High Energy Flash Radiography and Nuclear Data

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LLNL-PRES-xxxx
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BLUF: Data Needs

- Photoatomic interactions are an important component of radiation transport, transmission, and detection simulations for security applications calculating flash radiography as a diagnostic.
  - Atomic data are an important piece of "nuclear data", for photon energies up to about 50 MeV
  - Data library support is limited – community utilizes historical LLNL compilations with known issues in data and formatting
  - Uncertainty quantification of these cross sections is also needed

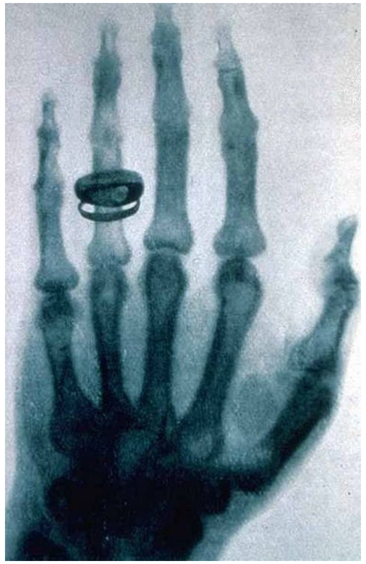
- A new data need is photonuclear reactions ((γ,n), $(\gamma,n+\gamma)$, $(\gamma,fission+\gamma)$) vs. photon energy and as a function of emission angle, particularly for high Z shielding metals.

- (n,n') cross sections are needed for many isotopes as we begin to do more neutron radiography.

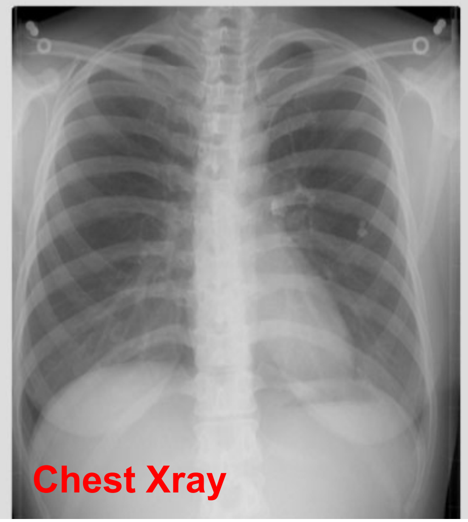
- For protons with energies between 800 MeV to 70 GeV, particle production processes need to be mapped out as this becomes a "scatter" component in proton radiography.

- We always look for
  - Other ways of inexpensively making intense, high energy and short flashes of Photons, Neutrons and Protons
  - Brighter, faster scintillators for imaging
  - Better ways of doing fast, high resolution imaging of photons, neutrons or protons

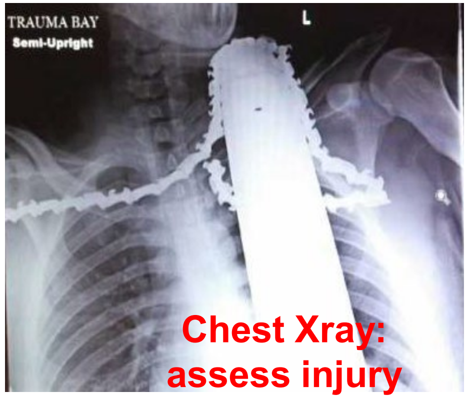
For Over 100 Years, Radiography has been used as a diagnostic tool



