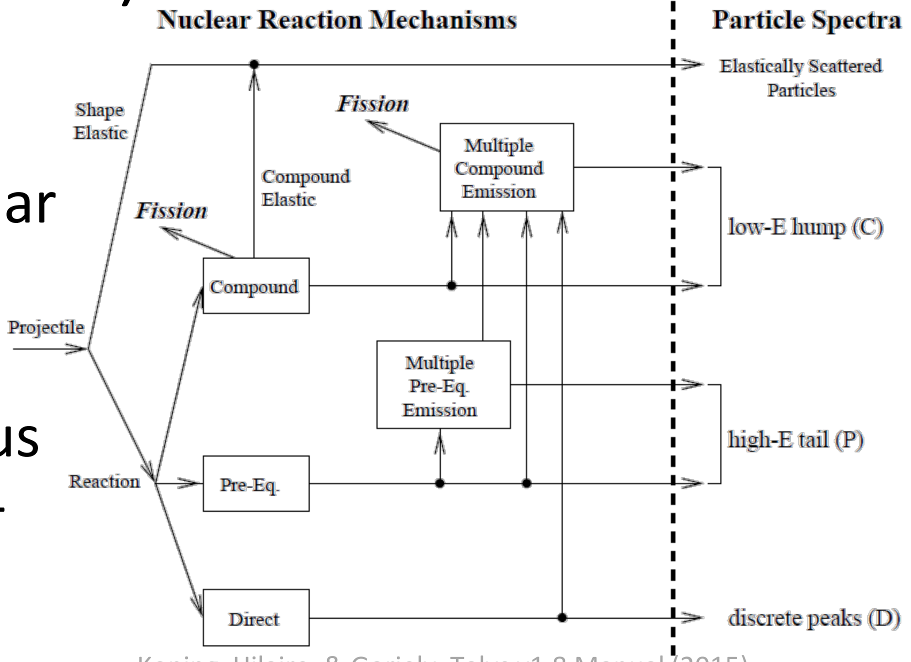
Lecture 19: Other Reactions

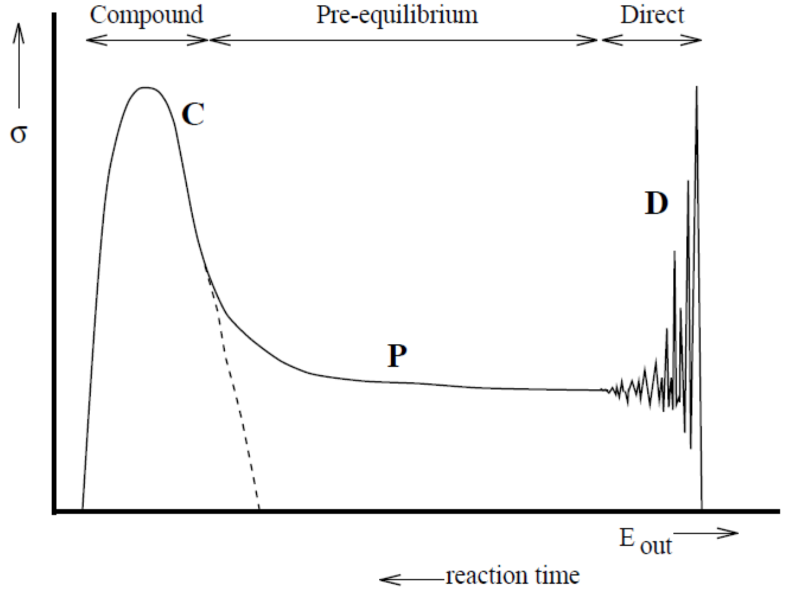
- Preequilibrium
- Photonuclear
- Coulomb excitation/dissociation
- Charge exchange
- Surrogate method
- Radioactive isotope production

Pre-equilibrium (a.k.a Incomplete Fusion) Reactions

- For relatively high projectile energies, we saw that the direct reaction mechanism typically dominates
- For the direct case, the ejectiles typically have momenta similar to the projectile and such reactions (e.g. (d,p)) tend to populate discrete states of the residual nucleus
- For relatively low energies, we found that a compound nucleus is formed and it "cools" by evaporating ejectiles in a Maxwell-Boltzmann-like energy distribution (at really low energies, discrete compound nuclear states might be populated in a resonant reaction, leading to discrete ejectile energies)
- But surely there must be a transition between direct and compound!
- This in-between region is described by the "pre-equilibrium" reaction mechanism, which gets the name because the projectile and target haven't quite fused to reach an equilibrium state as a compound nucleus
- As such, ejectiles form a high-E tail on the evaporation spectrum

