The Neutron and Early History

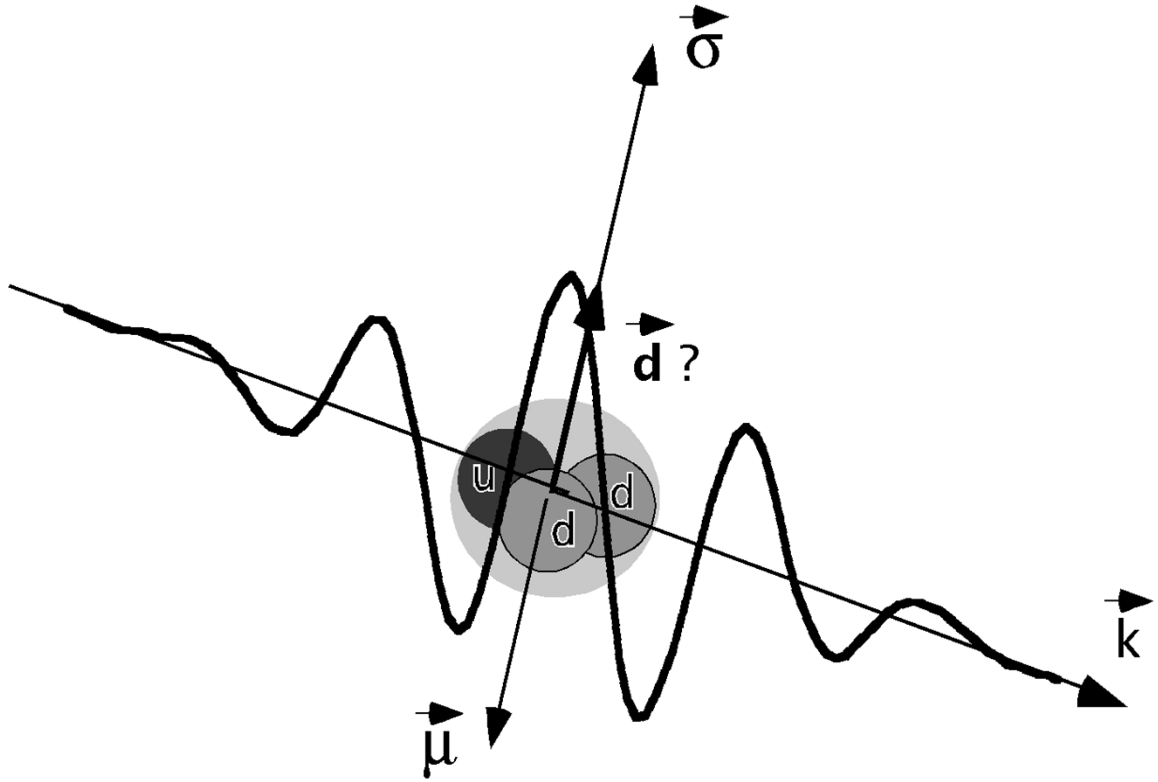
XIII School of Neutron Scattering (SoNS)

International School of Neutron Science and Instrumentation

Erice, Sicily, 28 July-4 August 2015

John M. Carpenter
Argonne National Laboratory and
Oak Ridge National Laboratory

The Neutron



The neutron and its quark structure (udd), wave packet, wave vector, spin, and magnetic dipole and electric dipole moments.

The Neutron

Neutrons consist of three quarks, one “up” quark and two “down” quarks, udd. Protons are uud. Hadron charges are the sum of charges of constituent quarks. There are no free quarks.

Neutrons interact with other hadrons through the strong force, and with each other and with their surroundings through the electromagnetic force.

To a very small extent, neutrons can have an electric dipole moment (so small as not yet to have been observed, in spite of long-term efforts).

The Quarks

Quarks are the fundamental constituents of the *hadrons*.

Generation	Flavor	Symbol	Charge, e units	Rest Mass, MeV
First	down	d	-1/3	≈ 5
First	up	u	2/3	≈ 10
Second	strange	s	-1/3	≈ 200
Second	charm	c	2/3	≈ 1500
Third	bottom	b	-1/3	≈ 5000
Third	top	t	2/3	≈ 173 000

The Hadrons

LOW-ENERGY HADRONS

MESONS

D-Mesons (1870 MeV)

D^-	D^+	D^o
$\bar{c}d$	$c\bar{d}$	$c\bar{u} + \bar{c}u$

ρ-Mesons (770 MeV)

ρ^-	ρ^+	ρ^o
$\bar{c}d$	$c\bar{d}$	$c\bar{u} + \bar{c}u$

η-Meson (550 MeV)

η
$u\bar{u} + d\bar{d}$

K-Mesons (500 MeV)

K^-	K^+	K^o
$\bar{u}s$	$u\bar{s}$	$d\bar{s} + \bar{d}s$

π-Mesons (140 MeV)

π^-	π^+	π^o
$\bar{u}d$	$u\bar{d}$	$u\bar{u} + d\bar{d}$

BARYONS

Δ-Particles (1230 MeV)

Δ^o	Δ^+	Δ^{++}	Δ^-	Δ^{--}
udd	uud	uuu	ddd	$\bar{u}\bar{u}\bar{u}$

Nucleons (940 MeV)

n	p
udd	uud

There are two families of Hadrons: *mesons*, with two quarks, and *baryons*, with three quarks.

Hadrons interact through the *strong* force; charged hadrons also interact through the *electro-magnetic* force.

Even uncharged hadrons have *magnetic moments* associated with their spins.

Where did this story begin?

Most discoveries have precedents of some kind.

Let’s start with the discovery of radioactivity in uranium (actually, gamma radiation) by Henri Becquerel in 1896.

In 1899, Ernest Rutherford first identified alpha-particle (^{4}He nuclei) decay from uranium and thorium.

Soon, scientists began using alpha particles from natural sources (~ 5 MeV) to induce nuclear transformations.

