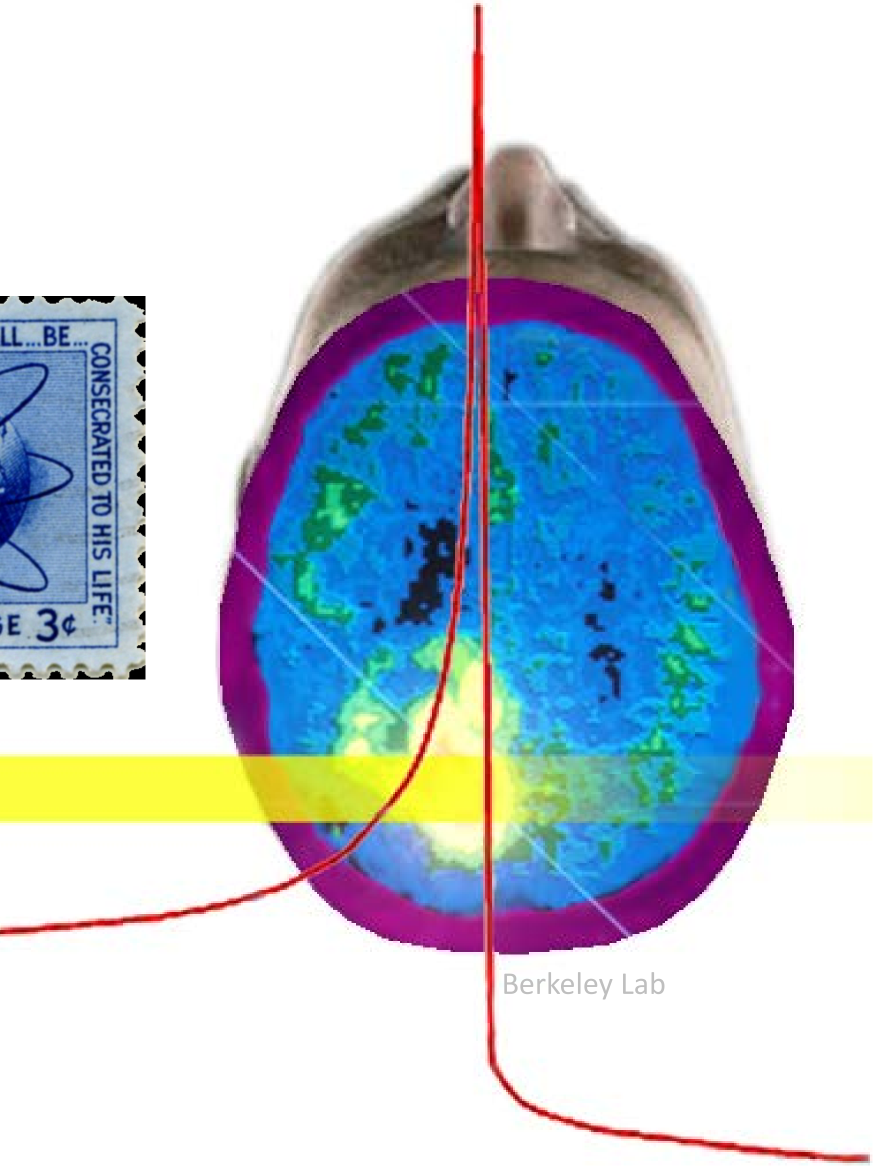
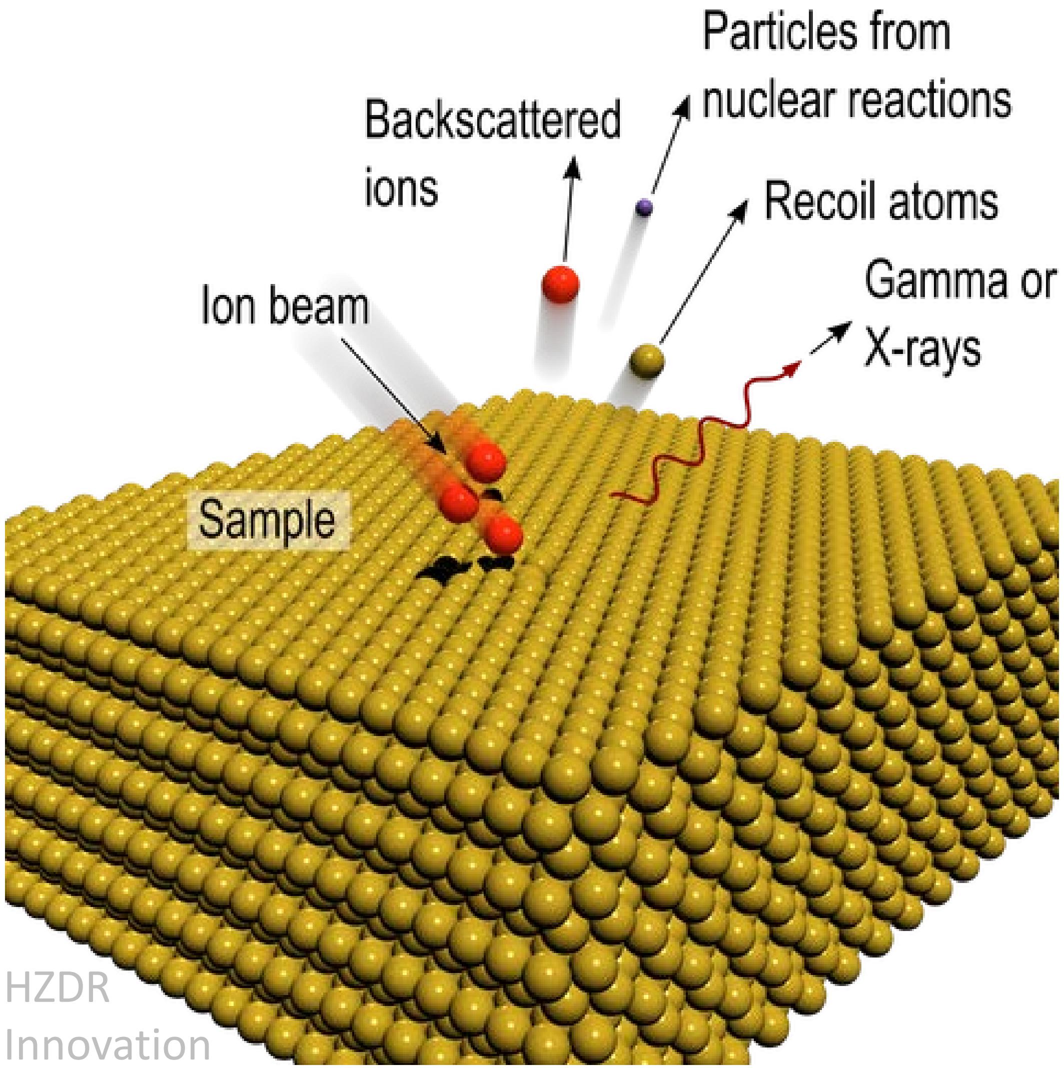
Lecture 22: Nuclear Applications

- Material analysis
- Medicine
- Dating
- Energy
- Weapons
- Defense


Berkeley Lab

Material analysis

- Material analysis consists of measuring a nuclear reaction between an ion beam (typically protons or alphas) and a sample that's under study
- The reaction products are analyzed to determine the chemical (and often isotopic) composition
- Typical reaction probes are scattering (Rutherford Backscattering and Elastic Recoil Detection), prompt photon emission (Particle Induced X-ray and Gamma Emission), and delayed photon emission (Activation)
- Distinct advantages of ion beam based materials analysis techniques are that they're non-destructive and high-precision



HZDR Innovation

Material analysis: *Rutherford Backscattering*

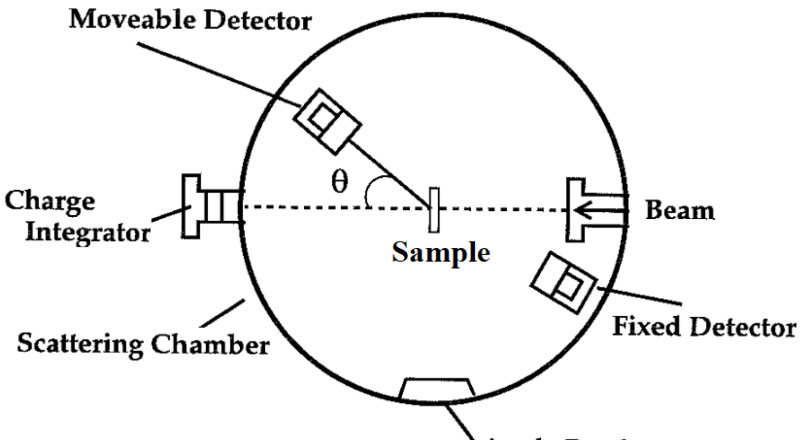
- Recall that the angular distribution for Coulomb scattering (a.k.a Rutherford Backscattering (RBS)) is

$$\frac{d\sigma}{d\Omega} = \frac{dI}{F_0}\frac{1}{d\Omega} = \left(\frac{Z_1 Z_2 \alpha \hbar c}{4KE_{cm}}\right)^2 \frac{1}{\sin^4(\theta_{cm}/2)}$$

- For a given angle of the elastically scattered projectile, the shift in energy is determined by the kinematic factor

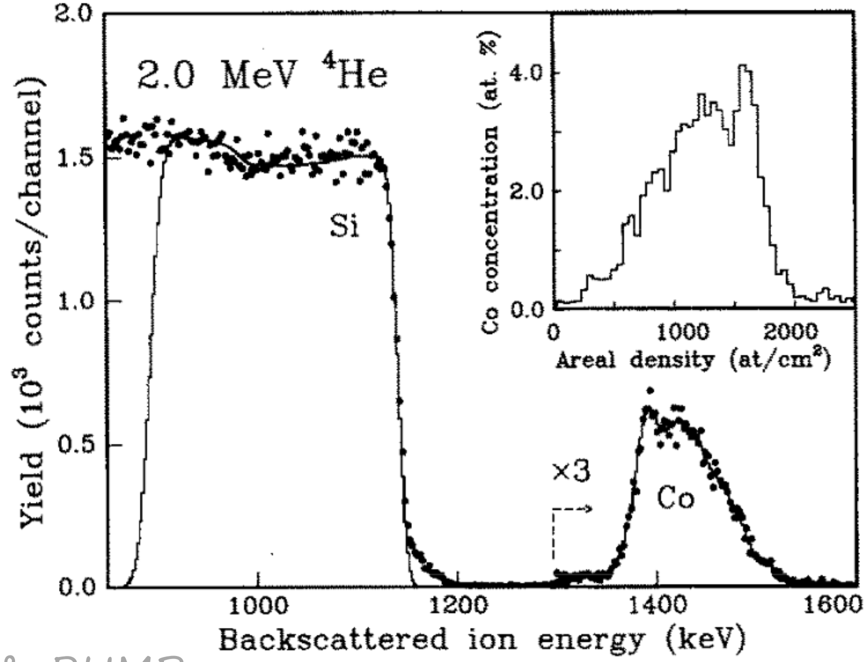
$$K = \frac{E_f}{E_i} = \left(\frac{\sqrt{A_t^2 - A_p^2 \sin^2(\theta)} + A_p\cos(\theta)}{A_p + A_t}\right)^2$$

