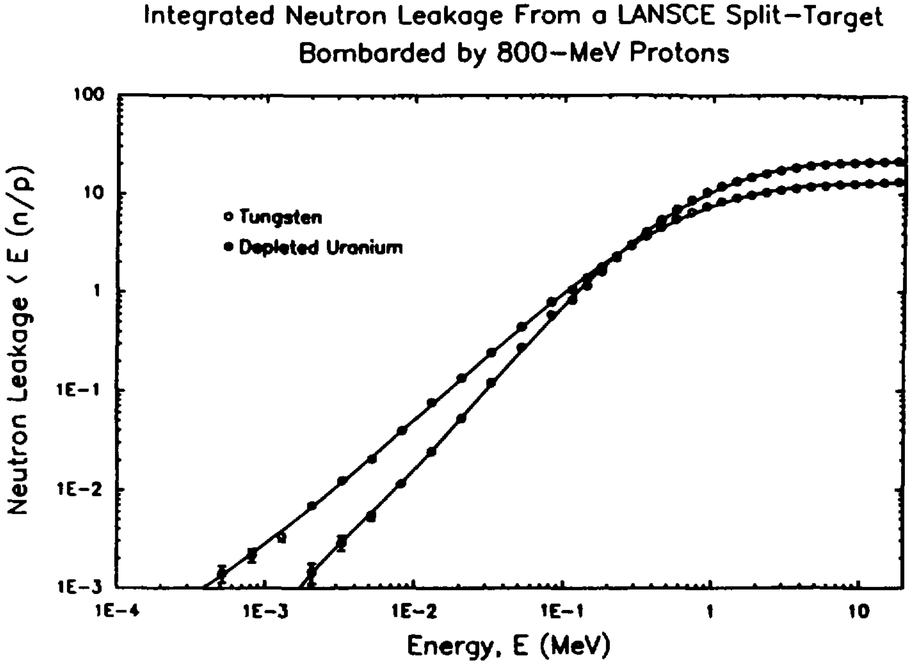


Figure 9. Low-energy neutron leakage from tungsten (○) and from depleted uranium (●) split targets, both bombarded by 800-MeV protons. More low-energy neutrons leak from the tungsten target than from the depleted uranium target.

IV. SUMMARY

Spallation is a method of producing neutrons for materials science research. Contrasted to fission, spallation differs in the following ways: a) in the nuclear debris remaining after the reactions; b) in the amount of energy deposited per neutron produced; c) in the amount of gamma-ray energy produced; and d) in the energy distribution of the emitted neutrons.

The energy of incident protons and the target material and geometry affect the number of neutrons produced. More importantly, these factors also influence the energy and spatial distribution of neutrons leaking from the target. Figure 11 illustrates the difference in spectra of neutrons produced in the target and those that leak from the target. This difference occurs because the target can be viewed as a moderator that reduces the energy of neutrons produced. For hydrogen and other moderating materials, the lower the energy of neutrons leaking from the target, the more readily these materials can moderate neutrons to energies suitable for neutron scattering experiments.