Frau Röntgen’s Hand
(note enhancement of image



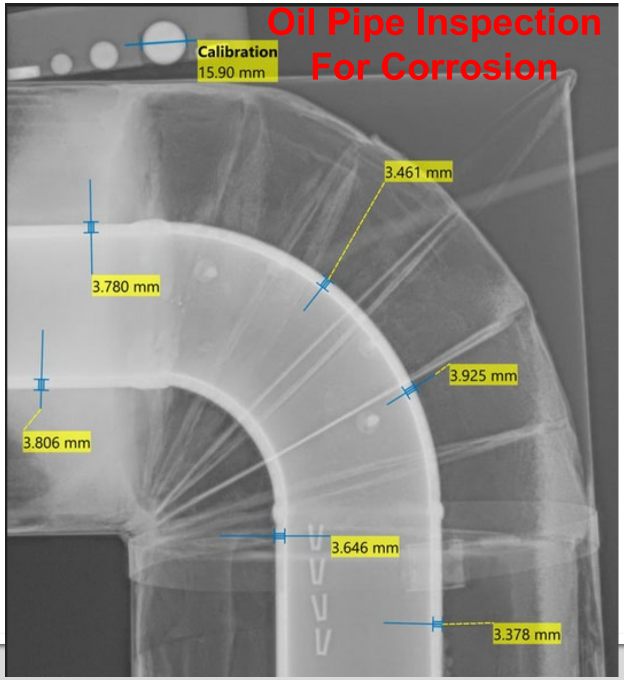
Chest Xray



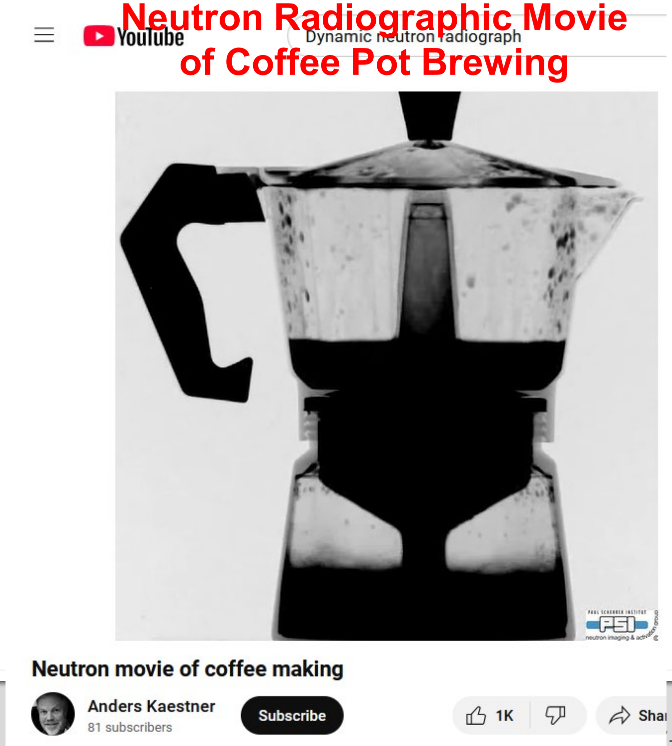
Chest Xray:
assess injury

Dental Xray

Baggage Inspection



Oil Pipe Inspection
For Corrosion



Neutron Radiographic Movie
of Coffee Pot Brewing

The Nature of the Object and the Availability of Source and Imaging Detectors Dictate the Type of Radiography

- Medical applications: Human Body is a "bag of water" + bones, which dictates 70 KeV to 150 KeV Xrays, ~300 MeV protons, and thermal up to 14 MeV neutrons.
  - Generally little motion of target, so fractions of seconds are long enough pulses to produce good images.
  - A major concern is limiting dose to patient and shielding the rest of the world from the source.
  - Neutron and proton radiography is limited for medical applications because of dose concerns and source cost. One exception is protons with energies above the Bragg peak for proton therapy alignment.

- Industrial applications: generally denser, thicker objects, which dictates up to 300 keV to 1 MeV photon sources and thermal up to 14 MeV neutrons
  - Generally little motion of target, so fractions of seconds are long enough pulses to produce good images. Some exceptions: looking through an engine block, movies of engines, coffee pots, etc.
  - A major concern is shielding the rest of the world from the source. Dosing the "patient" may not be of concern.

Department of Energy Weapons Labs focus on stewardship of the US nuclear stockpile

- Stockpile Stewardship is the effort to “maintain a safe, secure, reliable, and effective nuclear stockpile” (Page v of the 2025 SSMP at right).
  - As the stockpile ages and US priorities change, new questions emerge about aspects of these weapons.
  - Experiments are used to address some of these questions and improve our modeling of weapons.
  - Radiography is an important diagnostic used in many of these experiments.
- Types of Experiments can vary, leading to different radiographic requirements.
  - Focused experiments may test selected properties of a metal or material, or pieces of a weapons system, requiring a less penetrating source (100 keV up to 2 MeV).
  - Integrated experiments test all or most of the components of a weapon together. (2 MeV up to 20 MeV).
- These same capabilities are also applied to conventional weapons and NDE at the labs.

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Fiscal Year 2025
Stockpile Stewardship and Management Plan – Biennial Plan Summary

Report to Congress
September 2024

National Nuclear Security Administration
United States Department of Energy
Washington, DC 20585

https://www.energy.gov/sites/default/files/2024-10/FY2025 Stockpile Stewardship and Management Plan.pdf

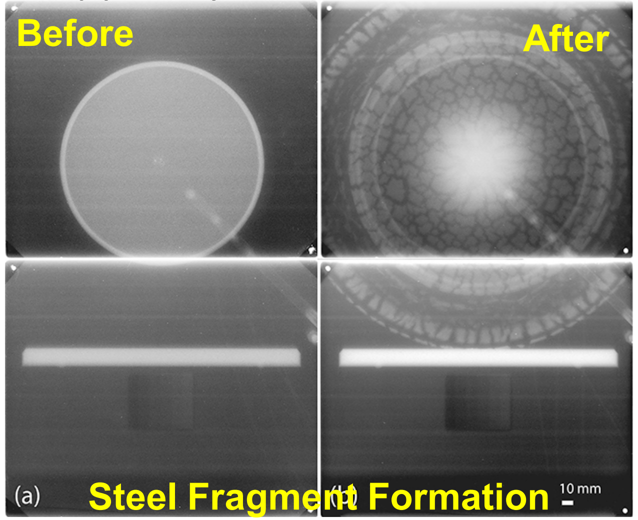
At LLNL and LANL, we use radiography to look through rapidly evolving experiments for weapon applications.

- Our objects differ from medical and industrial cases in several ways:
  - Often materials are much denser and have much higher Z (up to Z=94); many different materials, such as Beryllium, Plastics, Aluminum, Glasses, Steel, Copper, Silver, Gold, Tungsten, Tantalum, Lead, Uranium, Plutonium and many others.
  - Details of evolution are obscured by smoke and fragments blasting outward. This necessitates more penetrating radiation and much higher intensity.
  - Timescales vary from picoseconds (NIF experiments) to microseconds (integrated tests). Longer timescales can matter, but this is rarer.
  - Sizes of objects can range from microns (NIF) to a meter (integrated tests).