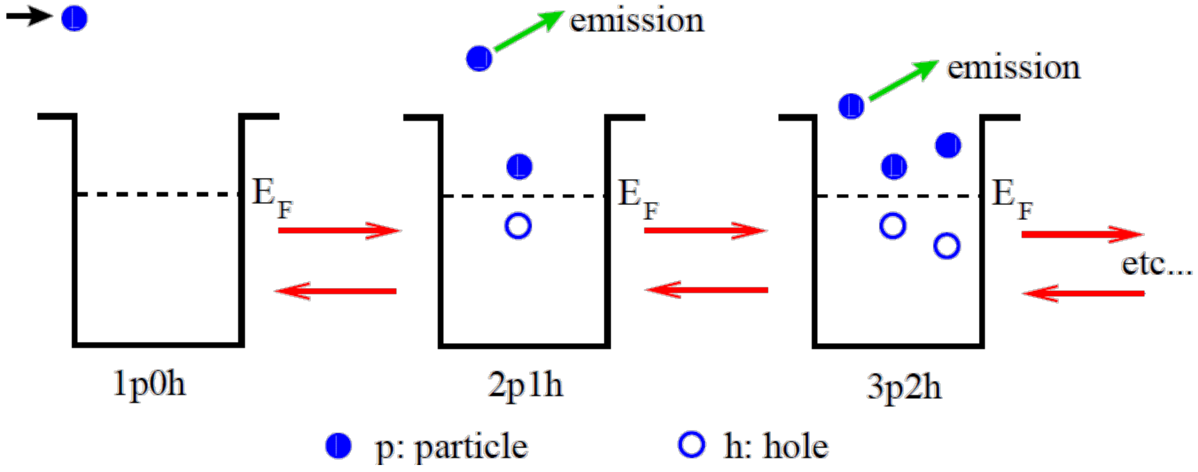


Koning, Hilaire, & Goriely, Talys v1.8 Manual (2015)



Pre-equilibrium (a.k.a Incomplete Fusion) Reactions

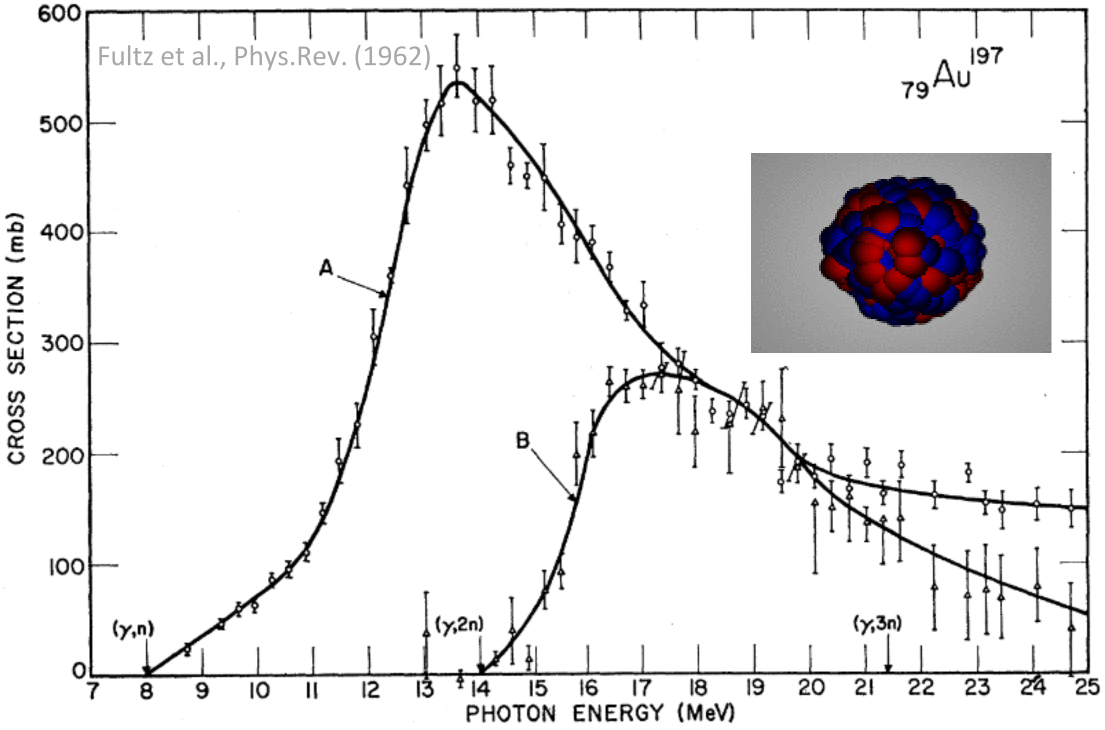
- Roughly speaking, pre-equilibrium becomes important in the low tens of MeV per nucleon, where the continuum is being populated in the compound nucleus
- One way to model pre-equilibrium is the Exciton Model: The projectile deposits energy as it plows through the target, promoting nucleons above the Fermi energy and creating holes below. This has to sound fancy, so a particle or a hole is referred to as an exciton.
- Typically new particle-hole pairs are formed as the projectile deposits energy, but the particle-hole pairs can be annihilated as well
- If the number of excitons approaches the number of nucleons in the compound nucleus, then we just have the statistical model



Koning, Hilaire, & Goriely, Talys v1.8 Manual (2015)

- Classical or quantum descriptions can be used to calculate the likelihood of one nucleon or cluster having a large enough share of the energy to be emitted to the continuum, as well as for creating new excitons
- In the classical case, nucleon scattering cross sections can be used to get such estimates

Photonuclear reactions


Fultz et al., Phys.Rev. (1962)

- Photons are an alternative probe for studying nuclei which provide complementary and often unique information on nuclei and nuclear reactions
- A famous example is the evidence for the Giant Dipole Resonance (GDR) we discussed way back when considering collective motion
- For the GDR, there is a broad resonance in the (γ, xn)
- That the position of the peak scales as $A^{-1/6}$, which you'll recall is $\propto 1/R^2$, is part of the evidence that this resonance corresponds to a giant oscillation of neutrons vs protons, which will alter the area of the nuclear surface
- Since transmission coefficients describe the probability for a particle or photon going into or out of the nucleus, the Lorentzian-like shape of the GDR provides the functional form for the gamma-strength function (as we saw back when discussing gamma-decay)