- I.e. measuring the angle and energy of the elastically scattered projectile, for a projectile of known mass A_p and incident energy E_i uniquely determines the mass of the target atom that scattering occurred on
- A sample with a multi-atom composition will have several different energy peaks for a measurement at a fixed angle
- Peak widths are due to energy straggling and so they indicate the thickness (# of atoms) for that component of the sample (and can even provide a depth distribution)



PHYS6751 RBS Lab Manual

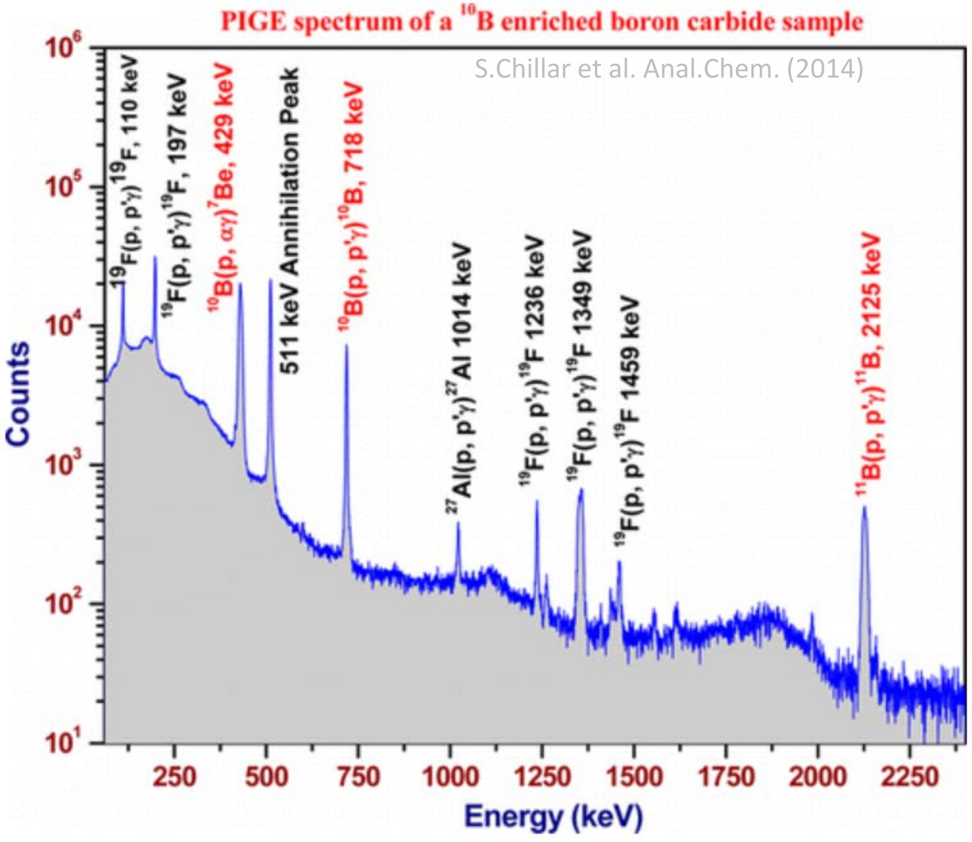
Saarilahti & Rauhala NIMB (1992)



Typically analyzed with standard codes, such as SIMNRA & RUMP

Material analysis: *Particle-induced Gamma-ray Emission*

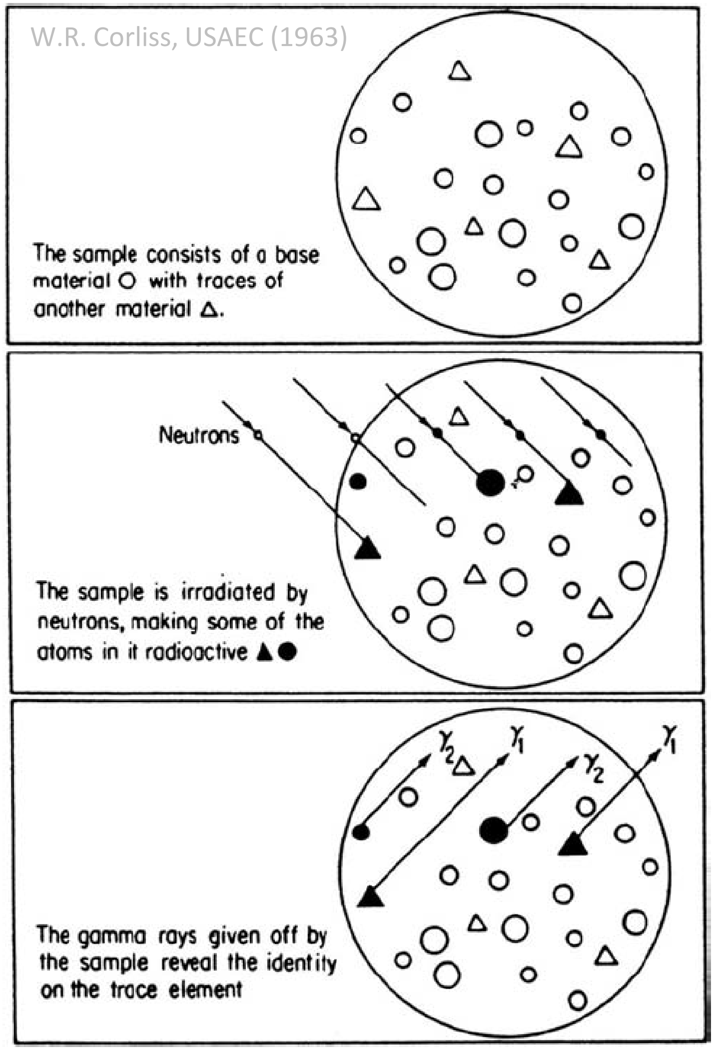
- Particle-induced Gamma-ray Emission (PIGE) takes advantage of the fact that isotopes have unique γ-decay spectra which can be probed by populating excited states via a nuclear reaction
- Typical reaction probes include (p,γ), (p,p'γ), (p,$\alpha\gamma$)
- For known cross sections and well-characterized set-ups, the γ-ray yield indicates the abundance of an isotope and the γ-spectra indicate which isotopes are present
- When using resonant reactions, PIGE can be used to assess the composition as a function of depth by slowly increasing the beam energy
- Atomic excitations can be taken advantage of instead, where de-excitation x-rays are measured, which is known as PIXE



For PIXE & PIGE reference data, see the IAEA's Ion Beam Analysis Data Library (IBANDL)

Material analysis: *Activation*

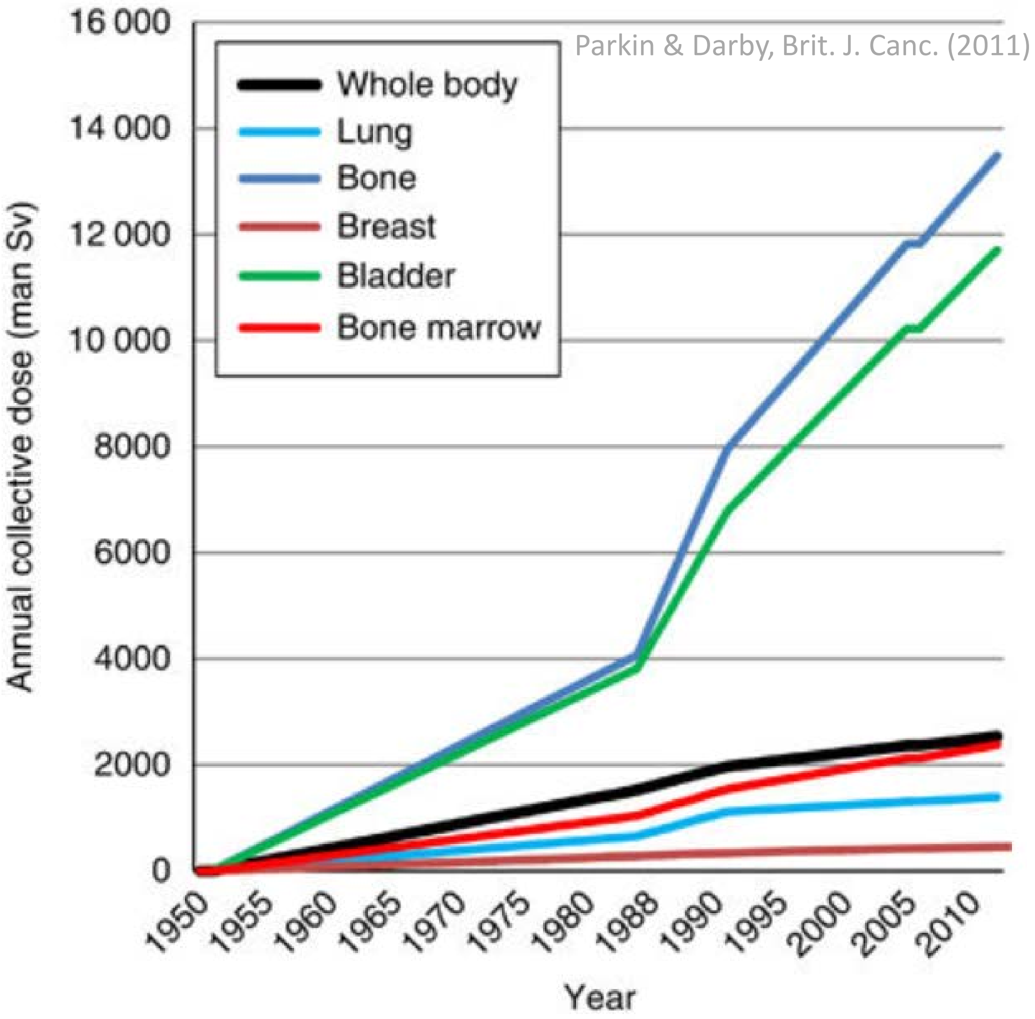
- Activation analysis instead employs delayed γ-emission
- Recall that in secular equilibrium, i.e. the case where a parent decay feeding a daughter isotope is effectively infinite compared to the daughter decay lifetime, the activity of the daughter species is $A_2(t) \approx R_{12}\left(1 - e^{-\lambda_2 t}\right)$, where $R_{12} = N_p n_t \sigma_{12}$ *(for a very thin target!)*
- So, for a daughter isotope with a measured activity A_2, known decay constant λ_2 produced by a reaction over a known irradiation time and number of incident projectiles N_p using a reaction with a known cross section σ_{12}, one can determine the aerial density of the target species for the reaction n_t
- A relative measurement can be performed, e.g. by sandwiching the sample in between gold foils, for an easier analysis
- Using neutrons for the incident projectile enables bulk samples to be investigated
- Complications include requiring known cross sections and leaving a sample irradiated for some time



A nice web-tool to calculate medical isotope production via activation is the IAEA's Isotopia