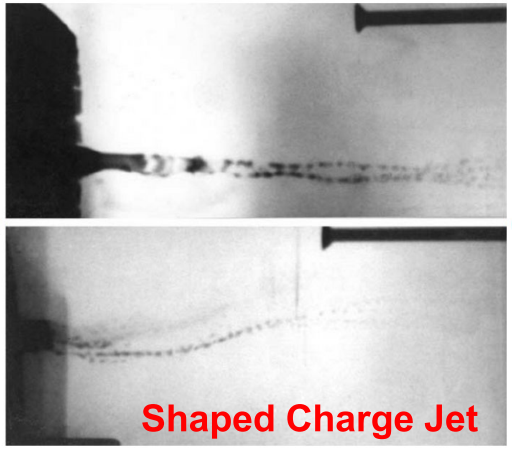
- Types of Experiments can vary, leading to different radiographic requirements.
  - Focused experiments may test selected properties of a metal or material, or pieces of a weapons system, requiring a less penetrating source (100 keV up to 2 MeV)
  - Integrated experiments test all or most of the components of a weapon together. (2 MeV up to 20 MeV)

Some examples of focused and integrated experiments

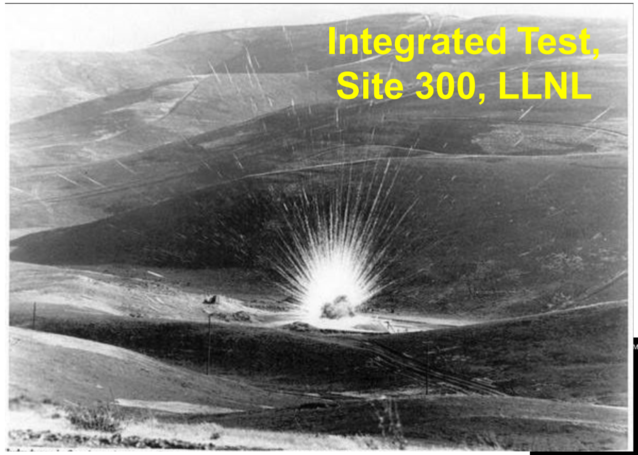
Callahan, MI, et al.
J. Appl. Phys. 134, 155105 (2023)

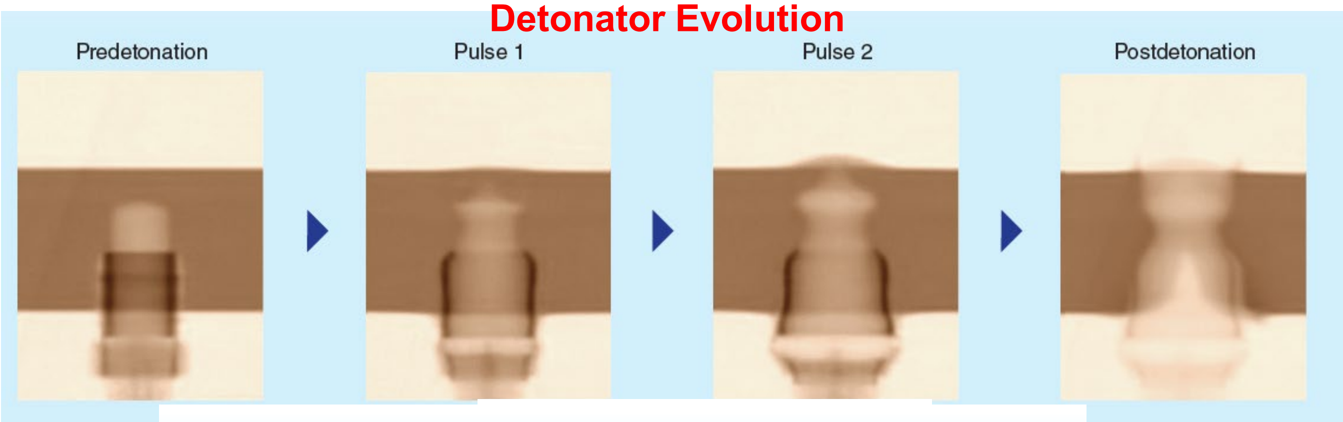


Fedorov, S.V., et al.
Journal of Applied Mechanics and Technical Physics
48(3):393-400, May 2007



X-ray photographs of shaped charge jets formed with the generation of a magnetic field in a shaped-charge liner: B 0 = 0 . 84 (a) and 1.4 T (b).



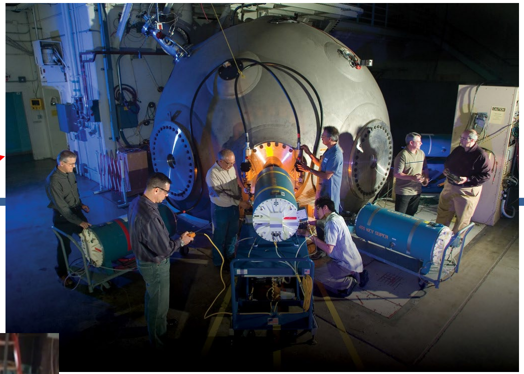


S&TR July/August 2018

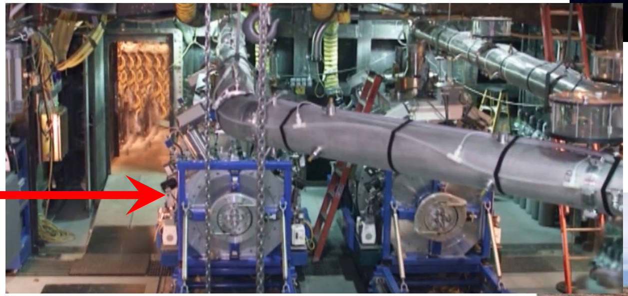
Flash X Ray

7.8 and 10.8 microsconds after detonation, respectively.