Photonuclear reactions

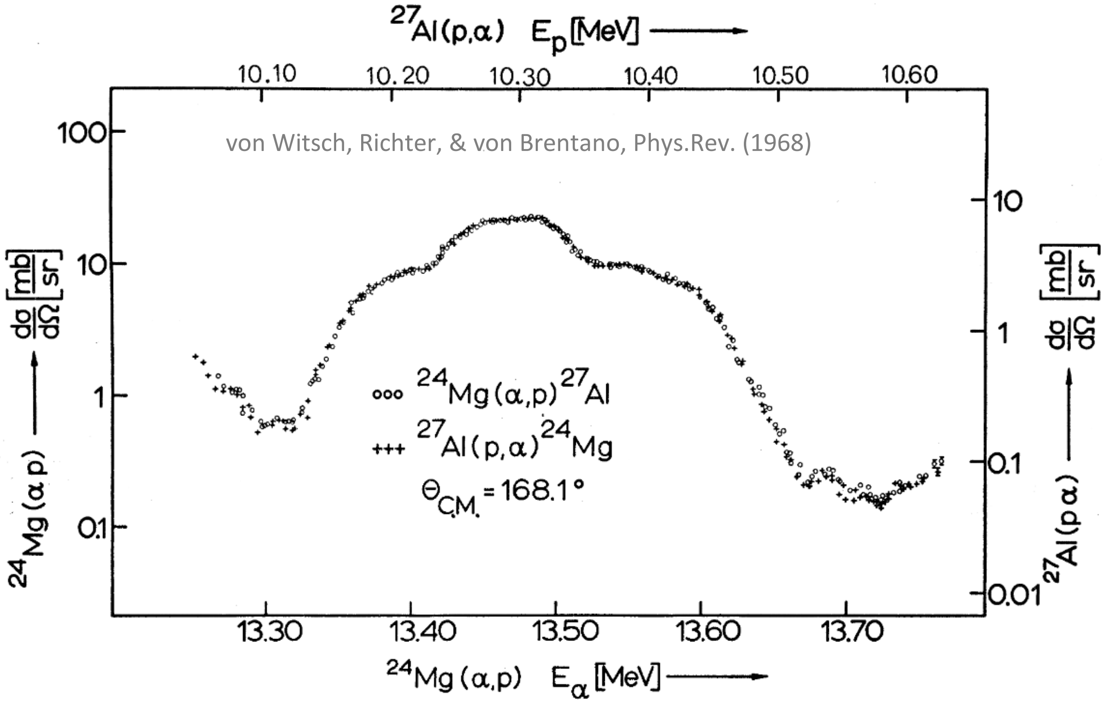
- For low-energy radiative capture reactions, sometimes the experimentally achievable yield is higher for the reverse process (and/or there's much less background)
- The probability for going from one *state* to another *state* is related to the reverse process via the ***reciprocity theorem***:

2 for a photon, since, in terms of a photon, the 2J+1 statistical factor corresponds to the polarization directions

- E.g. For $X(a,\gamma)Y$

$$(2J_a+1)(2J_X+1)\left(\frac{2\pi}{\lambda_{a,\gamma}}\right)^2\sigma_{a,\gamma} = (2J_\gamma+1)(2J_Y+1)\left(\frac{2\pi}{\lambda_{\gamma,a}}\right)^2\sigma_{\gamma.a}$$

- Since photons don't interact very strongly, an advantage of photonuclear measurements is that extremely thick targets can be used (e.g. ~g/cm^2 as opposed to mg/cm^2)
- A disadvantage is that it's hard to make intense photon beams and new detection schemes are needed for the unusually thick targets (e.g. Bubble chambers [B.Digiovine et al. NIMA 2015])
- Production mechanisms include
  - In-flight e$^+$ annihilation, Bremsstrahlung, and Inverse Compton scattering of a laser off an electron beam (e.g. HIγS in North Carolina)

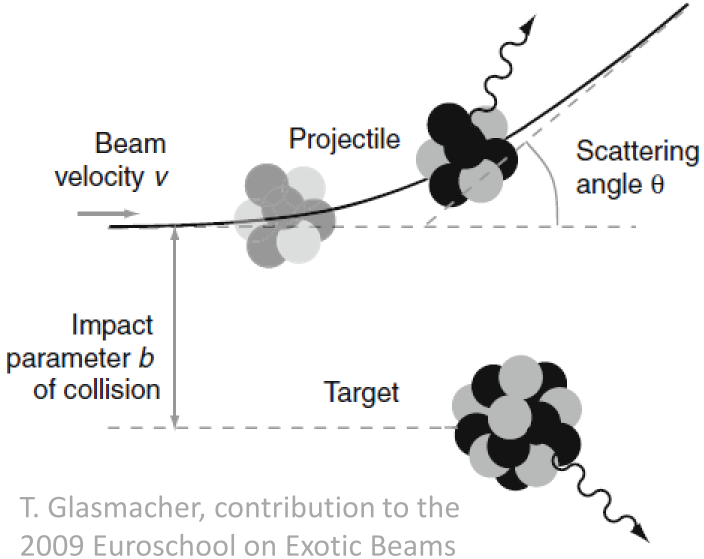


von Witsch, Richter, & von Brentano, Phys.Rev. (1968)