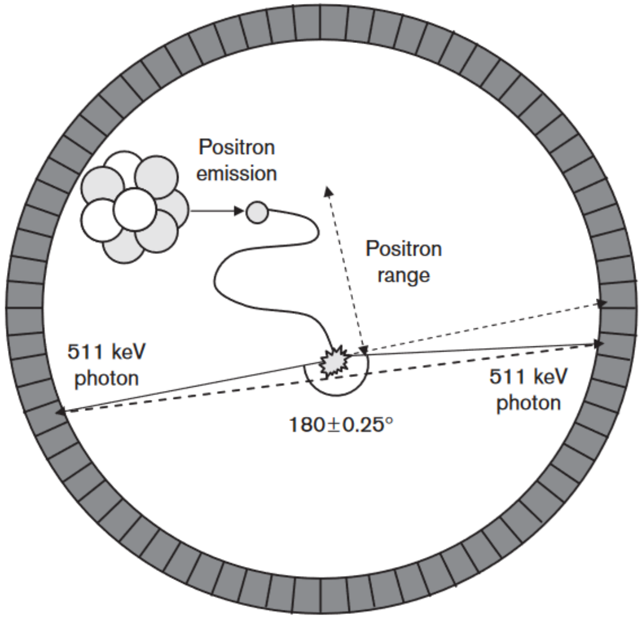
Nuclear Medicine

- Nuclear medicine generally breaks down into *imaging* and *cell destruction*
- Imaging uses the signature from radioactive decays to tag components of interest in living organisms, e.g. cancerous cells, blood flow
- Cell destruction uses energy deposited by photons, electrons, or nuclei to do localized damage. (To make ourselves feel better, this is usually referred to instead as *therapy*)



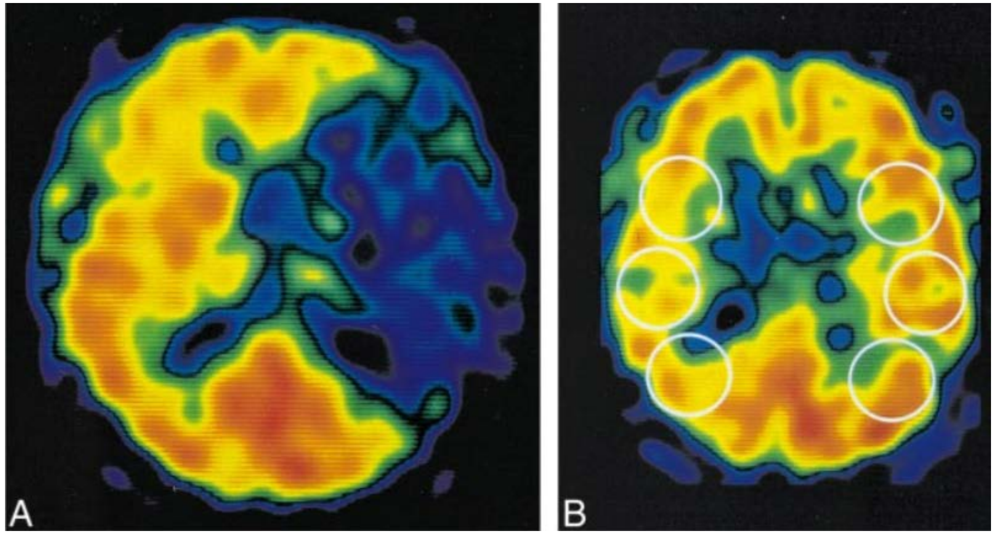
Nuclear Medicine: *Imaging with radioactive decay*

- Imaging using radioactive decays within the body is accomplished via Positron Emission Tomography (PET) or Single Photon Emission Computed Tomography (SPECT)
- In both cases, a radioactive nucleus is ingested or injected into a patient. For ingested cases, the radioactive nuclei are typically bound to a molecule such as a sugar which the cells of interest preferentially uptake
- PET imaging involves detection of back-to-back 511keV γ-rays which are created upon the annihilation of a position emitted from a β^+-decaying isotope (e.g. ^{18}F)
- SPECT imaging involves the detection of a single photon emitted from the γ-decay from an isomeric state (e.g. ^{99m}Tc)
- PET resolution suffers from positron travel distances and expensive radiotracers and detection set-ups
- SPECT resolution suffers from background (due to the lack of coincidences) and uncertain γ-attenuation but tends to be less expensive



Rahmim & Zaidi, Nuc. Med. Comm. (2007)

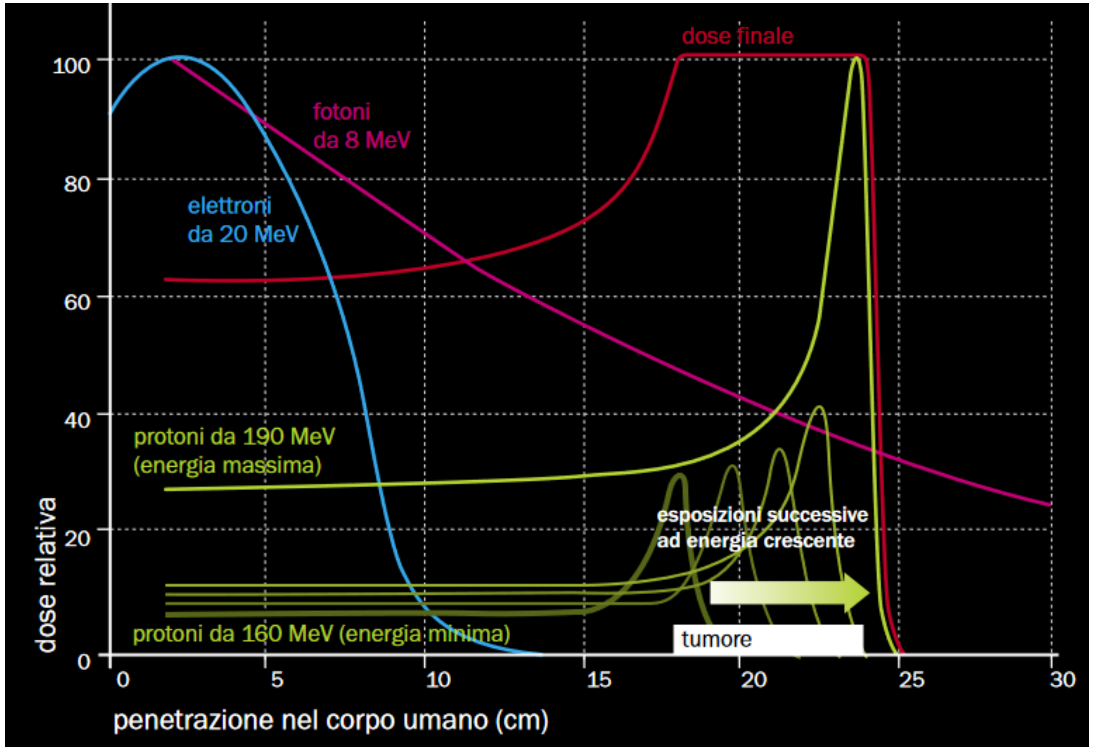
SPECT (with ^{99m}Tc) of blood flow



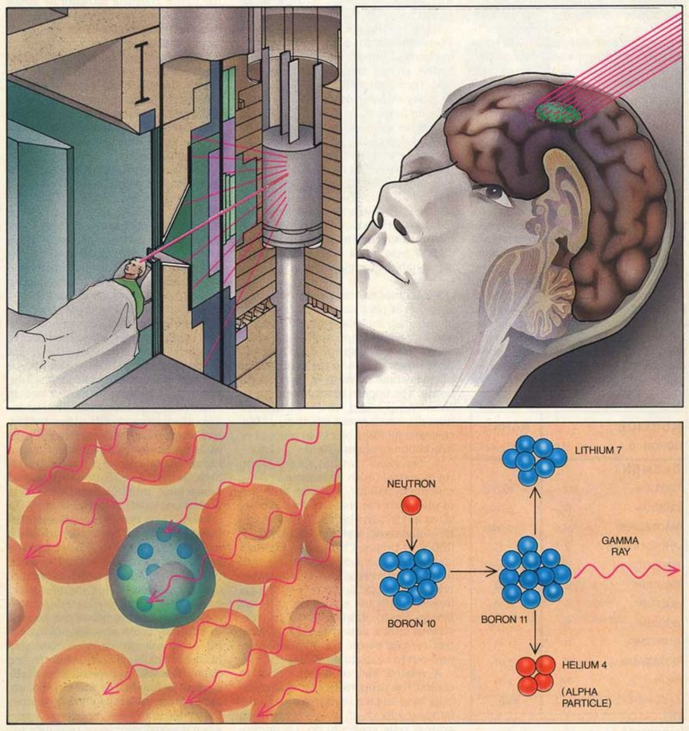
K. Ogasawara et al. American Journal of Neuroradiology (2001)

Nuclear Medicine: *Therapy with radiation*

- All radiation types will have some sort of interaction with matter and, in the process, it will deposit energy. The energies associated with nuclear interactions are far larger than molecular binding energies and so nuclear energy deposition can be used to destroy unwanted cells
- X-ray and electron therapies are well suited to treating large cancerous regions, especially those located near the edge of the body, because their energy deposition is spread out
- Ions have a much narrower stopping region, known as the Bragg peak, and so are better suited for localized tumors
- Charged particles can be generate from within, e.g. via Boron Neutron Capture Therapy (BNCT), where tumors are boron doped and the patient is placed near a large neutron source, leading to $^{10}B(n,\alpha)$, or by implanting a radioactive source with low energy decay products



U. Amaldi, Asimmetrie (April 2008)

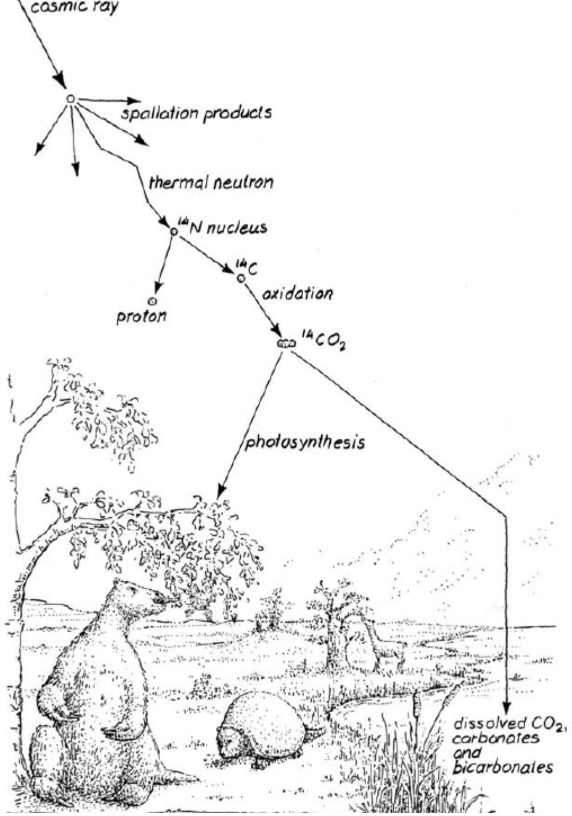


Barth, Soloway, & Fairchild, Sci.Am. (1990)