Neutron Decay

Free neutrons decay by e^- emission to a proton, accompanied by an anti-neutrino, and have a mean lifetime T_e = 881.5 seconds = 14.7 minutes and a half-life $T_{1/2}$ = 611.0 seconds:

$$n \xrightarrow{T_{1/2}=611s} e^- + p + \overline{\nu}_e + 782\ keV.$$

Although the decay process is interesting from a fundamental physics point of view, we don't need to account for it in materials science applications. The lifetime of neutrons far exceeds the duration of our measurements.

Cosmic Rays

In 1912, Austrian scientist Victor Hess discovered cosmic rays, identified as high-energy (~ 10 GeV) particles from extra-solar sources.

For a long time, these were the only high-energy particles available to scientists.

In 1932, Hess received the Nobel Prize in Physics for his discovery of cosmic rays.

Discovery of Cosmic Rays
Victor Hess, 1912

International Herald Tribune 8 August, 2012

A balloon ride that gave physics a lift

BAD SAAROW-PIESKOW, GERMANY

Grandson relates lessons from family member who discovered cosmic rays

BY BILL BREISKY

Precisely where Victor Hess, his electroscopes and his balloon touched down is a mystery.

What is known is that Hess and his crew of two landed shortly after noon, 100 years ago, near this little town in eastern Germany, and that a farmer brought the men to the Pieskow railroad station, where they took a train to Berlin and then another train home to Vienna.

The physicist Michael Walter says he found no reporting of the event in local newspapers at that time. But this week, there is something: an international symposium of physicists in Bad Saarow-Pieskow is being held to celebrate the centennial of the discovery of cosmic rays by Victor Francis Hess.

Dr. Walter, of the Institute for Theoretical Physics in Zurich, will be on hand

The early 20th century was a time of prolific discoveries:

Atomic nucleus

Bohr atom

Special relativity

X-ray diffraction

Quantum mechanics

Electron diffraction

Nuclear masses

Cyclotrons

… … … … … …

1932

By this time, a number of unsolved mysteries had accumulated:

What constitutes the mass of nuclei?

Can electrons in nuclei neutralize the charge of some nuclear protons?

Why are nuclear masses not exactly in round numbers proportional to their charges? Cl (A=35.4 amu)?

What are the radiations from Be and B bombarded by alpha particles?

… … … … … …

Chadwick

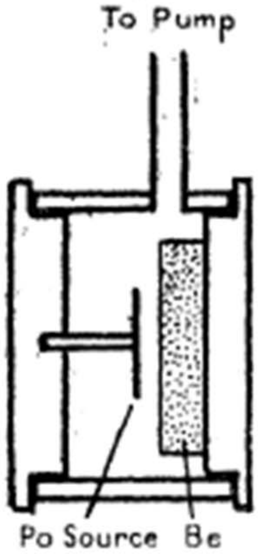
In 1932, James Chadwick investigated the radiation from beryllium and boron bombarded by alpha particles, then widely and implausibly thought to consist of very high energy photons (gamma rays).

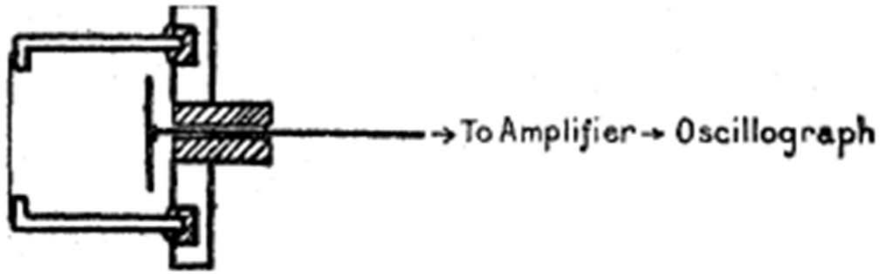
Chadwick's Apparatus

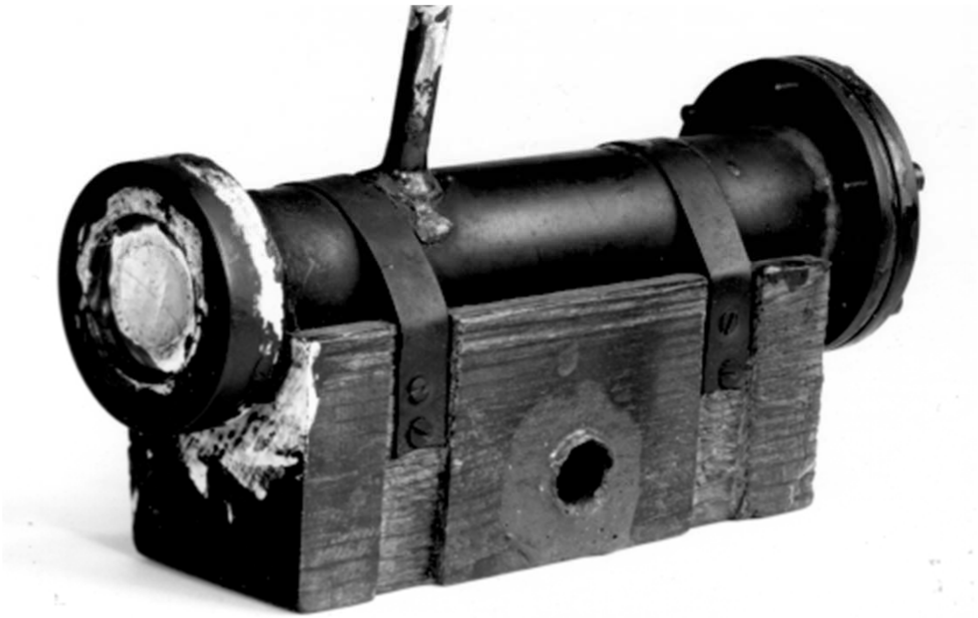
"… When a sheet of paraffin wax about 2 mm thick was placed in the path of radiation just in front of the counter, the number of deflections recorded on the oscillograph increased remarkably. This increase was due to particles ejected from the paraffin wax so as to pass into the counter. …"

Chadwick could stop them by placing a thin metal sheet between the wax and the counter. He reasoned that these were heavy charged particles, that is, protons.