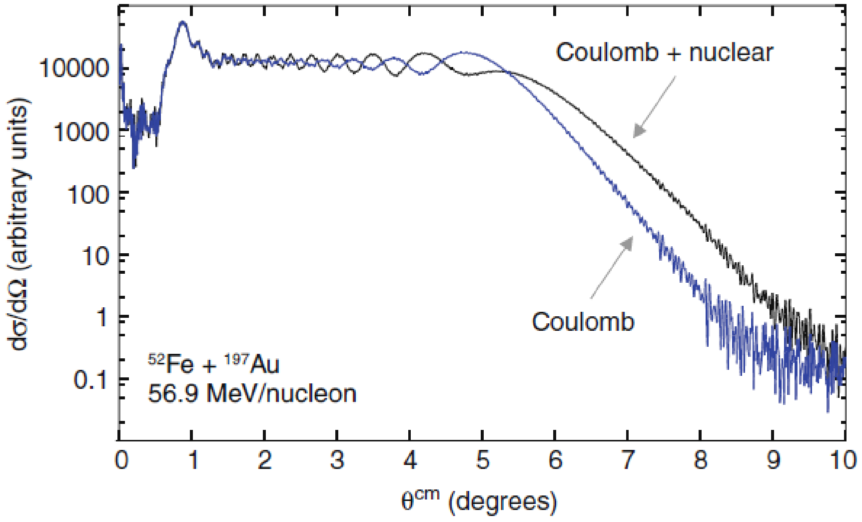
Coulomb Excitation

"Coulex", for people who want to feel cool

- Coulomb excitation is a process whereby the target and projectile nuclei interact only via their electromagnetic fields
- Exchange of virtual photons leads to excitations in the target and projectile, which promptly de-excite (typically via γ-decay)
- The fact that this is an electromagnetic interaction means that it occurs for high impact parameters and has a high cross section (making it an attractive candidate for spectroscopy with radioactive ion beams)
- To isolate Coulomb excitation relative to other reaction mechanisms, small recoil angles are chosen, which ensures the reaction took place at a high impact parameter
- The field strength scales with the charges involved, so e.g. for radioactive ion beam experiments a heavy target (typically lead) is employed
- By deducing the virtual photon flux, one can assess the transition rate between the ground-state and the state populated via Coulomb excitation (e.g. $B(E2)$)
- Virtual photon fluxes can either be obtained via the equivalent photon approximation (Weizsacker Z.Phys. (1934) & E.J. Williams, Phys.Rev (1934)) or via a semi-classical approach (Winther & Alder, Nuc.Phys.A (1979)) which relates the coulomb excitation cross section to the transition rate for photons of various multipoles



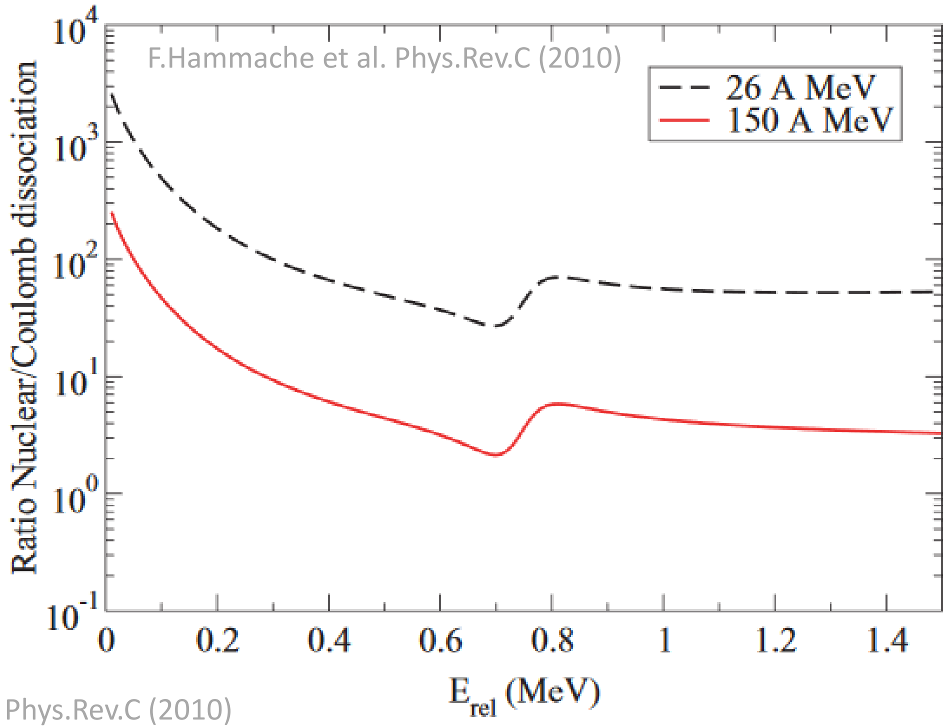
T. Glasmacher, contribution to the 2009 Euroschool on Exotic Beams