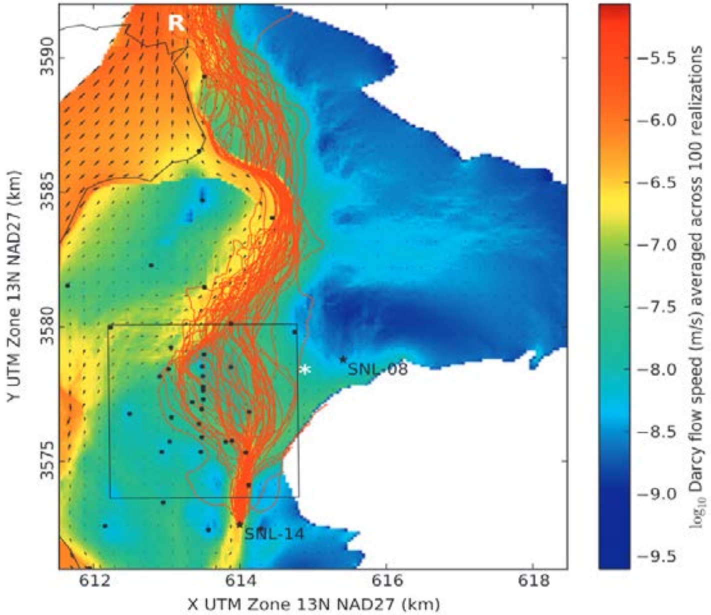
Dating with Radionuclides

- Cosmogenic isotopes are particularly useful for dating terrestrial objects
- Cosmic rays generate an equilibrium abundance of radioactive nuclides in the Earth’s atmosphere and on the Earth’s surface
- Departures from the equilibrium abundance correspond to the loss from radioactive decay, enabling objects to be dated
- As we noted in the Radioactive Decay lecture, isotopic ratios are generally employed to remove the complication of determining absolute abundances

R. Taylor, Am. Sci. (2000)

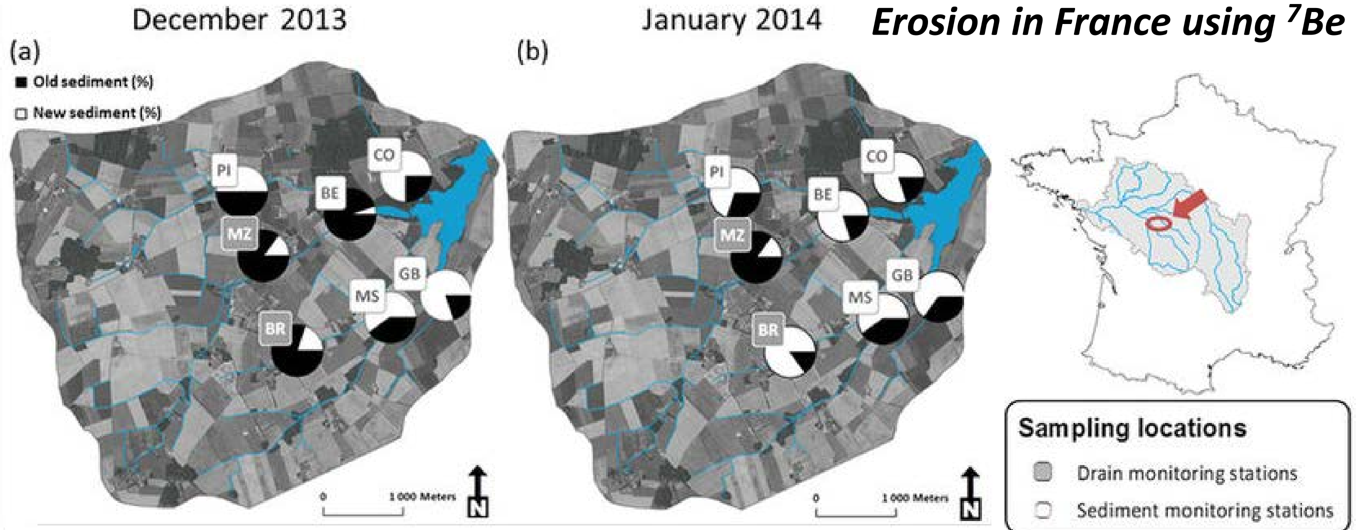


Water flow near WIPP using ^{81}Kr/K



N. Sturchio et al. J. Contam. Hydrol. (2014)

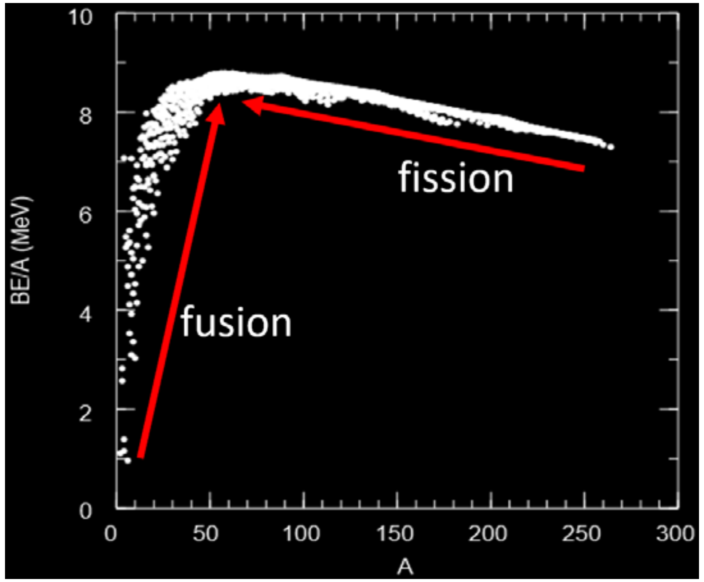
Erosion in France using ^{7}Be



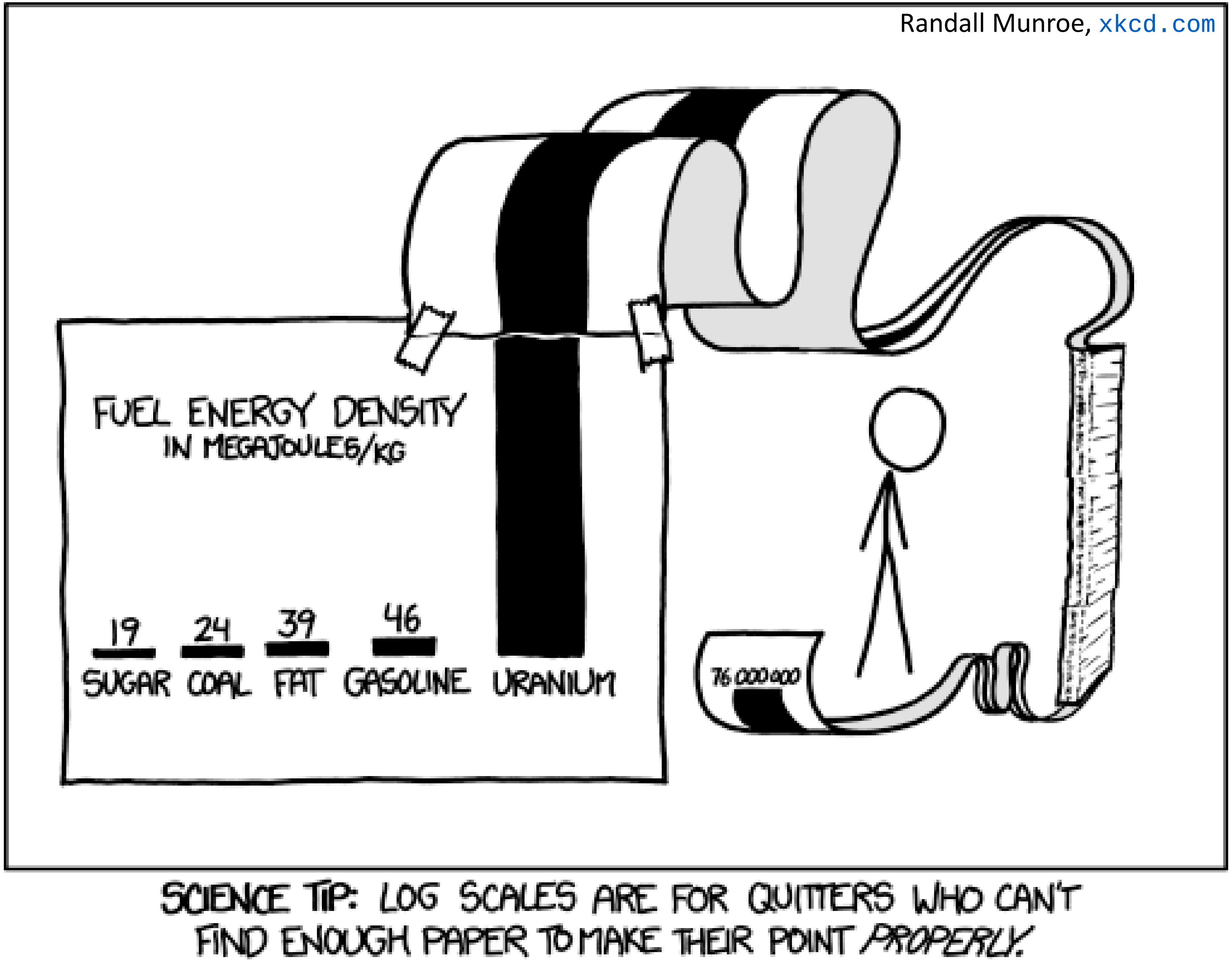
Le Gall et al. Sci. Rep. (2017)

Nuclear Energy

- In terms of energy sources, nuclei are far and away as good as it gets
- Options to liberate that energy are fusion, which pays out a ton of energy but is hard to do, or fission which is easier but messier