Chadwick's Apparatus







Voilà! Neutrons!

Chadwick reasoned that the particles that registered in the detector were protons recoiling from neutron collisions. He proceeded to infer the mass and other properties of the neutron in a brilliant *tour de force* exposition.

His 1932 presentation to the British Royal Society: J. Chadwick, FRS, “The existence of a Neutron”, *Proc. Roy. Soc.*, A **136**, p. 692-708.

Chadwick received the 1935 Nobel Prize in Physics for his work.

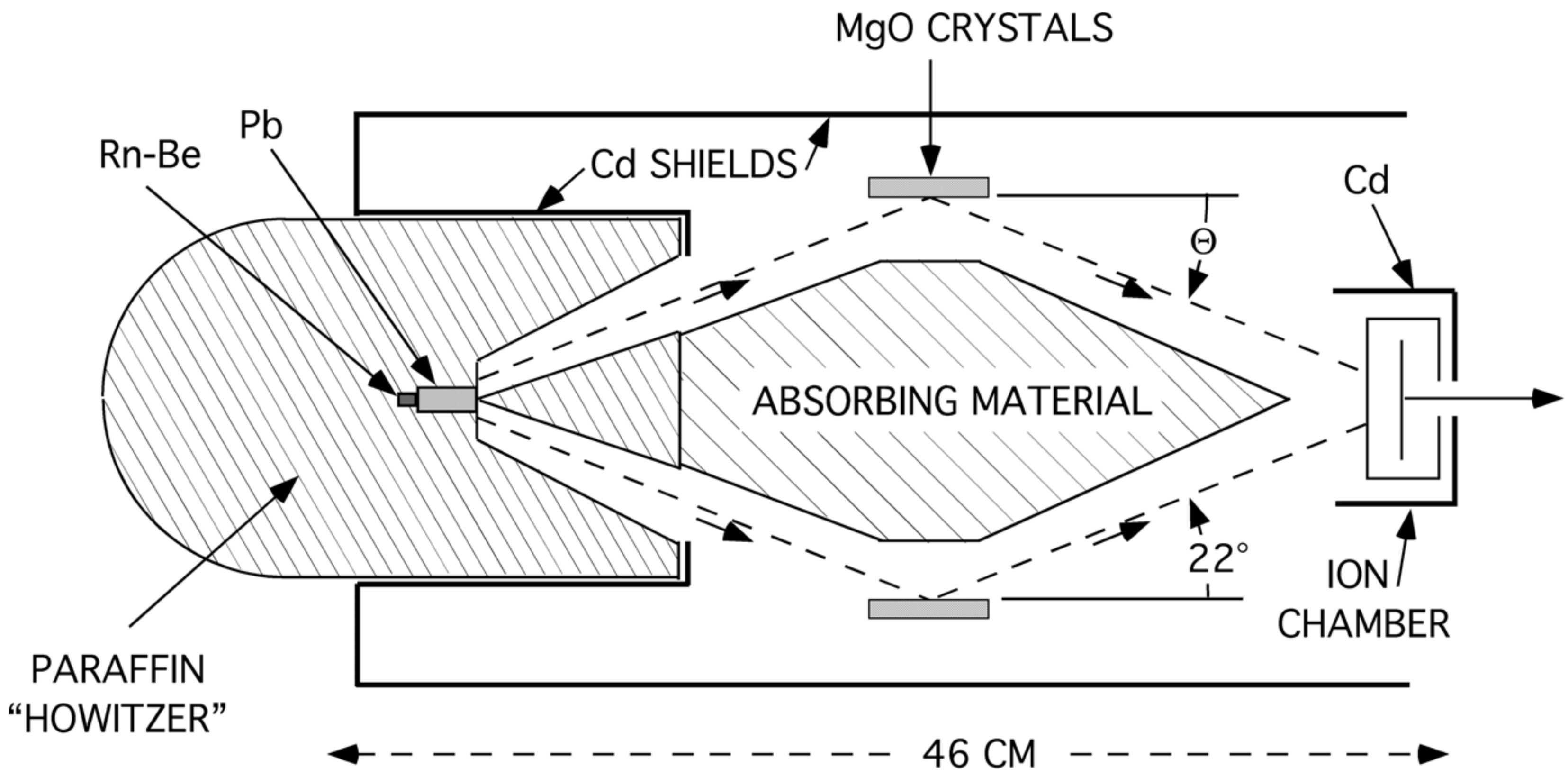
The Immense Importance of Chadwick's Discovery

- Debunked earlier conjectures about the nature of radiations from alpha-irradiated beryllium and boron.
- Explained the existence of isotopes and the variation of nuclear masses.
- Enabled nuclear transformations with modest-energy particles.
- More

Neutrons as Waves

In 1936 Mitchell & Powers and Halban & Preiswerk first demonstrated coherent neutron diffraction (in Bragg scattering by crystal lattice planes) as an exercise in wave mechanics. Neutrons behave as waves; they diffract from crystals as x-rays do.

Mitchell and Powers’ Apparatus



Thermalization

In 1935, Enrico Fermi, then in Rome, discovered that some materials irradiated by neutrons in water bath activated much more than when exposed to a bare isotope-driven neutron source.

He reasoned that by scattering from protons in the water, neutrons slow down to energies at which the nuclei capture the neutrons more effectively than at higher energies. We now know this process as *thermalization*.