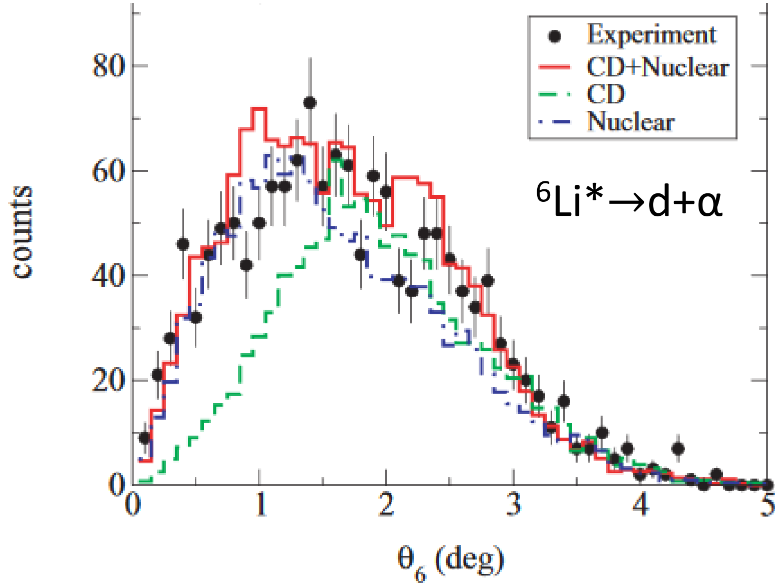
Coulomb Dissociation

Alas, "Couldis" isn't a name …yet!

- For a weakly bound system, you can see that a Coulomb excitation can excite the nucleus to an unbound state, resulting in the system breaking-up
- This is the reverse process for radiative capture that creates a weakly-bound system, and so Coulomb dissociation can be used to indirectly measure the forward rate of interest
- A serious challenge for this technique is that our old friend the direct nuclear reaction mechanism also leads to break-up …typically many times more than Coulomb dissociation does!
- Separating the two relies on the different angular distribution predicted for recoils produced by the different processes


F.Hammache et al. Phys.Rev.C (2010)

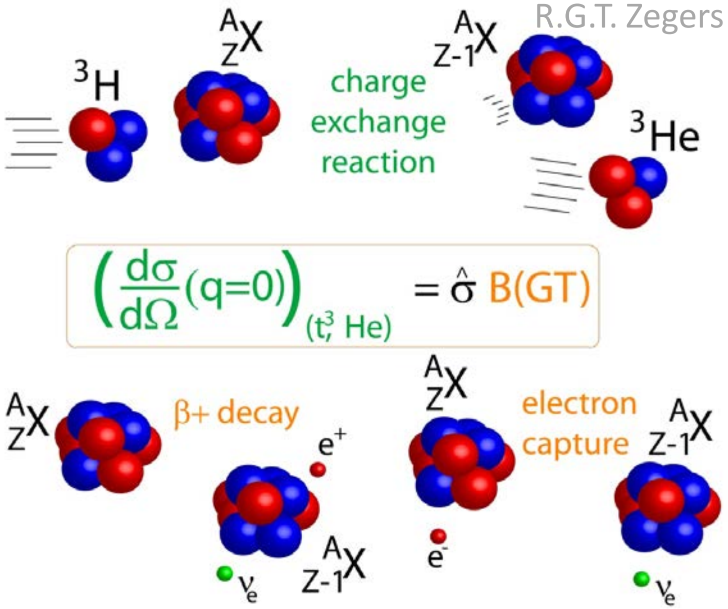
F.Hammache et al. Phys.Rev.C (2010)



Charge Exchange

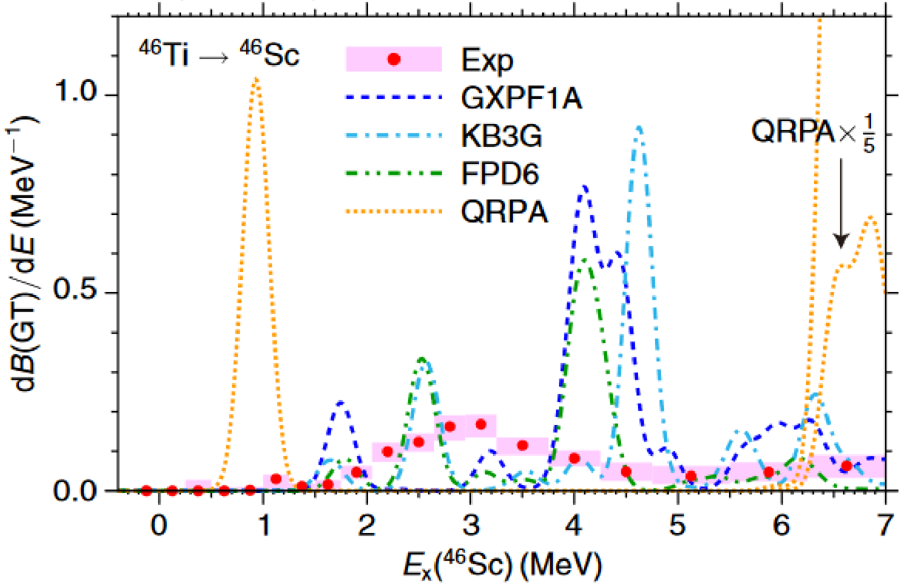
- Recall that in a direct reaction, it is possible for the projectile to pick-up and/or transfer one or a few nucleons to/from the target
- Consider the case where a single neutron of the projectile swaps places with a single proton of the target (or vice versa)
- If we measure this process for very small recoil angles and at rather large energies (~100MeV/u), then we're measuring the rate for a one-step transition of $p \rightarrow n$ (or $n \rightarrow p$)
- But that's just the weak transition strength $B(GT)$!
- …sort of, they're related by the "unit cross section" which one can calculate, but is usually calibrated to data (R.Zegers et al. Phys.Rev.C (2006))
- Wait a second, why do I want to use this rather than just measure the weak transition itself using β-decay?
- Because you can't always do that!
  In particular, electron-capture into excited states
  (important for core collapse supernovae and accreted neutron star crusts)
  can only be constrained this way and theoretical predictions are frankly not that great