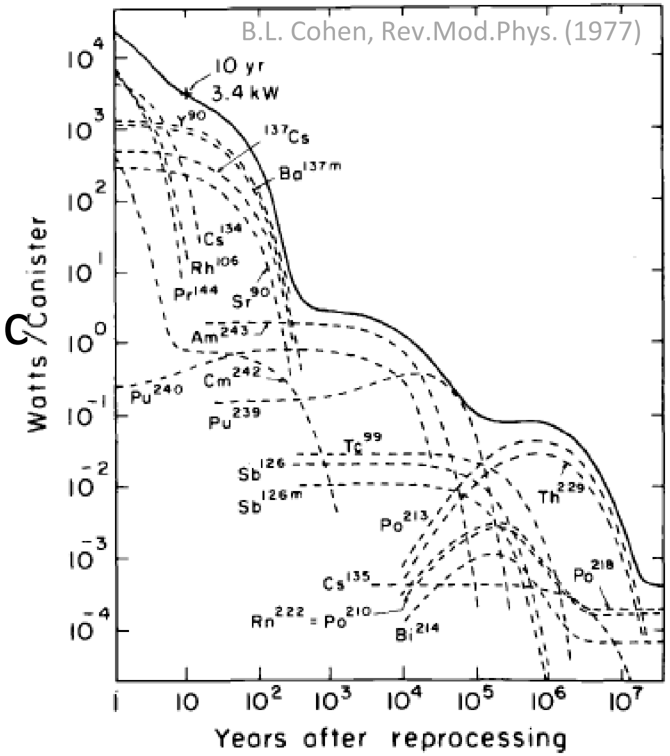


Randall Munroe, xkcd.com

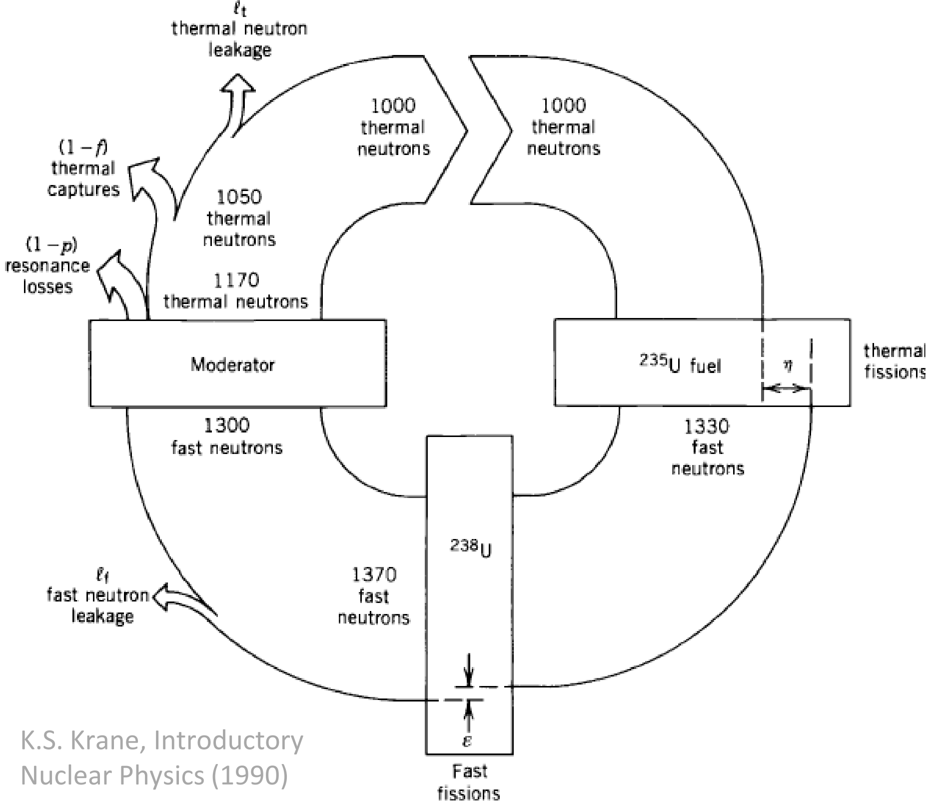


Nuclear Energy *by fission*

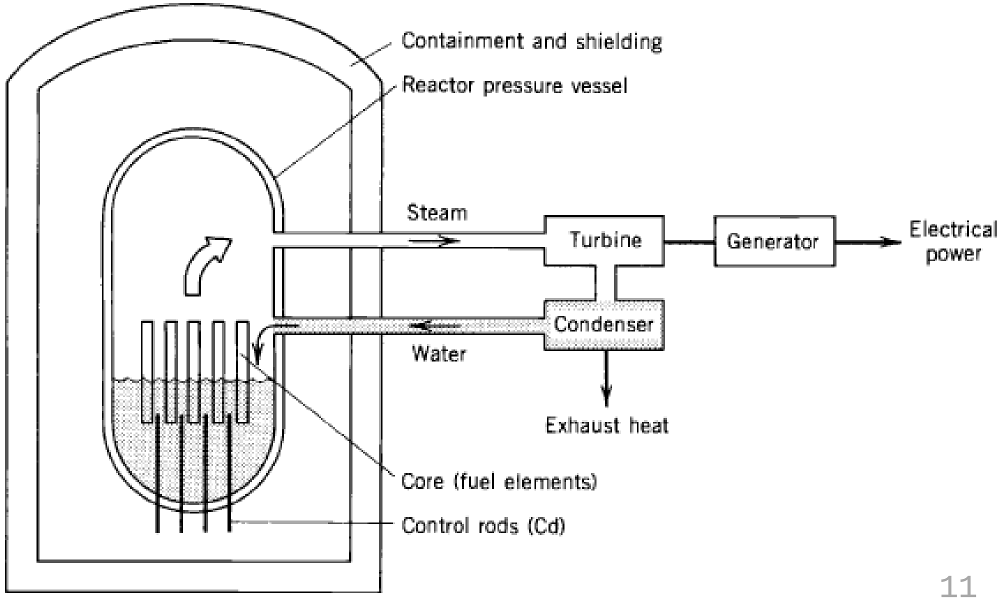
- If a sustained chain of fission reactions can be achieved (i.e. just the right number of neutrons from a fission event initiating new fissions) then the heat from these events can be collected, e.g. via steam from boiled water, for a reliable power source
- The trick is to wind up with one captured thermal neutron for every fast neutron generated. This is quantified by the neutron multiplication factor k, number of neutrons per a fission event which goes on to cause another fission ($k = 1$ is "critical")
- An on-line tool is moderation modification as needed with control rods
- Fission reactors are problematic because they involve fissile material (useful for weapons) and they generate a lot of extra stuff (though some of that stuff can be separated later, e.g. for medical isotopes)



B.L. Cohen, Rev.Mod.Phys. (1977)



K.S. Krane, Introductory Nuclear Physics (1990)



Nuclear Energy *by fission: simple estimate of criticality*

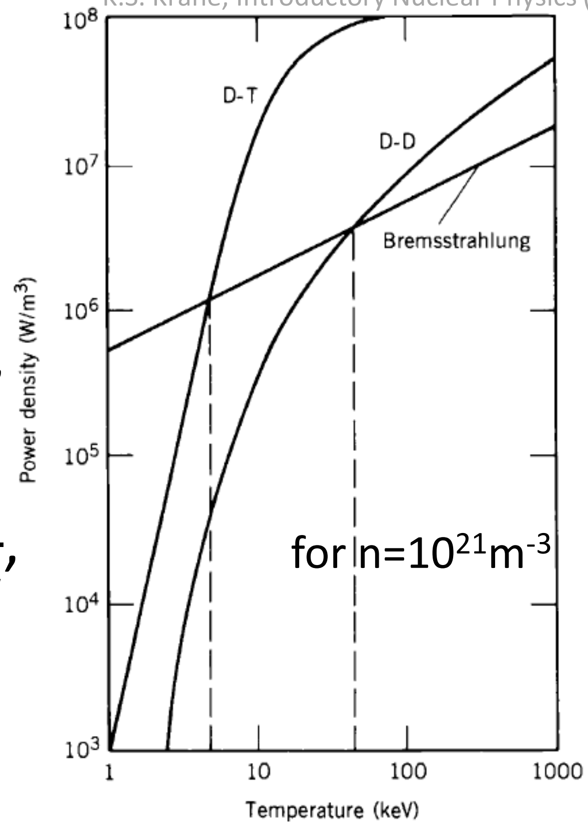
- The critical radius for a sphere of fissile material can be estimated by equating the neutron production rate from fission P_N and the neutron loss rate through the sphere's boundary L_N
- P_N is the product of the number of neutrons in the sphere $n_n V$ and the number of neutrons produced per fission ν, divided by the time between fission events (corrected for the loss of 1 neutron captured)
  - $P_N = n_n V \frac{\nu-1}{\tau} = n_n \frac{4}{3}\pi R^3 \frac{\nu-1}{\tau}$
    - The neutron mean-free path between fissions is $\lambda_f = \frac{1}{n\sigma_{n,f}}$, where n is the number density of the fissile nuclei and $\sigma_{n,f}$ is that fuel's fission cross section for a typical neutron energy
    - Taking a typical neutron energy from fission as $\sim MeV$, it turns out the typical time between fissions will be $\tau_f \approx \frac{\lambda_f}{v} \sim 10^{-8}$s, where v is the average neutron energy
- L_N can be estimated as the number of neutrons within λ_f of R, which will escape in time τ_f
  - $L_N = \left[\frac{4}{3}\pi R^3 - \frac{4}{3}\pi(R-\lambda_f)^3\right] n_n v \approx 4\pi R^2 \lambda_f$
- $P_N = L_N$ leads to the result that $R_{critical} = \frac{3}{\nu-1}\lambda_f$
- For ^{235}U: $E_n \sim 5MeV$, $\sigma_{n,f}(E_n) \sim 1b$, $\nu \sim 3$, $n \sim 10^{23} cm^{-3}$: $R_c \sim 15cm$, i.e. $M_{sphere} \sim 270kg$

The actual value determined with Monte Carlo (and verified empirically) is $M_c(^{235}U) \approx 52kg$. Because of similar ν and λ, all fissile nuclei with appreciable $\sigma_{n,f}$ require this order of mass.

Nuclear Energy *by fusion*

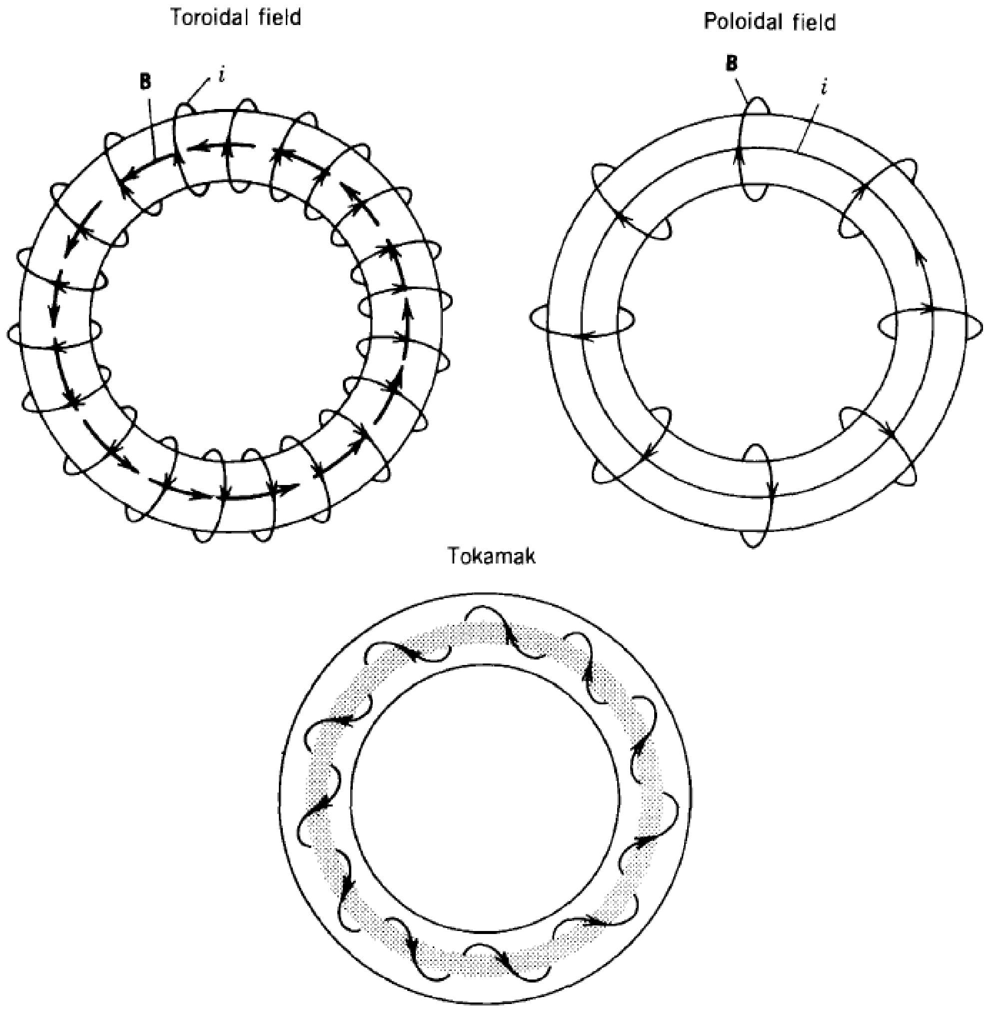
- Fusion has the advantage of liberating far more energy per reaction and producing much shorter-lived by-products ..but an energy debt has to be paid to overcome the Coulomb barrier
- The temperatures achieved while fusing light nuclei is on the order of 10^8K, so any sustained fusion reactor requires sustaining and confining a plasma
- Plasma confinement can either be achieved with magnetic fields or with inertia (i.e. rapidly compressing a pellet of material)
- To keep a manageable Coulomb barrier and limit bremsstrahlung losses, the fuel of choice is deuterium+tritium [d(t,n)α]
- A net energy gain is achieved if the nuclear energy release $\epsilon_{12} = Q_{12} r_{12} = Q_{12} n_1 n_2 \langle\sigma v\rangle_{12}$ exceeds the thermal energy $E = \frac{3}{2} k_B T$, where the energy is generated over some time τ
- Declaring $n_D = n_T \equiv \frac{1}{2} n$ results in the Lawson criterion: $n\tau > \frac{12 k_B T}{\langle\sigma v\rangle_{DT} Q_{DT}}$, ….so for $k_B T = 10keV, n\tau > 10^{20} \frac{s}{m^3}$ **nobody has achieved this yet*
- From these reactions the α's will deposit their heat in the plasma, while the neutrons will escape (and be captured to generate heat)