Stockpile Stewardship uses Flash Radiographic Sources All are Bremsstrahlung Sources, by necessity



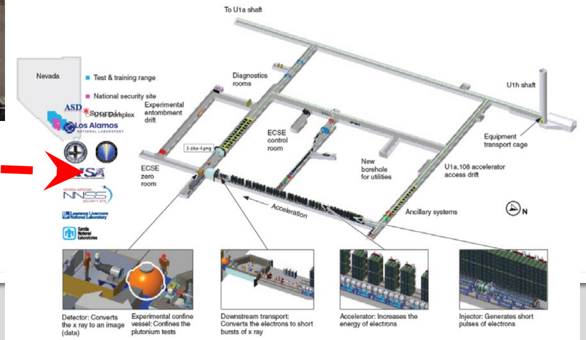
- ScandiFlash (450 keV endpoint) Used in many experimental sites (picture is at LLNL's HEAF).



- Cygnus 1&2 (2.2 MeV endpoint) At PULSE facility at NNSS, 960 feet underground.

- FXR (9 MeV or 17.5 MeV endpoint) At the Contained Firing Facility (CFF) at LLNL's Site 300.

- DARHT 1&2 (Dual Axis Radiography Hydro Test facility) (20.5 and 17 MeV endpoints) at LANL.
- Scorpius (20 MeV endpoint) at NNSS PULSE facility