R.G.T. Zegers



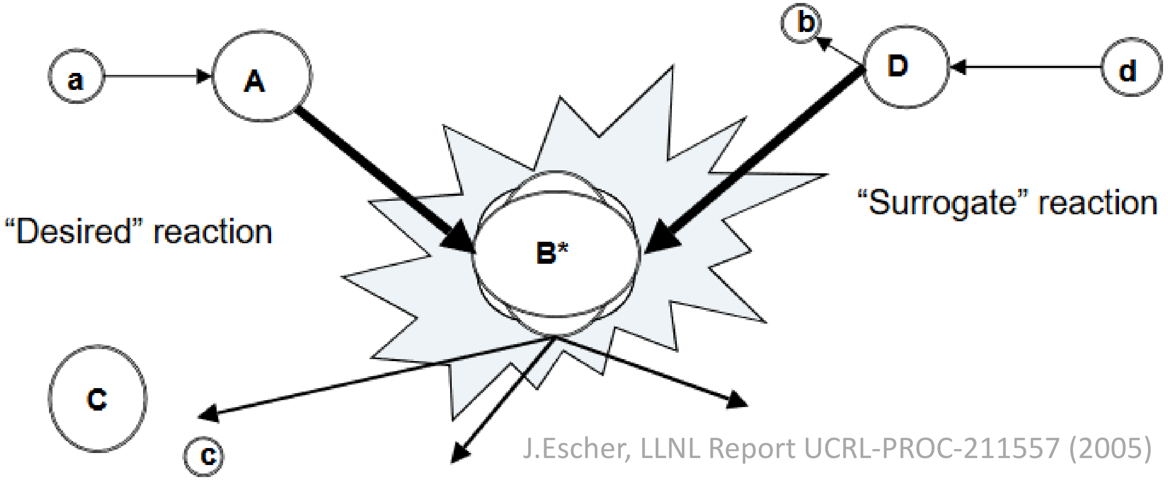
$$\left(\frac{d\sigma}{d\Omega}(q=0)\right)_{(t,{}^3He)} = \hat{\sigma}\, B(GT)$$

S.Noji et al. Phys.Rev.Lett (2014)

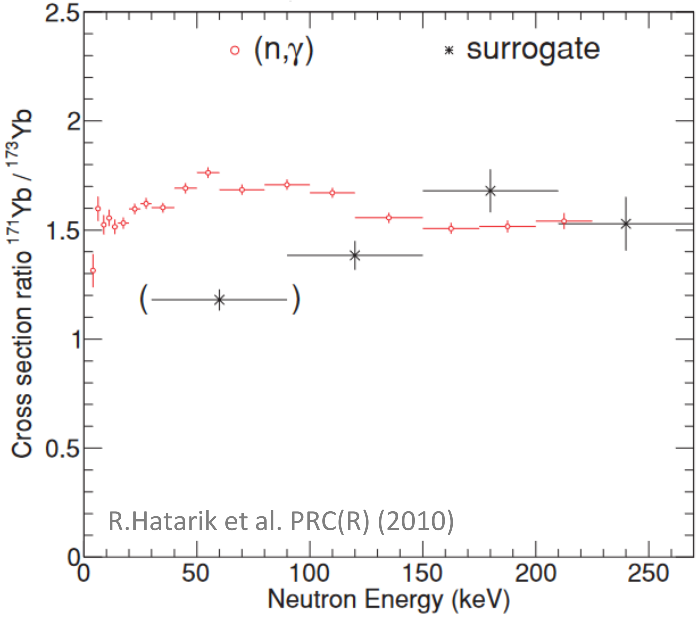


Surrogate method

- When a nucleon is captured by a target nucleus, what's the difference if that nucleon was originally a part of a nucleon group?
- This simple idea is the motivation for the surrogate method, where the compound nucleus of interest is formed using a different channel than the formation channel you're actually interested in (e.g. (d,pγ) instead of (n,γ))
- This method is particularly appealing for neutron-capture reactions on radioactive nuclei, since a neutron target doesn't exist as of yet
- Unfortunately, as you'll recall, the independence hypothesis doesn't exactly hold for statistical nuclear reactions and the entrance channel does matter
- In particular very different J^{π} are populated for e.g. (d,pγ) vs (n,γ)
- The difference can be accounted for using reaction theory, but accurate results require some more theoretical work