Neutron Terminology

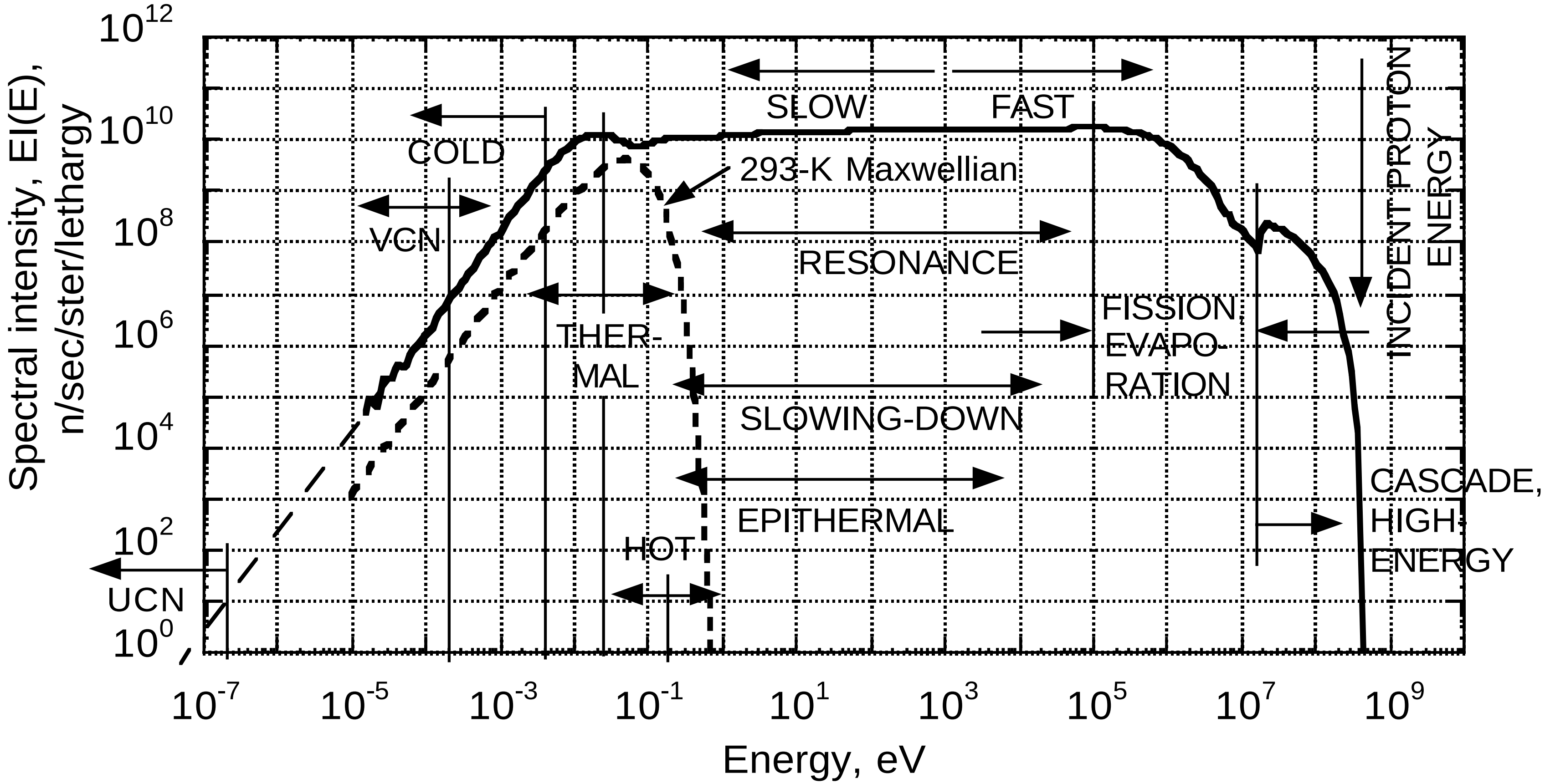
A gross distinction: slow and fast neutrons.

- *Slow neutrons,* E < 1 keV, used in neutron scattering studies.
- *Fast neutrons,* E > 1 keV, are all those of higher energies.

Further distinctions involve more restrictive energy ranges having to do with sources or applications, or with typical types of interactions.

- *Thermal neutrons* in general are those with a Maxwellian distribution at some temperature. Sometimes, specifically, thermal neutrons are those with energy exactly 0.025 eV, the average for a 300-K Maxwellian distribution, that is, wavelength 1.8 Å.

Some Neutron Terminology



The neutron spectrum shown is typical of cryogenic moderators at accelerator-based neutron facilities: 100-K liquid methane at IPNS.

Cyclotrons

Ernest Lawrence, U. C. Berkeley, invented the cyclotron in 1930. Cyclotrons evolved rapidly.

Workers (Seaborg, …) accelerate particles to multi-MeV energies to produce isotopes.

In the late 1930s, cyclotrons accelerated protons and other particles at rates greater than radioisotope sources.

The Weizsäcker Mass Formula

In 1935, Carl von Weizsäcker derived the semi-empirical nuclear mass formula: good accounting of the nuclear binding energy in terms of the numbers of neutrons and protons in nuclei.

Discovery of Fission

IN 1938, Otto Hahn, Lise Meitner, and Fritz Strassmann discovered neutron-induced fission in uranium.

Scientists immediately realized that neutrons emerged from that process.

Neutron Interactions

In the mid-1930s, scientists studied the many kinds of neutron-nuclear interactions:

- Nuclear elastic scattering
- Nuclear inelastic scattering
- Magnetic
- Capture, Absorption
- Resonances

Later:

- Fission
- Spallation

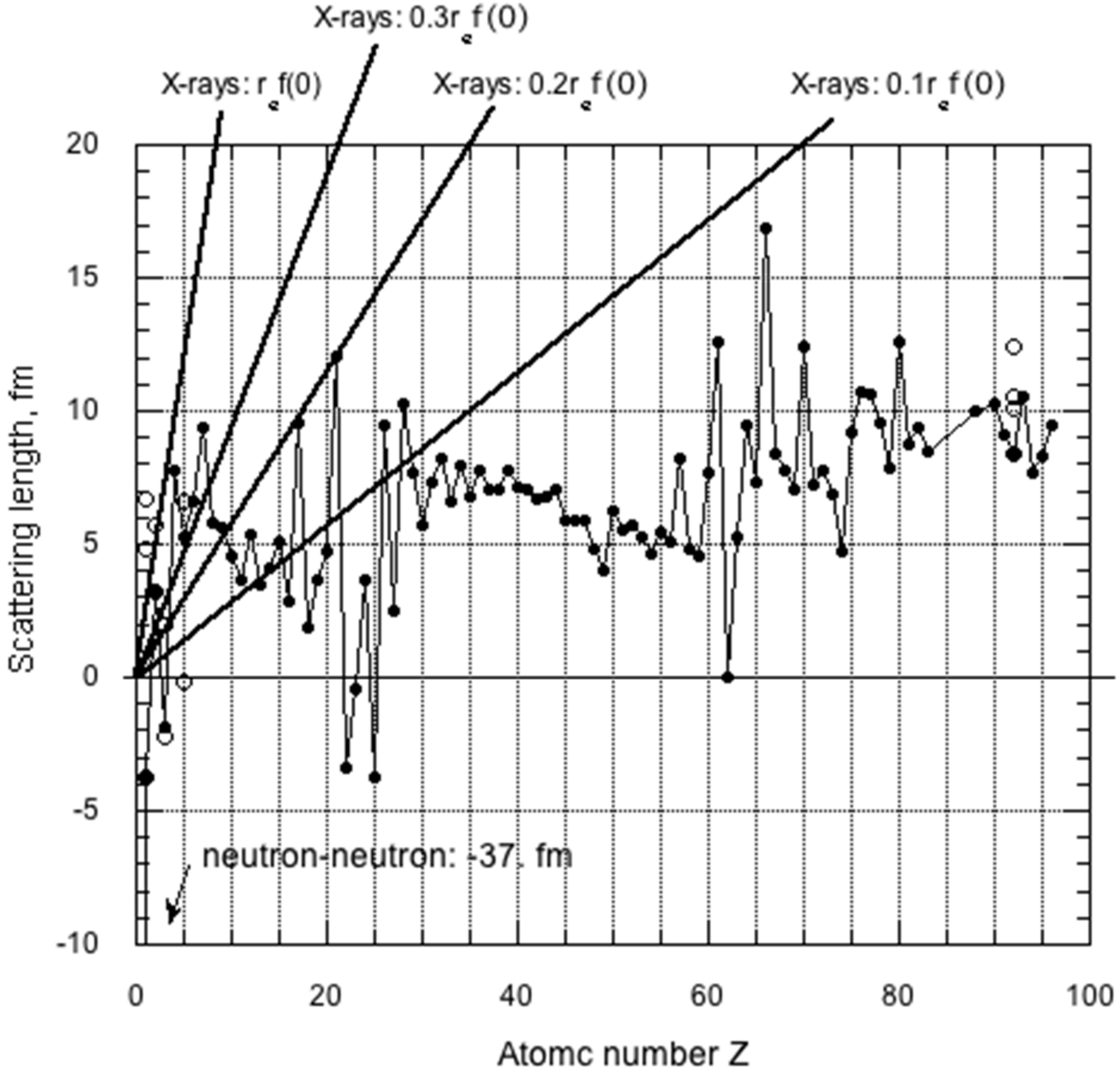
Neutron-Nucleus Scattering

Neutron-nucleus scattering is most common in materials science applications.

Scattering lengths characterize these interactions and are measured quantities and are independent of wavelength. There are two, except for spin-zero nuclei, b^+ and b^-, according to whether the spins of the neutron and of the nucleus align or anti-align.

Scattering cross-sections $\sigma = 4\pi b^2$ are usually expressed in units of barn = 10^{-24} cm^2. Scattering lengths are usually tabulated in fermi = 10^{-13} cm units, so <u>be aware</u>.

Slow-Neutron and X-ray Scattering Lengths



Neutron Magnetic Interactions

Neutrons *scatter* from atomic electrons. The magnetic scattering depends on scattering factors that depend on the density distribution of unpaired atomic electrons, which are calculated quantities that depend on the atomic ionization state and on the neutron wavelength.

Neutrons paths *bend* traveling in magnetic fields, which are optically bi-refringent. That is, the energy of the field interaction is opposite for neutron spins aligned and anti-aligned with the magnetic field.

Neutrons *precess* at the *Larmor frequency* $\omega_L = \gamma_n B$.