Flash Radiographic Sources in US
All are Bremsstrahlung Sources

- ScandiFlash (450 keV endpoint) Used in many experimental sites
- Cygnus 1&2 (2.2 MeV endpoint) Used in PULSE facility at NNSS 960 feet underground.
- Febetrons (2 MeV endpoint) used at some outdoor facilities.
- FXR (9 MeV or 17.5 MeV endpoint) at the Contained Firing Facility (CFF) at LLNL's Site 300.
- DARHT 1&2 (Dual Axis Radiography Hydro Test facility) (20.5 MeV endpoint) at LANL
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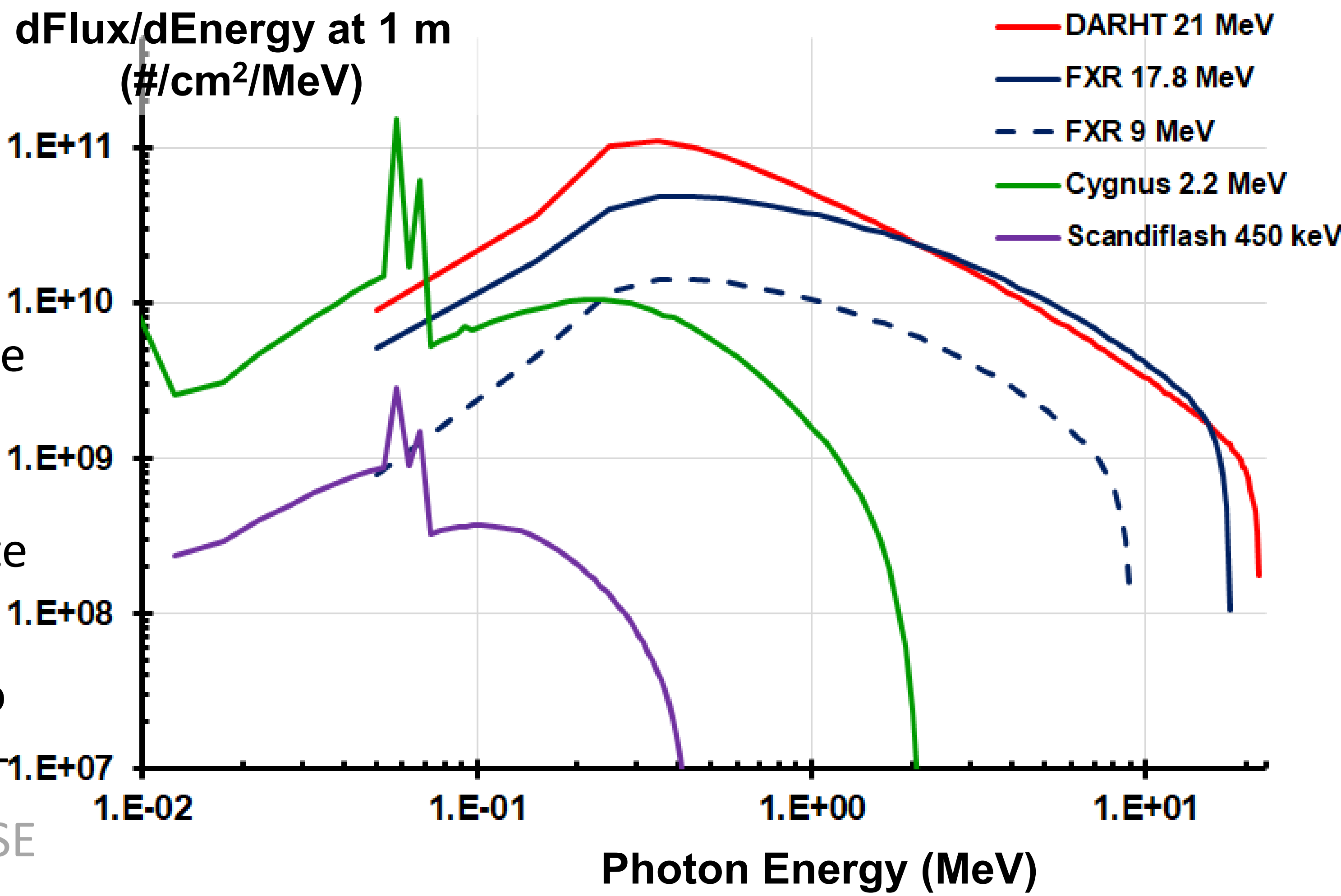
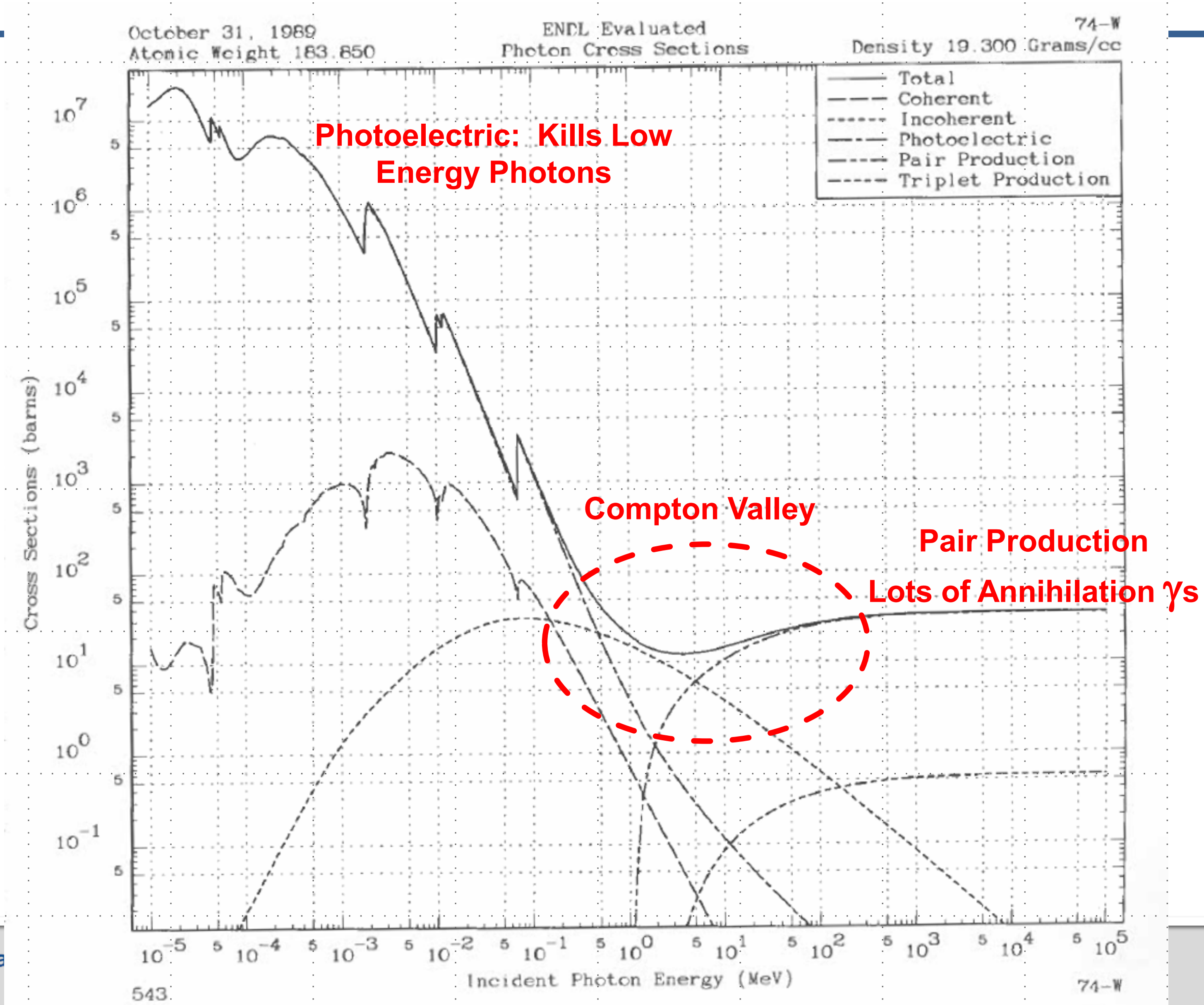
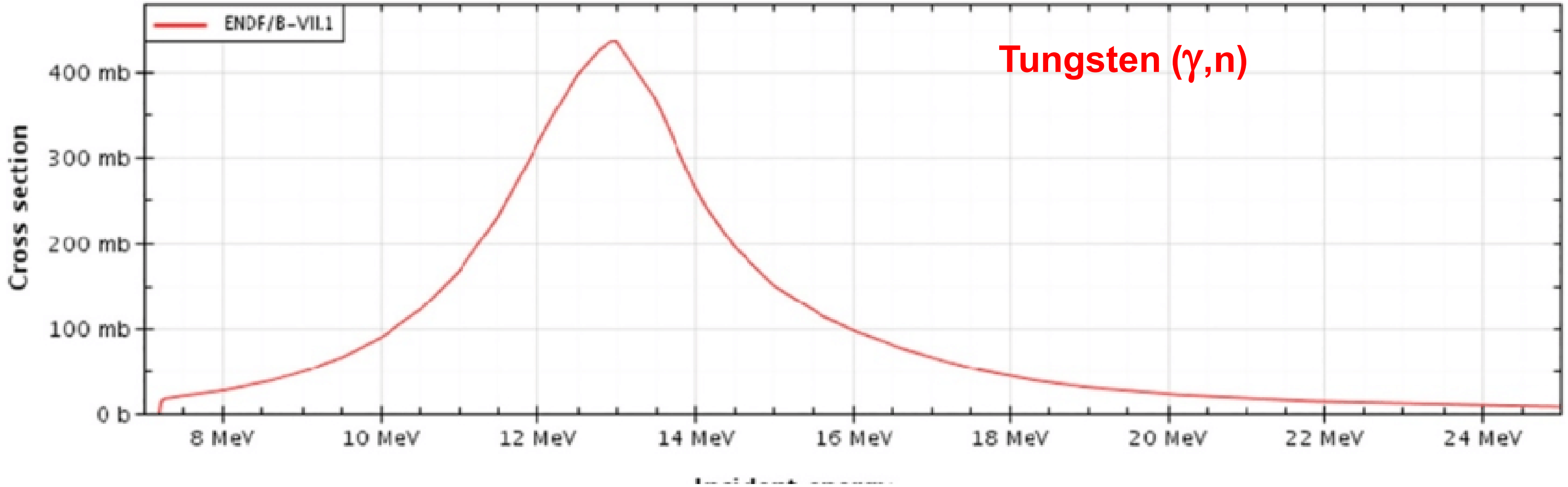