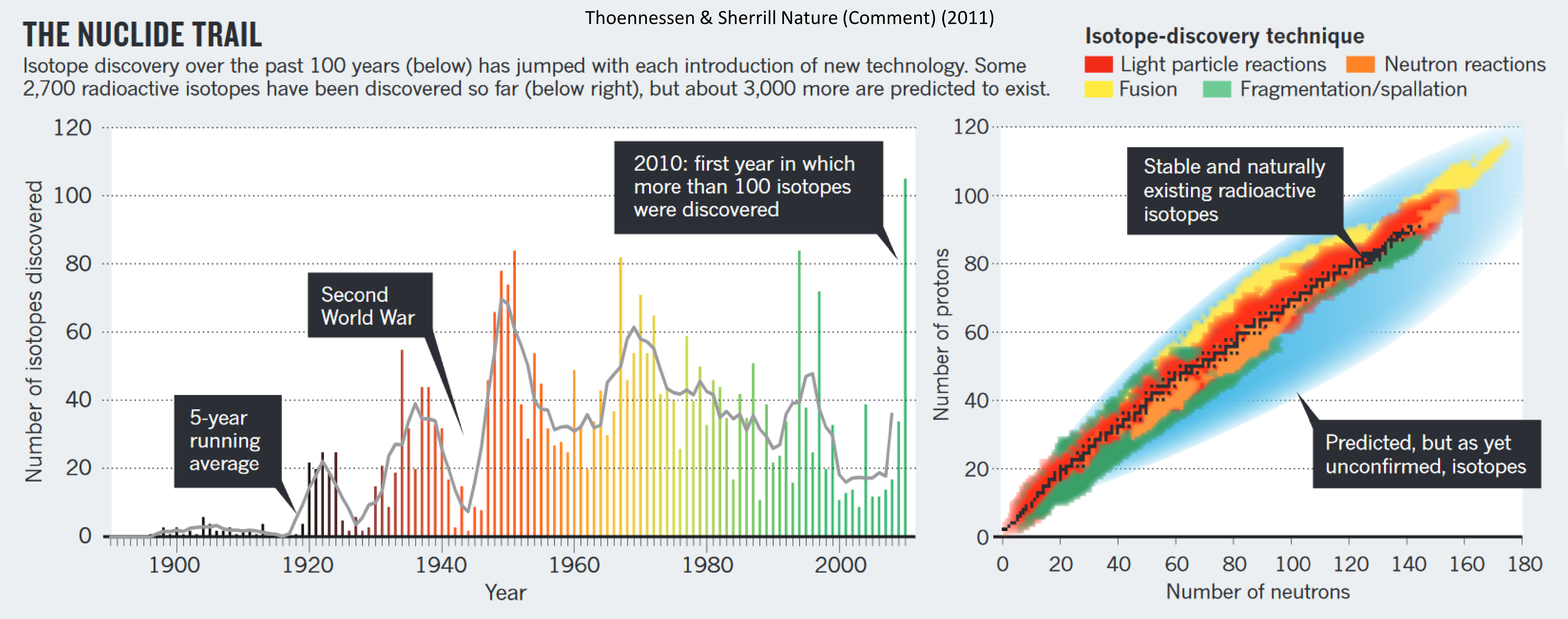
J.Escher, LLNL Report UCRL-PROC-211557 (2005)



R.Hatarik et al. PRC(R) (2010)

Radioactive isotope production

- Producing nuclei which are short-lived or not naturally very abundant has been done with many different techniques over the years
- Each of these either relies on fusing nuclei together, busting them apart, or some combination, where the chosen technique depends on feasibility and inherent strengths/weaknesses



Thoennessen & Sherrill Nature (Comment) (2011)

THE NUCLIDE TRAIL

Isotope discovery over the past 100 years (below) has jumped with each introduction of new technology. Some 2,700 radioactive isotopes have been discovered so far (below right), but about 3,000 more are predicted to exist.

5-year running average

Second World War

2010: first year in which more than 100 isotopes were discovered

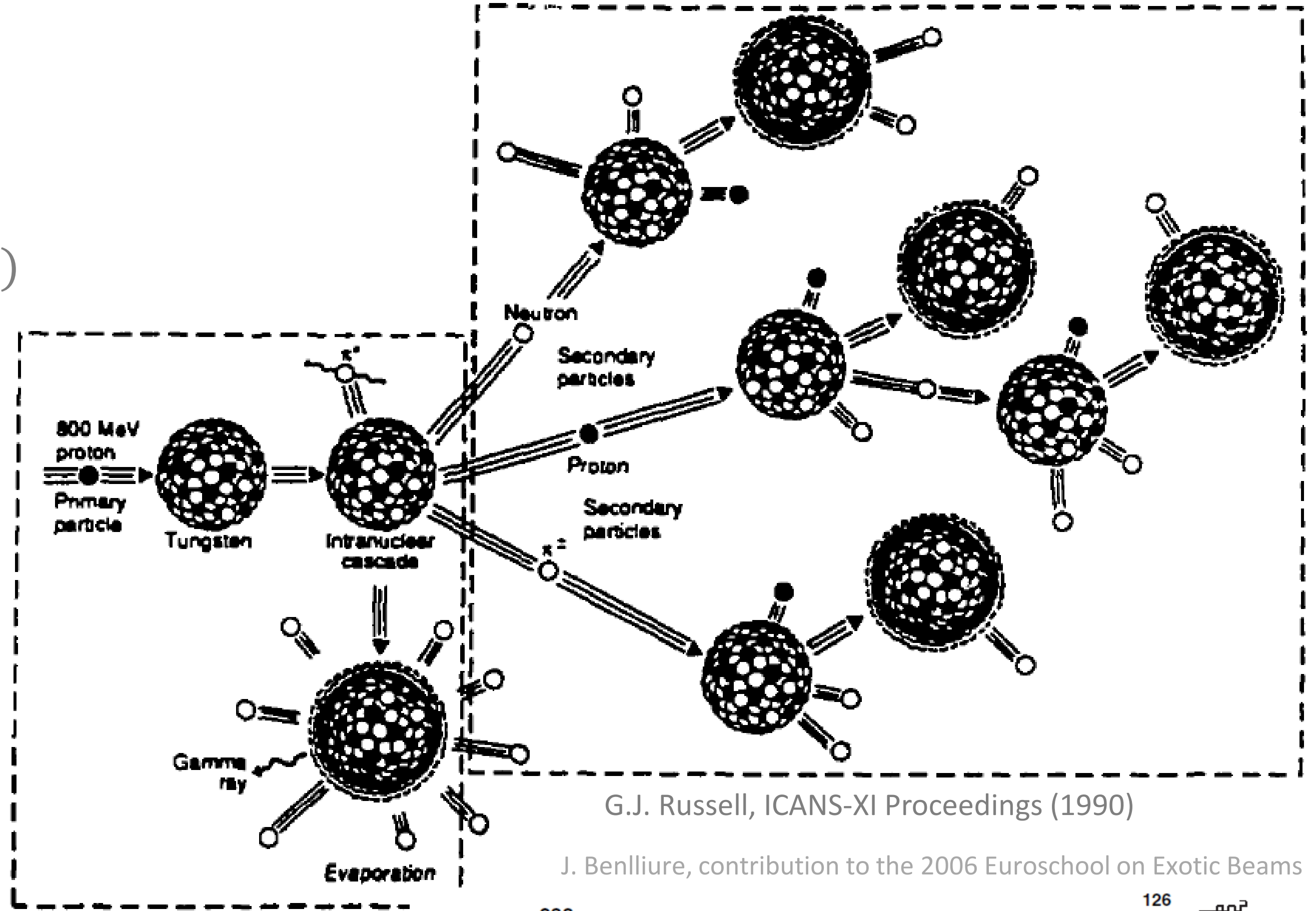
Stable and naturally existing radioactive isotopes