K.S. Krane, Introductory Nuclear Physics (1990)



Nuclear Energy *by magnetic confinement fusion*

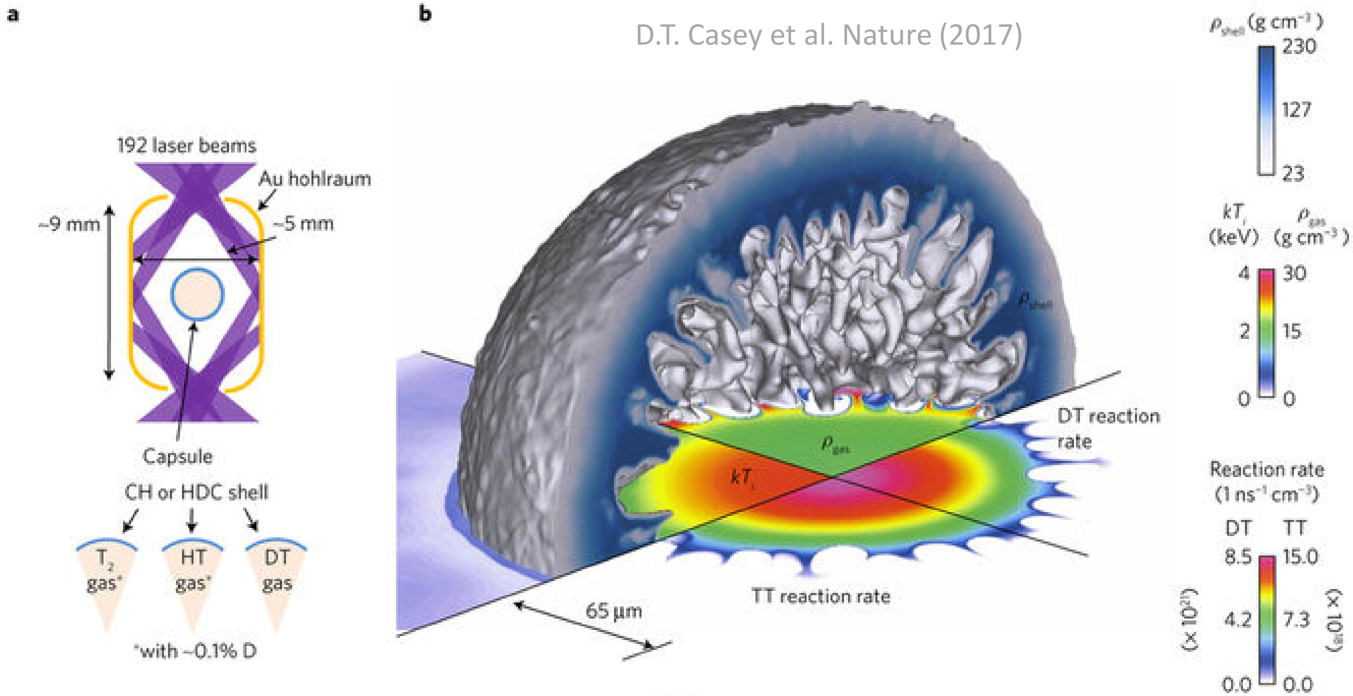
- Magnetic confinement of a plasma requires an interesting combination of magnetic fields that results in a design known as a Tokamak (from a Russian acronym)
- Heat must be pumped in via a neutral beam of some sort and/or an external radiofrequency source
- Practically speaking, such a device requires operation at temperatures of ~0.1GK in fields >10T producing neutrons at a rate of $>10^{19}$Hz
  …which is completely absurd
- This is the approach adopted by ITER, an international collaboration that began in 1988 and is forecasted to turn-on in 2035 …and is just a proof of concept



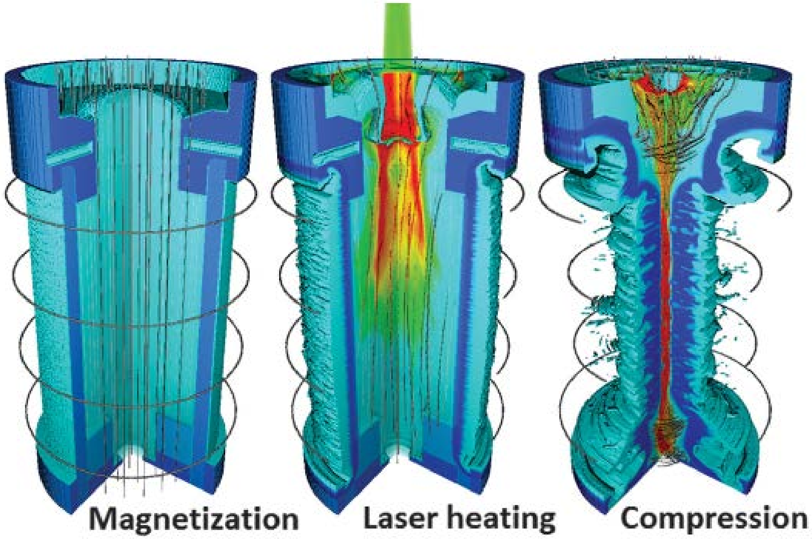
K.S. Krane, Introductory Nuclear Physics (1990)

Nuclear Energy *by inertial confinement fusion*

- Inertial confinement fusion is based on the concept of rapidly compressing a pellet of deuterium and tritium to momentarily achieve fusion
- One way to do this is by blasting the pellet with a lot of laser light either directly or reflected from reflective housing (to uniformly heat the pellet).
  This is the strategy of NIF and OMEGA.
- Another approach is to discharge massive capacitors to drive a large current through a plasma, which then will compress due to the Lorentz force via a phenomenon known as a Z pinch.
  This is the strategy of Sandia’s Z Machine.



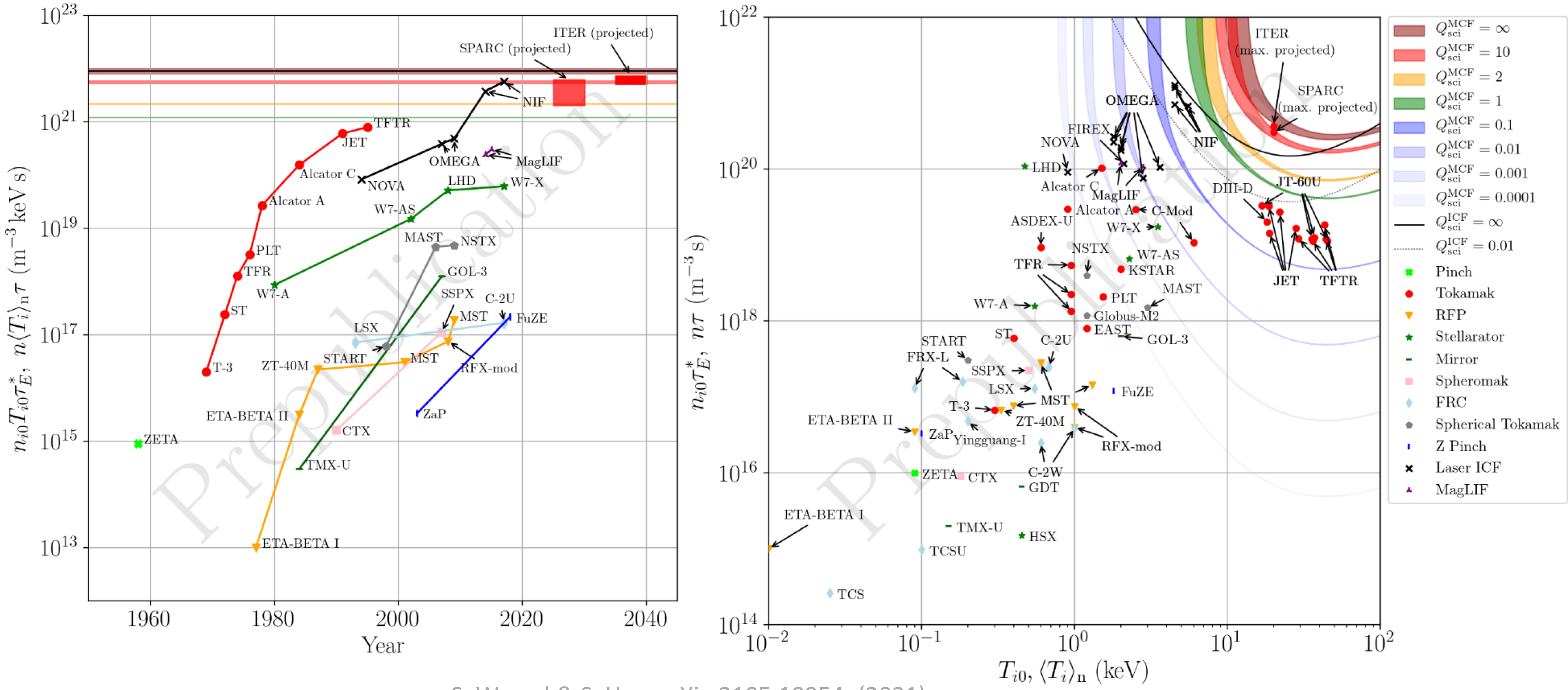
D.T. Casey et al. Nature (2017)



M.R. Gomez et al. PRL (2014)

Achieved Fusion Energy Gain Q=(Energy Out)/(Energy In)