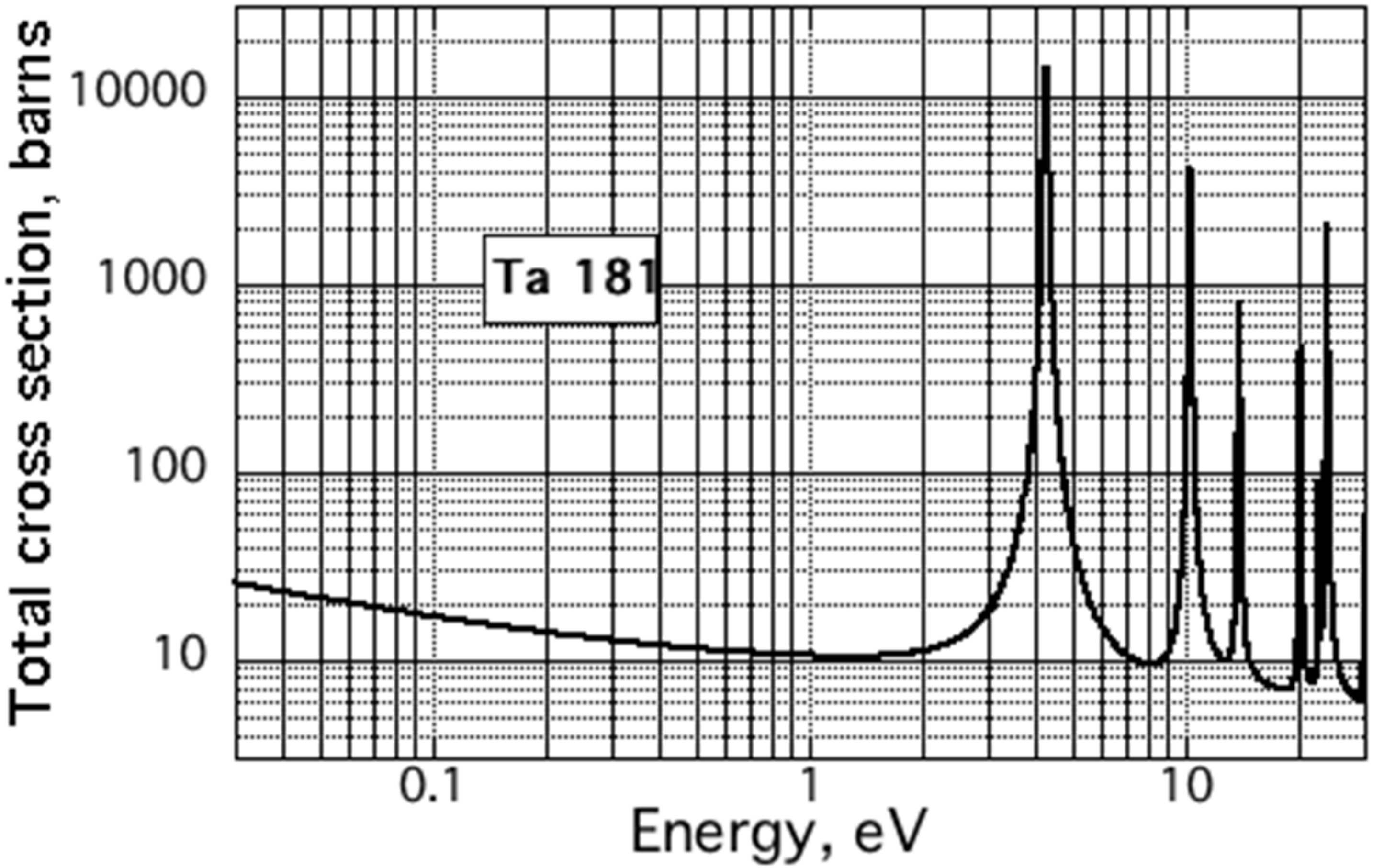
Resonance Interactions

- Strong variation in interaction probabilities at specific energies.
- Formation of *compound nuclei* with energies that correspond to quantum states—think of exciting vibrations of a many-body system of interconnected springs and masses.

Gregory Breit and Eugene Wigner (1936) worked out the formula for the interaction cross-sections. For resonance capture, for example,

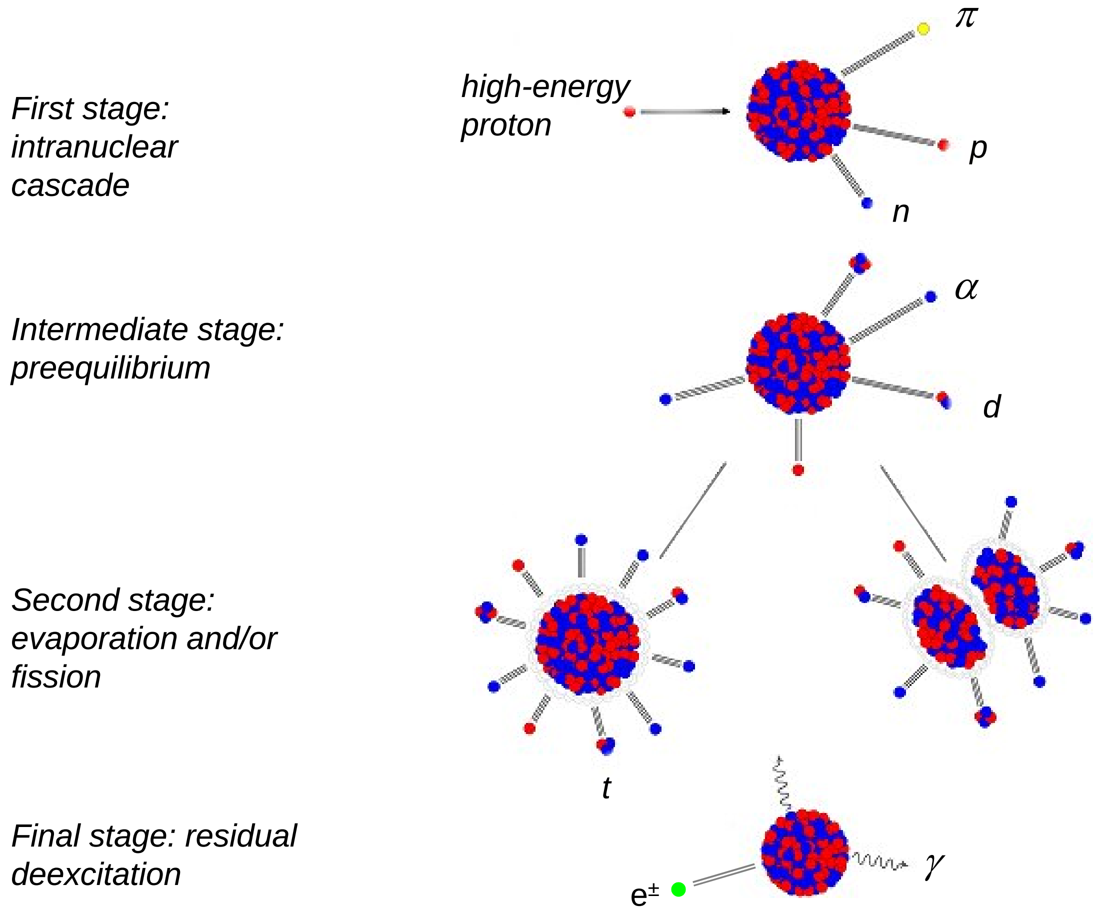
$$\sigma(E) = \frac{\sigma_0}{4}\sqrt{\frac{E_0}{E}}\frac{\Gamma_\gamma \Gamma}{(E-E_0)^2 + \left(\Gamma/2\right)^2} \quad .$$

Tantalum-181 Cross-Section



The Spallation-Fission Process

Schematic illustration of our modern understanding of the spallation-fission process (when fission is possible).