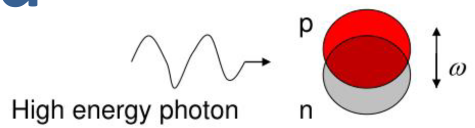
Photoatomic Cross Section for Tungsten



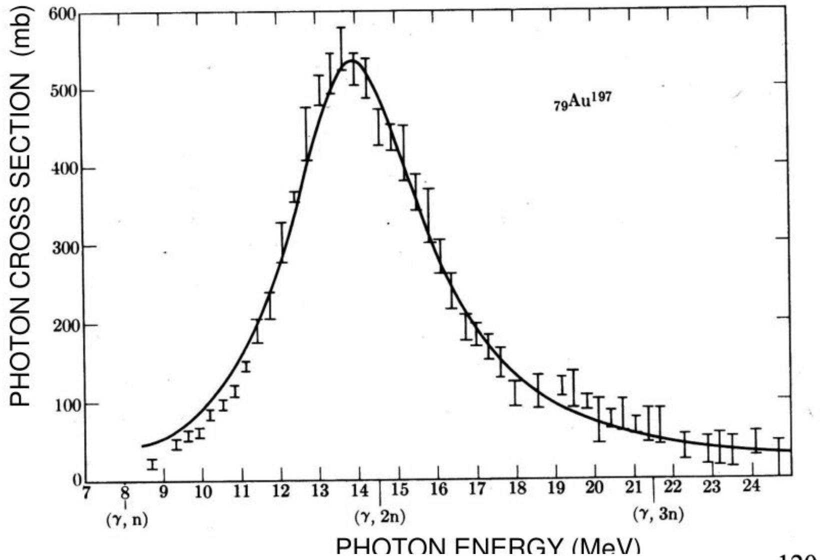
Photonuclear Cross Sections are Dominated by the Giant Dipole Resonance

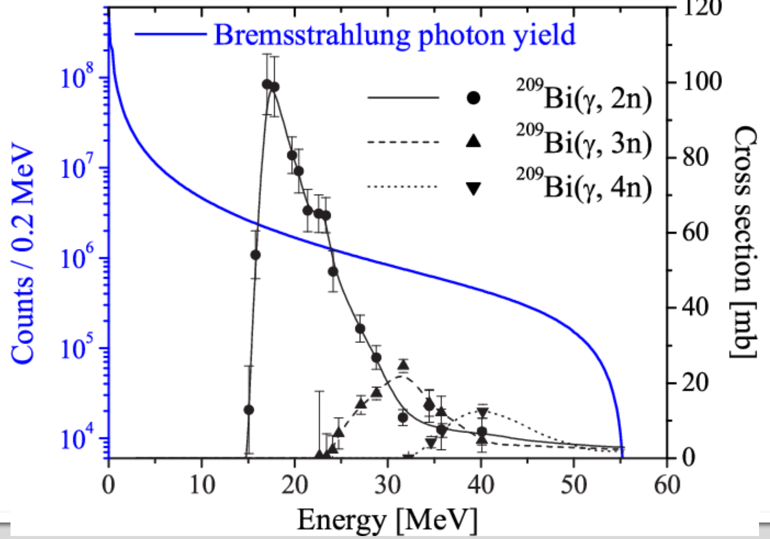


The giant dipole resonance



$$\omega = \frac{E}{\hbar} = \frac{E}{\hbar c}.c = \frac{14MeV}{197MeV.F}.3x10^{23}Fs^{-1}$$
$$= 2x10^{22}s^{-1}$$

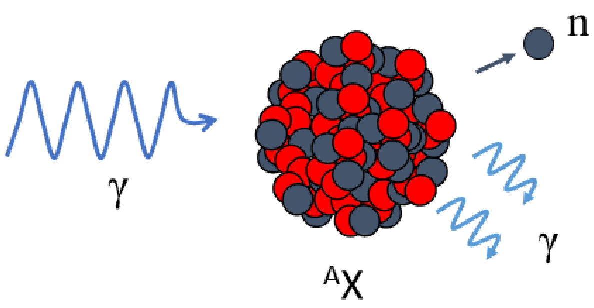




- GDR varies with Z and nuclear structure
- High Energy gammas stimulate the resonance, as their wave function matches nucleus scales.
- Excited nuclei have reduced barriers to n, 2n , 3n, … and fission
- New gamma rays can be produced, leading to more scatter in the image