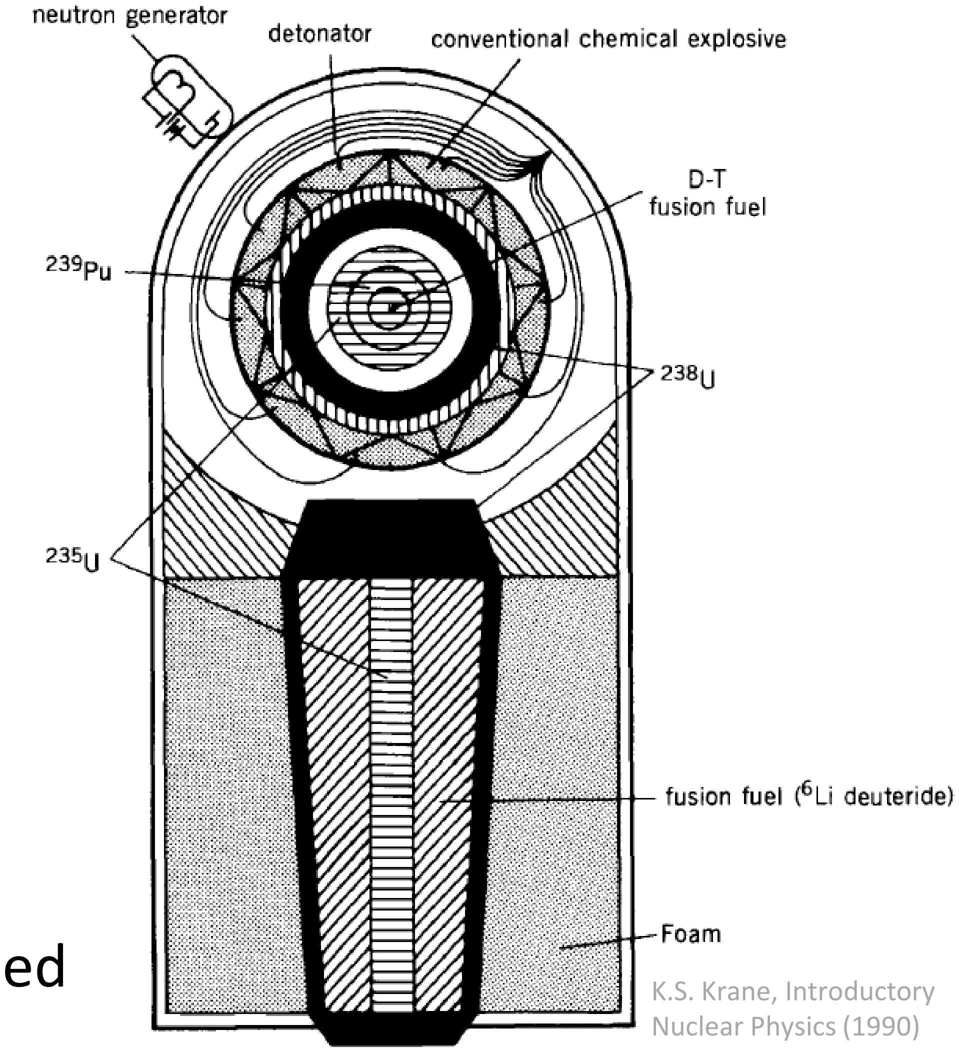
status as of Fall 2021



S. Wurzel & S. Hsu, arXiv:2105.10954 (2021)

Nuclear Weapons: *Warheads*

- The nuclear reactor concept is to have a nice slow burn that is controllable and outputs energy at a rate that can be easily used and stored …but what if we burn all the fuel as fast as possible?
- The favored approach to this problem is to use conventional explosives to rapidly combine two pieces of sub-critical fissile material so that they become supercritical and a chain reaction ensues.
  Once the chain reaction ensues, it becomes hot enough to initiate fusion of deuterium+tritium fuel located nearby, boosting the chain reaction (with neutrons from d(t,n)α)
  and also releasing a large amount of energy in its own right
  (^{6}Li provides a local fuel creation via ^{6}Li(n,t)α)
- A major design challenge is to ensure the material goes supercritical when you want it to and not before.
  Thus materials with large (α,n) cross sections need to be minimized (also implying (α,n) cross sections on stable nuclei should be well known)
- The amount of fuel required to go supercritical can be reduced from our previous estimate by surrounding the fuel with "tamping" material that reflects neutrons and helps contain the explosion

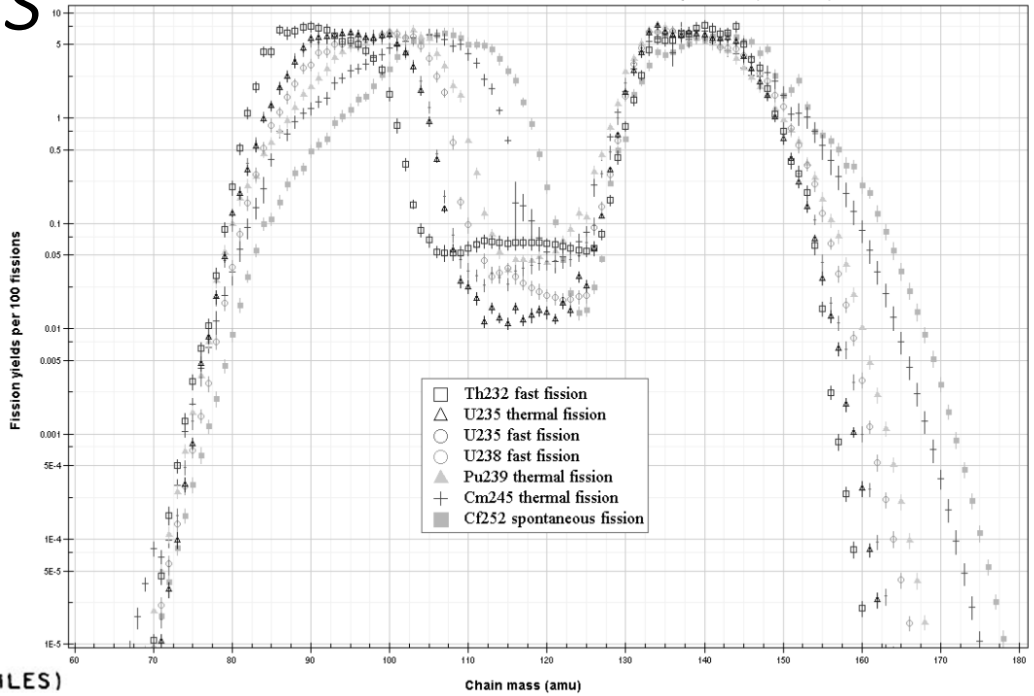


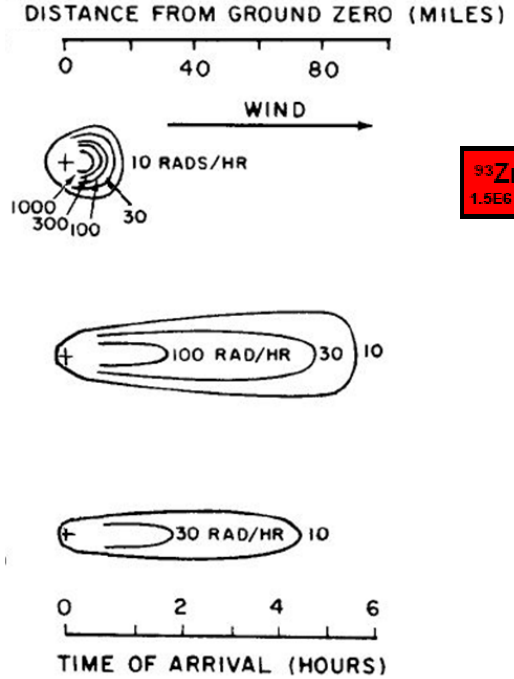
K.S. Krane, Introductory Nuclear Physics (1990)

Nuclear Weapons: *Abundance Yields*

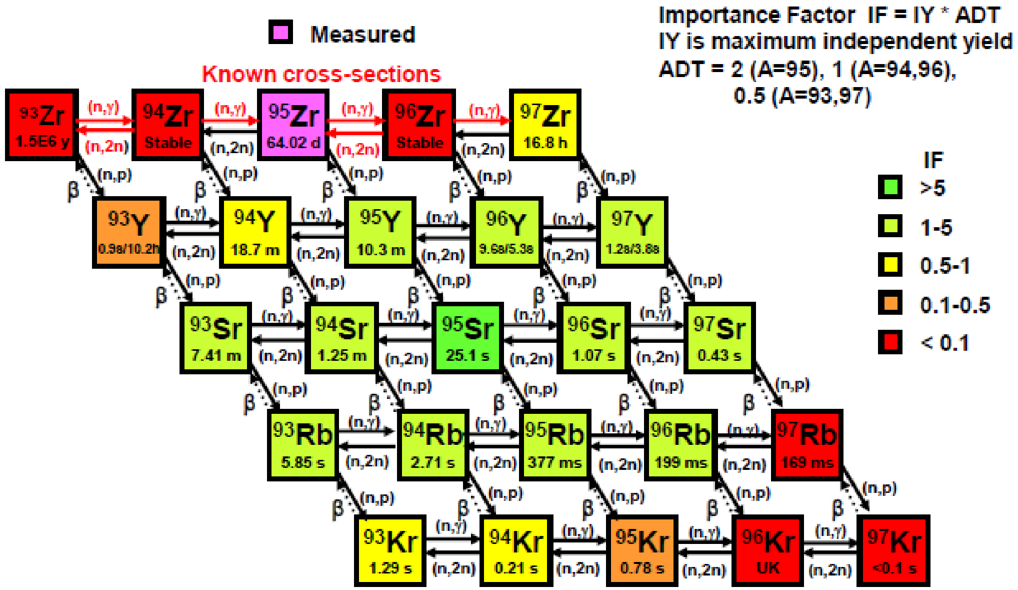
- The isotopic abundance distribution of nuclei produced in a nuclear weapon detonation will depend on the fissile material (e.g. ^{235}U vs ^{239}Pu vs some mixture) and the presence of additional fast neutrons (from D+T fusion)
- Weapons forensics aims to use this information to determine the content and quality of a weapon
- To do this well, one needs precise fission fragment distributions (both mass and charge), as well as precise neutron-capture cross sections an β-delayed neutron emission probabilities for nuclei produced in large abundances in the fission process (these are also goals for *r*-process studies)
- Fall-out radiation is mostly only a concern for the local area, however biologically concentrated isotopes (like iodine in the thyroid) increase the problematic range

Kellett, Bersillon, & Mills, JEFF Rep. 20 (2009)





Glasstone & Dolan, *The Effects of Nuclear Weapons* (1977)