V. ACKNOWLDEGEMENTS

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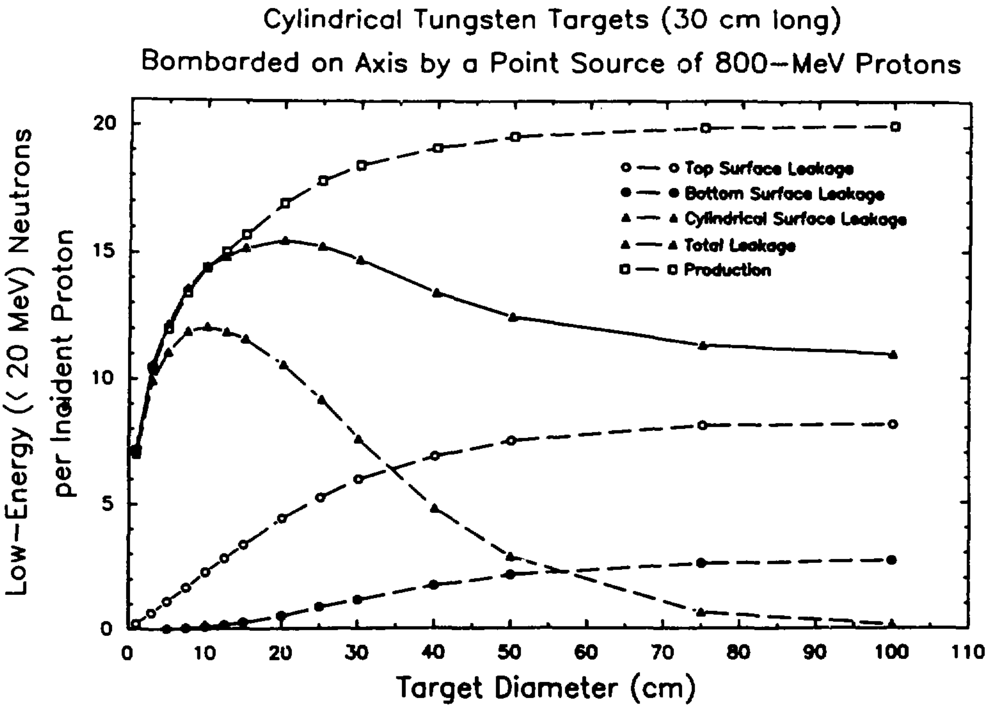

Figure 10. Low-energy (< 20 MeV) neutron production and leakage from machineable tungsten targets bombarded by 800-MeV protons.

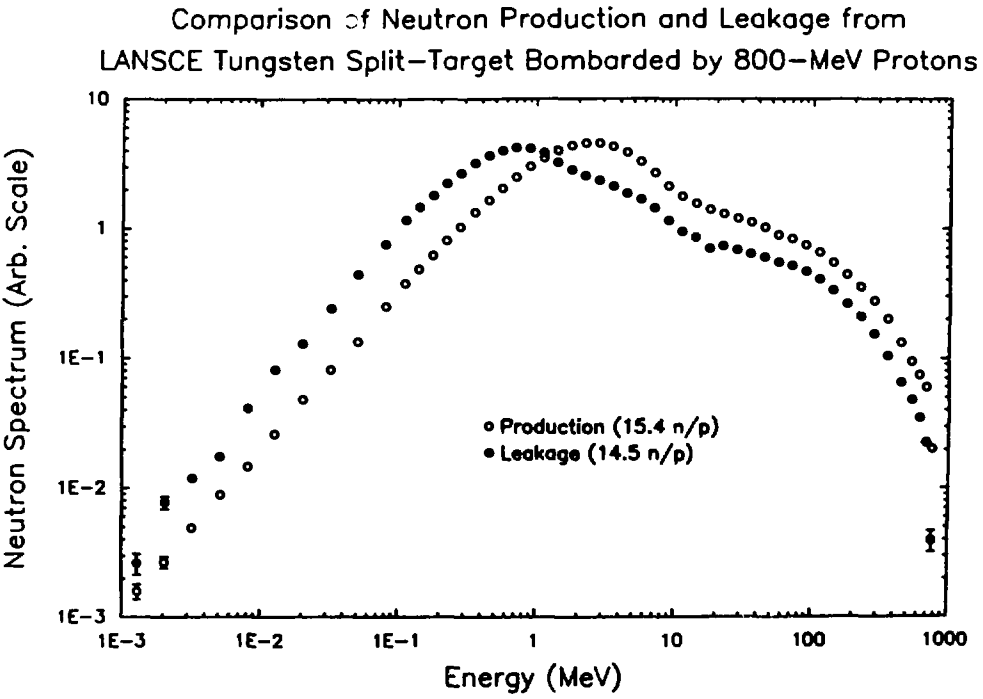

Figure 11. Spectra for neutron production (○) and neutron leakage (●) from the LANSCE target.