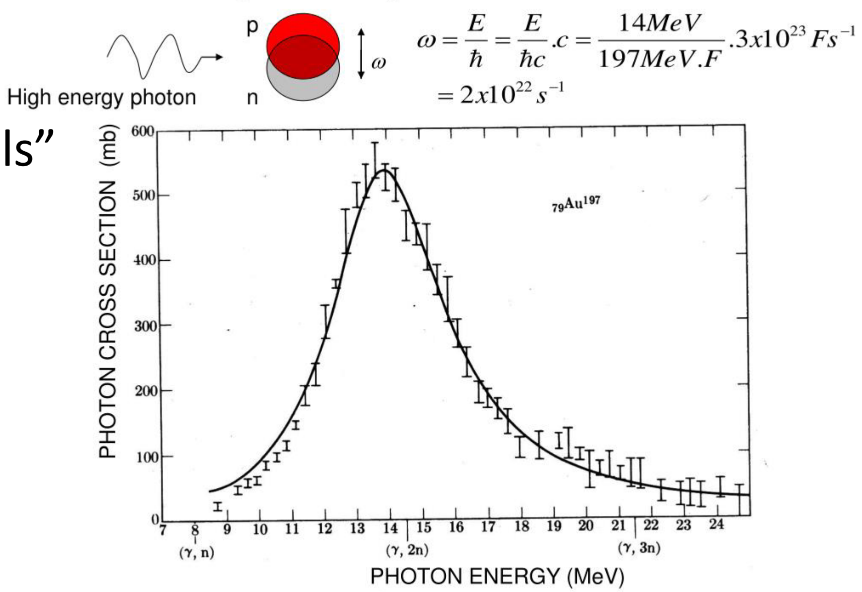
Photonuclear effects must be accounted for if the photon energy is above roughly 7 MeV

- Results of photonuclear events reduce radiographic quality in several ways:
  - Neutrons can produce “stars” which blot out data in the radiograph
  - Gammas which are produced which “fog” up the image from extra scatter
  - Neutrons and Gammas produced can affect shielding requirements as well as damage other diagnostics.



- Data gaps exist
  - No photons emitted in photofission…
  - Most data in library stored in MT4, “Sum Of Remaining Output Channels” (we call this the Junk Drawer)
  - WANDA 2022 session on photonuclear data also noted needs