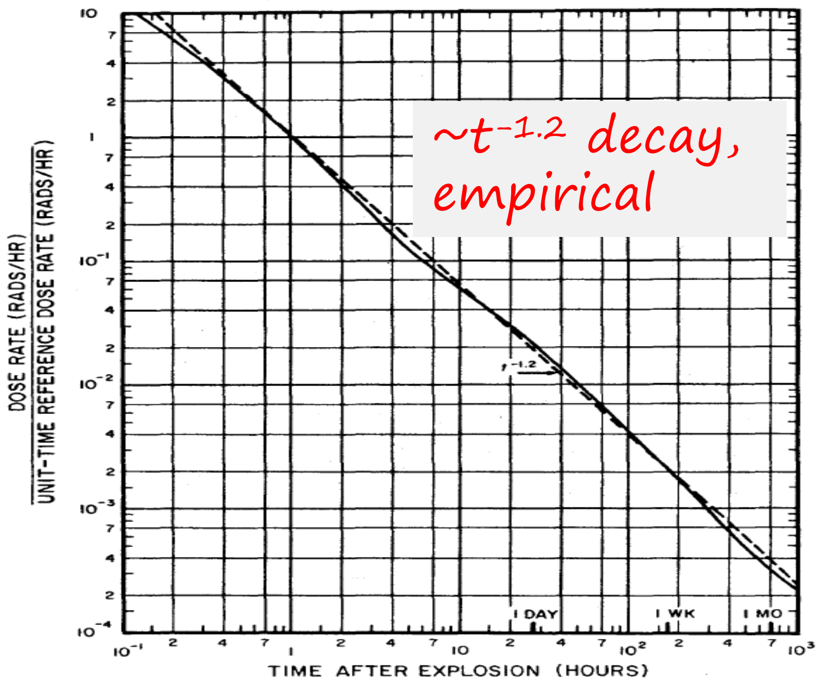


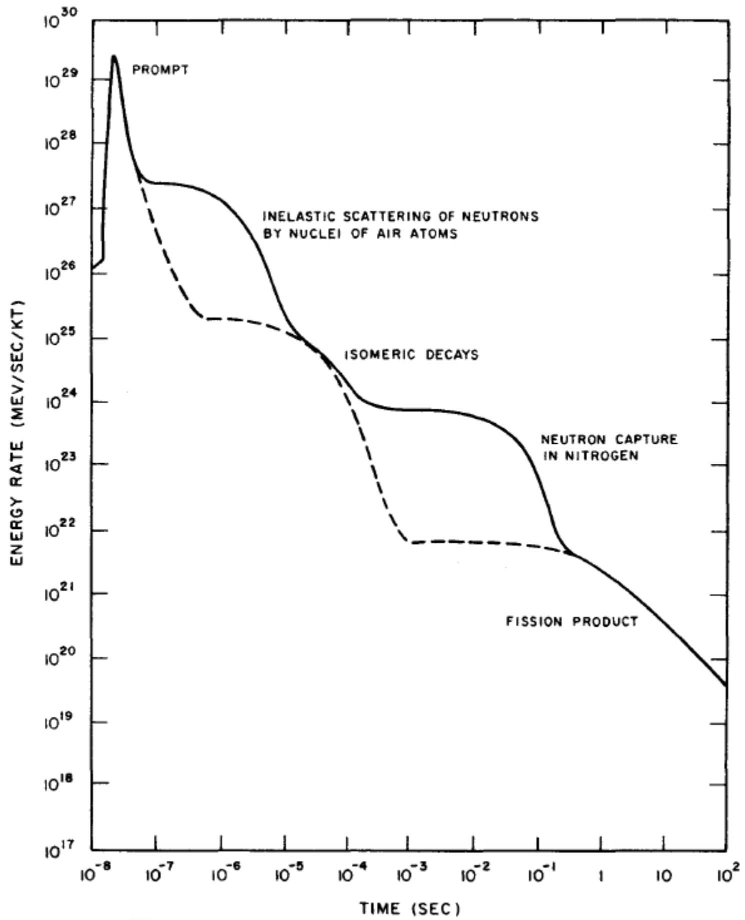
NSAC Long Range Plan (2015)

Nuclear Weapons: *Damage*

- Prompt:
  - Gammas & neutrons, which are very penetrating
  - Cut dose in half by being in a basement
  - Cut dose by x100 to x1000 by being 3ft underground

- Delayed:
  - Gammas & betas from fission products
  - Mostly rained down from atmosphere after being kicked up there in the fireball, “fallout”.
  - Obviously much less fallout if the detonation occurs in the atmosphere





Glasstone & Dolan, *The Effects of Nuclear Weapons* (1977)

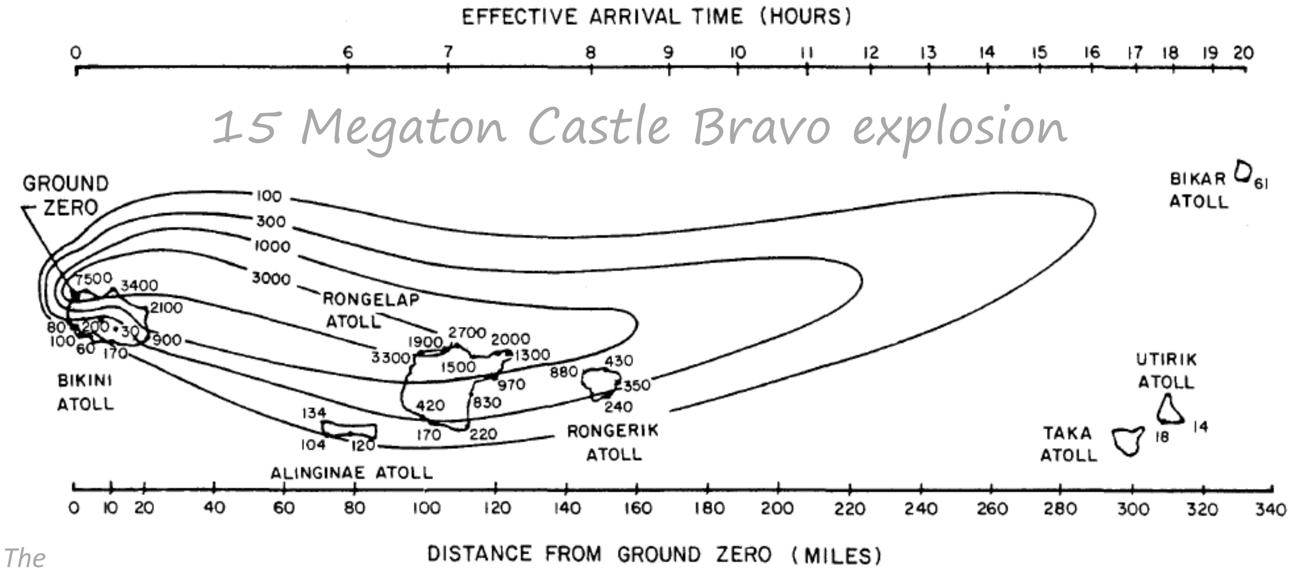
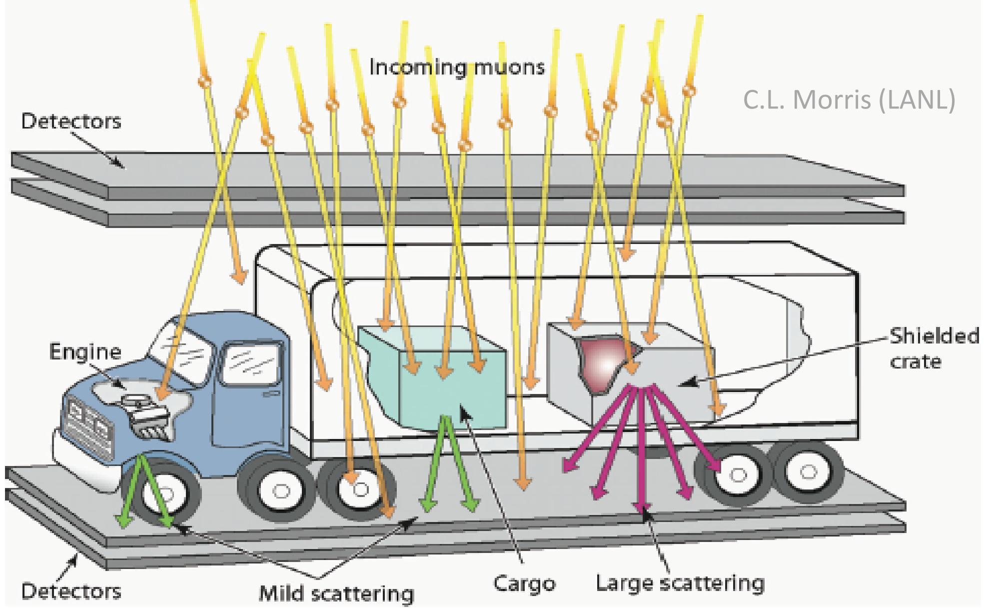


Figure 9.105. Estimated total (accumulated) dose contours in rads at 96 hours after the BRAVO test explosion.

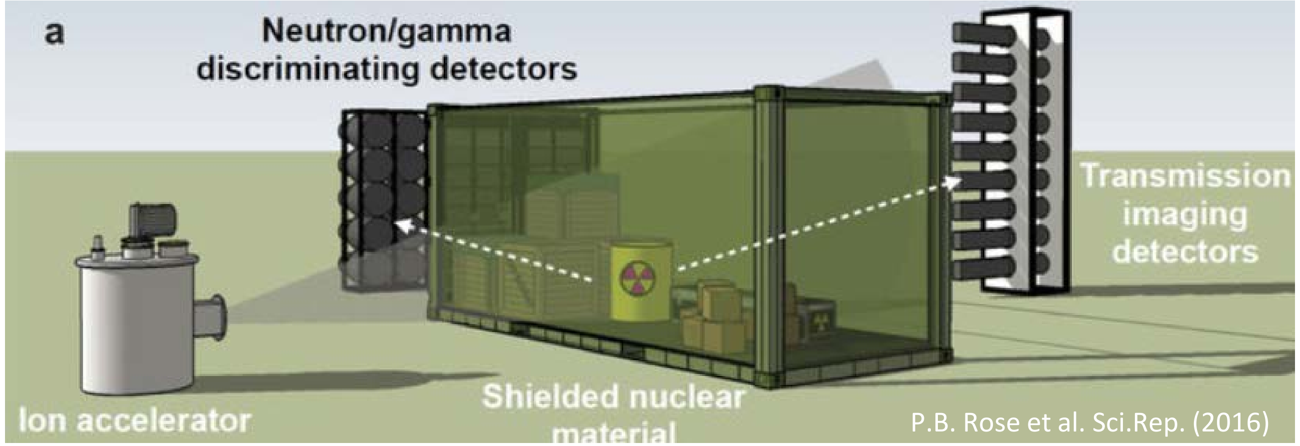
Defense

- Nuclear defense is generally divided into detecting fissile material to prevent it going where it shouldn't and detecting and analyzing yields from weapons tests
- A global monitoring network, set-up as a part of the Comprehensive Test Ban Treaty, constantly samples the air for radioactive fall-out from weapons tests (looking at noble gases for underground tests)
- Major ports (an probably a lot of other areas) use various techniques to search for fissile material, mainly relying on fissile material's radiation (natural or induced) and high density

https://www.youtube.com/watch?v=HDyU6nsUJqA



C.L. Morris (LANL)



P.B. Rose et al. Sci.Rep. (2016)

...of course most of this becomes useless if a pure fusion weapon is developed!

Many more applications exist…

- Magnetic resonance imaging (MRI)
- Active interrogation of potentially fissile materials with neutron and γ beams
- Interrogation of rock using γ-emitting sources for oil & gas exploration
- Doping of semiconductors using ion implantation
- Tracking of items and personnel with radiotracers for covert operations
- Material thickness monitoring using energy loss (typically of X-rays)
- Weld checking using radiotracers
- Power from radioactive decay for devices on satellites
- Smoke detection by monitoring for absorption of α's from an unstable isotope
- + probably many more I've forgotten about or am unaware of

Further Reading

- Chapters 13,14,16: Modern Nuclear Chemistry (Loveland, Morrissey, & Seaborg)
- Chapters 13 & 14: Introductory Nuclear Physics (K.S. Krane)
- Radiation Detection & Measurement (G.F. Knoll)
- Lecture Notes, Euroschool on Exotic Beams
- "Applications of Nuclear Physics", A.C. Hayes, Rep.Prog.Phys. (2017)