(Courtesy L. Waters, LANL)

Atmospheric Neutrons

Scientists gradually became aware of neutrons produced in the atmosphere by energetic cosmic-ray protons (~ 10 GeV) in the spallation reaction.

Atmospheric Spallation Neutrons

There are always neutrons around us. The thermal neutron flux at the Earth's surface is ~ 10^{-4}—10^{-3} n/cm^2-s, varying with atmospheric pressure.

E. Fermi, University of Chicago 1948 lectures—cosmic-ray-proton-induced neutron flux as a function of atmospheric depth.

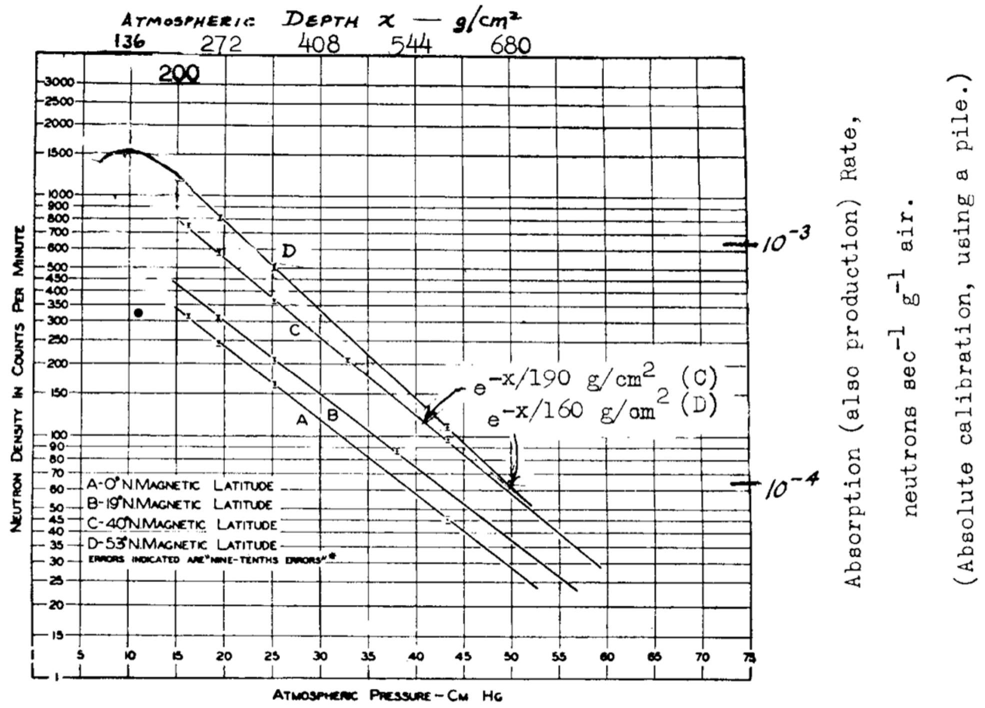


FIG. X.3 Apparent absorption of neutron-producing radiation at various magnetic latitudes*. See text, p. 220.

Harold Agnew's 1944 Flying Neutron Detector (B-29)

Carbon-14

High-energy spallation neutrons colliding with atoms in the atmosphere steadily produce carbon-14

$$n + {}^{14}N \rightarrow {}^{14}C + p \quad .$$

^{14}C nuclei have half-lives of 5730 years and constitute about 10^{-12} of carbon in the atmosphere, decaying by electron emission,

$$ {}^{14}C \xrightarrow{T_{1/2} - 5730\, years} {}^{14}N + e^{-} + 156\ keV \, .$$

The carbon appears in organic material, from which the decay electrons are easy to detect. This is the basis for ^{14}C dating of organic artifacts.

Reactors

In 1942 Enrico Fermi and his team demonstrated the first self-sustaining nuclear reaction in the CP-1 reactor in Chicago.

Reactors rapidly evolved to become the most prolific neutron sources.

CP-1

Forty-nine people attended the occasion on December 2, 1942, when the reactor went critical. Prominent were Enrico Fermi, Eugene Wigner, Leo Szilard, Walter Zinn, Herbert Anderson, Leona Marshall, Harold Agnew, Arthur Compton, Norman Hilberry, Frank Spedding, …. .

Neutron Scattering

- Manhattan Project reactors aimed to produce bomb fuel, ^{239}Pu and to develop the relevant nuclear data.
- The involved scientists, Walter Zinn, Enrico Fermi, Ernest Wollan, Clifford Shull, and others, were also interested to apply their neutron beams “on the side,” for scientific purposes.

Fundamental physics experiments and materials science measurements revealed the uses of neutrons in science. These revelations led eventually to reactors designed to produce neutron beams for thermal-neutron scattering applications.

Walter Zinn
at the neutron
diffractometer
at the CP-3
reactor, ~ 1944.

More on the early history of neutrons for scattering measurements: T. E. Mason, et al., “The early development of neutron diffraction: science in the wings of the Manhattan Project”, *Acta Cryst*. (2013) A**69**, p 37-44.

What Kind of Reactors?

Why not use power reactors to produce neutron beams for research?”