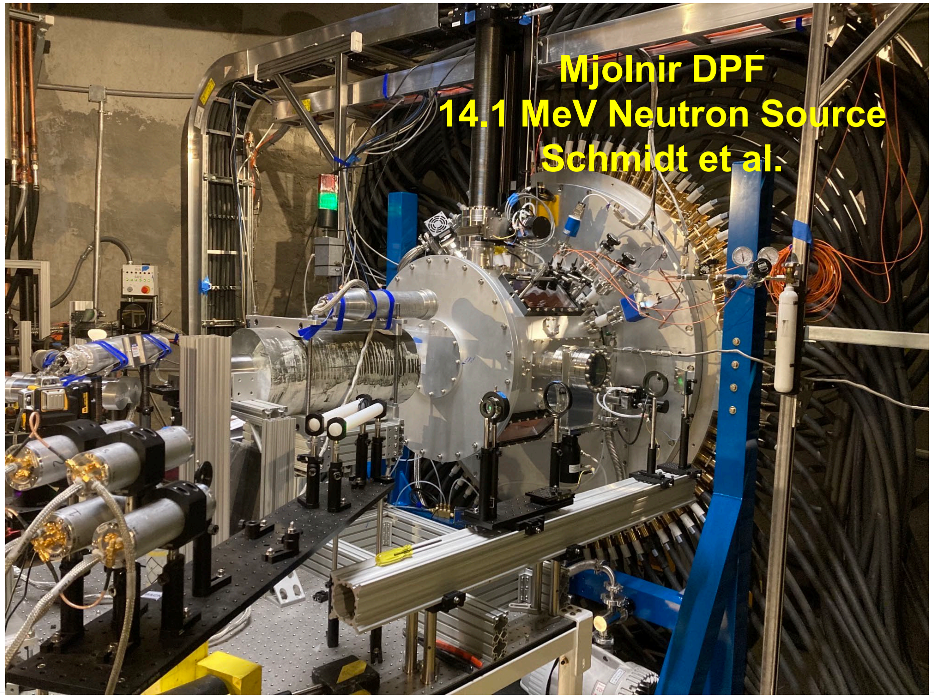
The giant dipole resonance

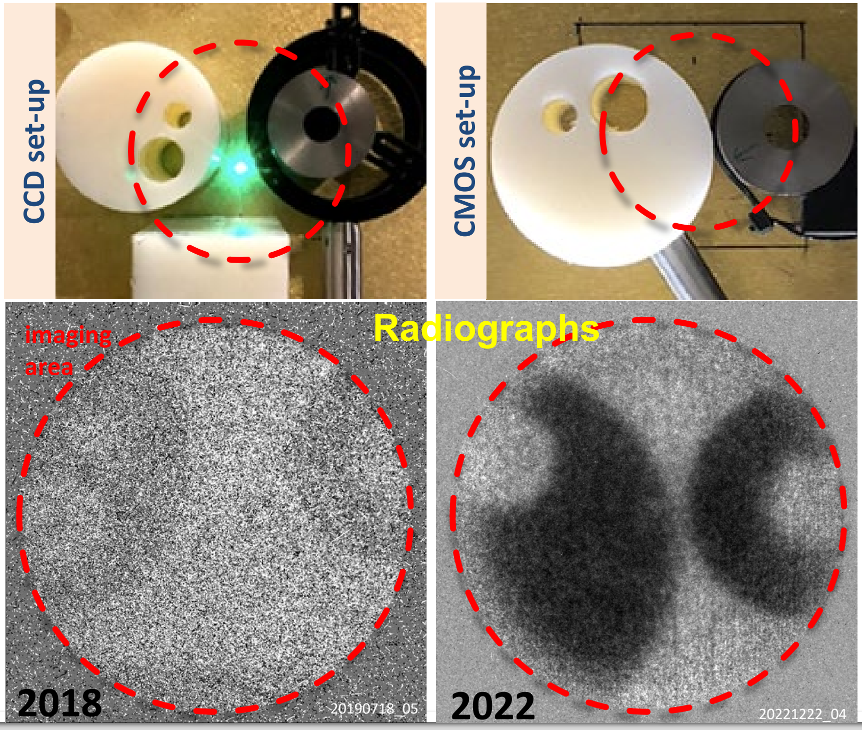


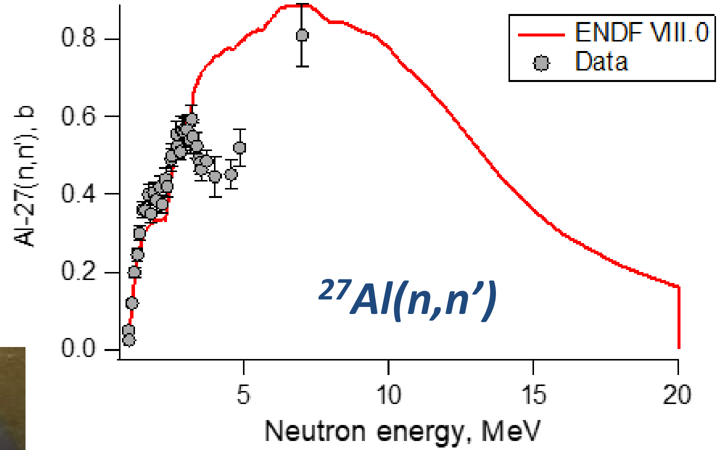
Neutron radiography involves multiple reactions

- Scatter reactions important, yet data are limited for most isotopes
  - Scatter changes energy, direction of neutrons
  - Experimental data measurements are challenging

- Need for accurate elastic and inelastic cross sections (and products)







Proton Radiography is of Interest for 800 MeV to 50 GeV Protons

Olson, R & Cerreta, Ellen & Morris, C. & Montoya, A & Mariam, Fesseha & Saunders, A & King, Robert & Brown, Eric & Gray, G. & Bingert, J. (2014). The effect of microstructure on Rayleigh-Taylor instability growth in solids. Journal of Physics: Conference Series. 500. 112048. 10.1088/1742-6596/500/11/112048.

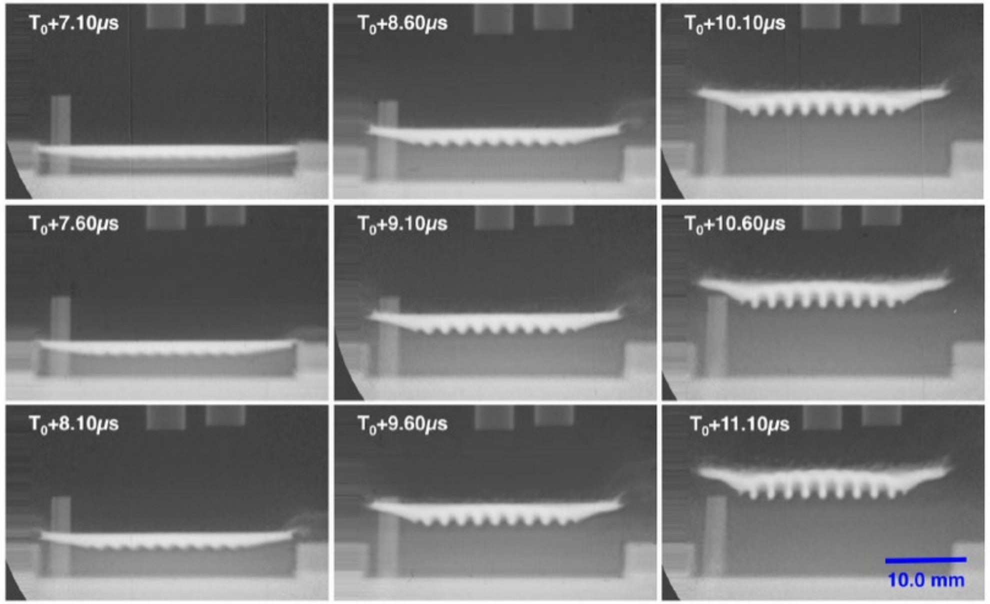


Figure 3. A sequence of nine transmission radiographs measuring the perturbation growth in annealed Cu with a 60 μm average grain size. T_0 is defined as the initiation time of the detonator attached to the plane-wave HE lens.

A challenge for quantitative proton radiography is to determine the scatter background.

“Scatter” is largely the result of p + Nucleus -> stuff reactions, in which the “stuff” (pions, Kaons, etc.) can get confused with protons.

These reactions become more important as proton energy increases.

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