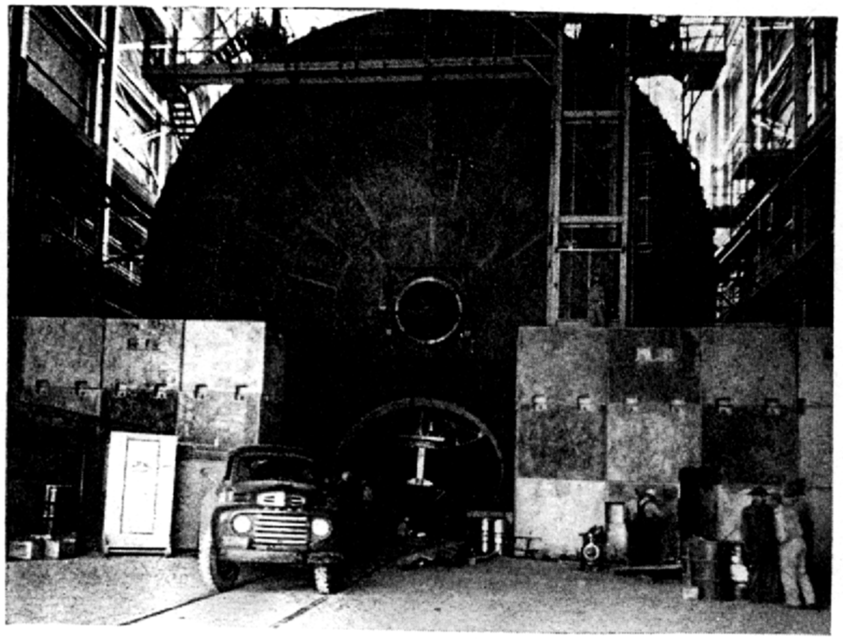
- Power reactors, high power— big and low-flux.
- Research reactors, high flux— small and dense, challenging heat transfer limitations; beam holes, a “no-no” for power reactors.

Accelerator-Produced Neutrons

Eventually, workers tried out high-power accelerator-based neutron-producing facilities.

The accelerating cavities were very large because available high-power klystrons operated at only 12 MHz (800 MHz is now common).

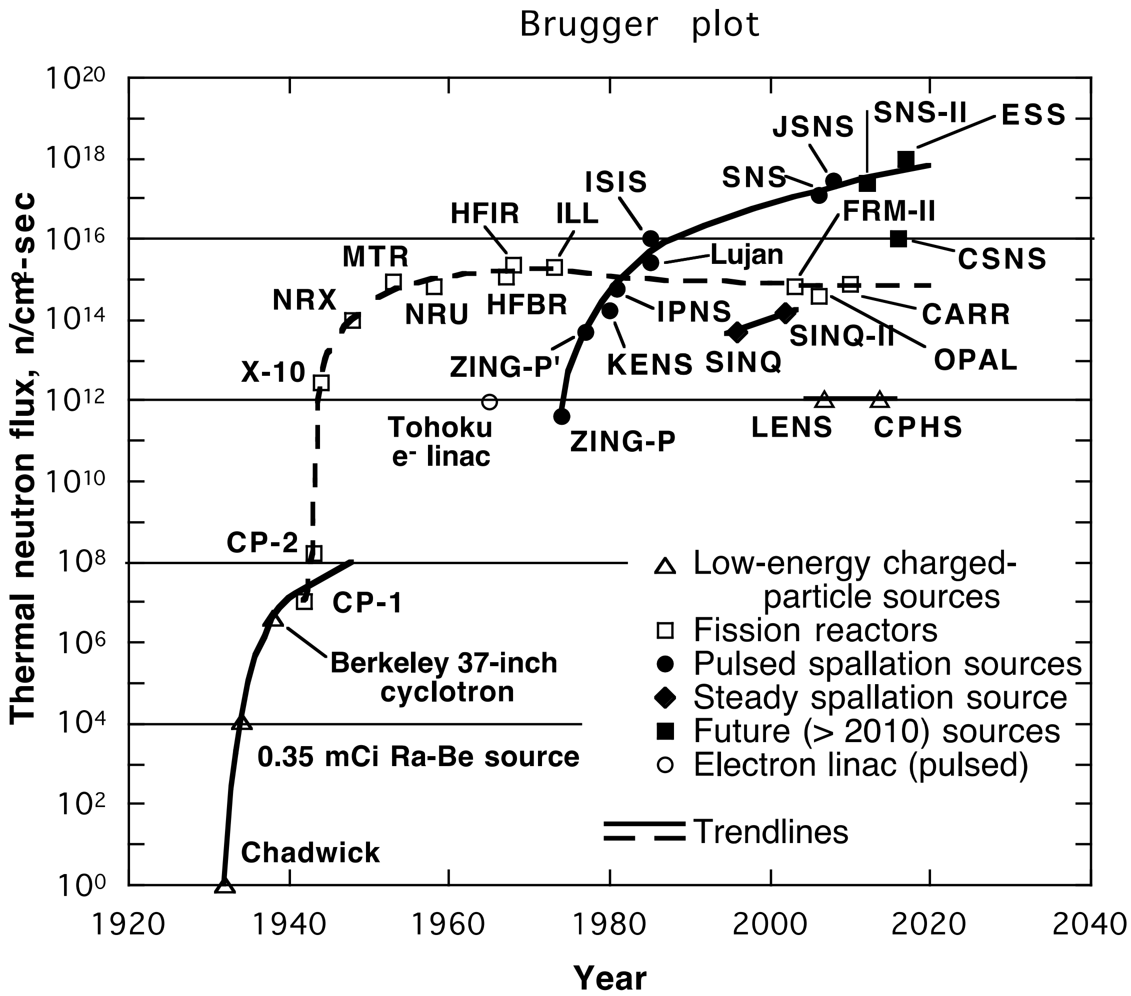
The MTA Linac ~1955



BIGGEST VACUUM VESSEL ever built, 60 feet in diameter and 87 feet long, housed Materials Testing Accelerator. Men and truck in photo show comparative size. Door 20 feet in diameter, opened at tank's bottom, admitted rail car handling drift tubes. Concrete blocks like those seen formed unbroken wall of shielding while the accelerator was running.

More about accelerator-produced neutrons in the next presentation.

Neutron Science Facilities



Reactors and Accelerator-Based Sources

THANK YOU!

QUESTIONS?