Predicted, but as yet unconfirmed, isotopes

Spallation

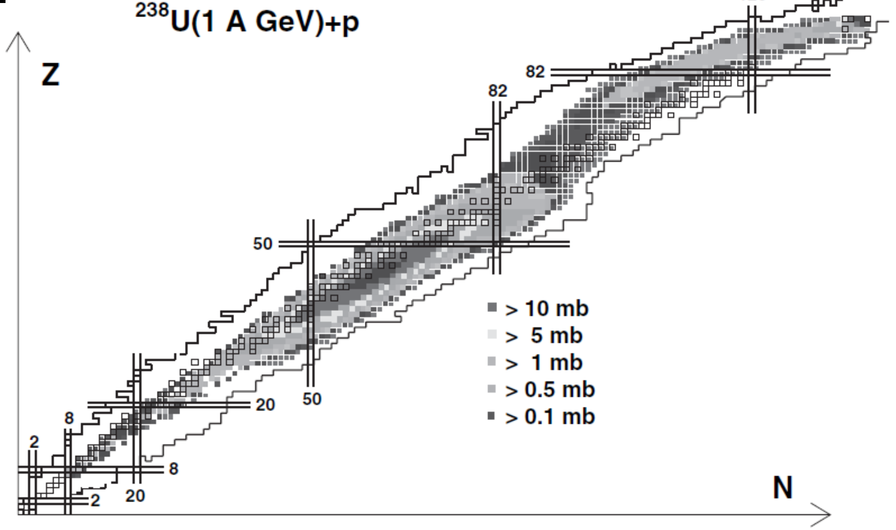
- Spallation is what happens when you blast a nucleus with a high energy particle $(\gtrsim 100\mathrm{MeV/u})$
- The projectile imparts a large amount of energy to the target, which then de-excites by evaporating particles, some of which are evaporated with such high energies that they can in turn blast apart neighboring nuclei
- The resulting fragment distribution from a large number of spallation reactions is some combination of nuclei produced via evaporation, the intranuclear cascades, and fission, since fissioning targets are typically chosen
- To use spalled isotopes for radioactive ion experiments, some collection and chemistry-related separation (e.g. with laser-induced excitations) is required, as is some post acceleration

Fun Fact: Cosmic rays routinely produce isotopes on earth and in the atmosphere via this process.



G.J. Russell, ICANS-XI Proceedings (1990)

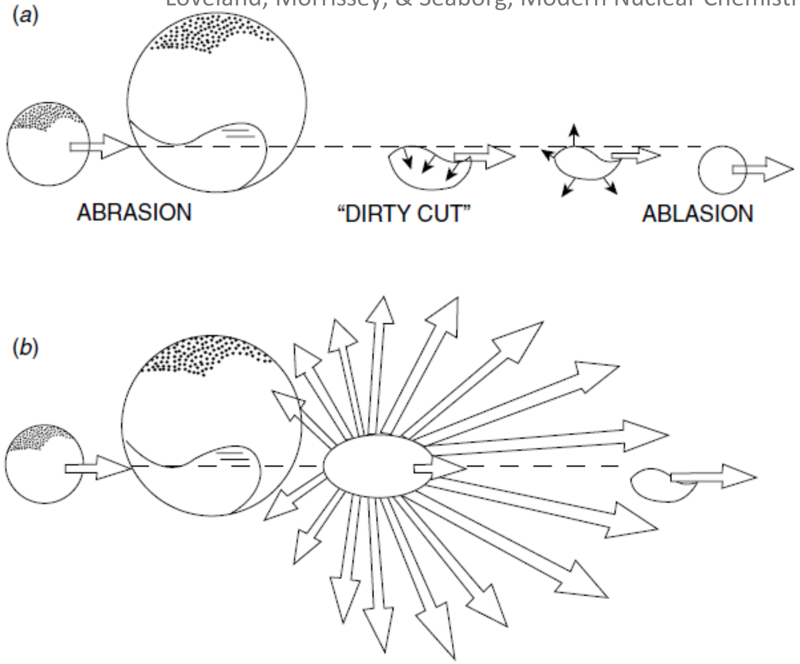
J. Benlliure, contribution to the 2006 Euroschool on Exotic Beams



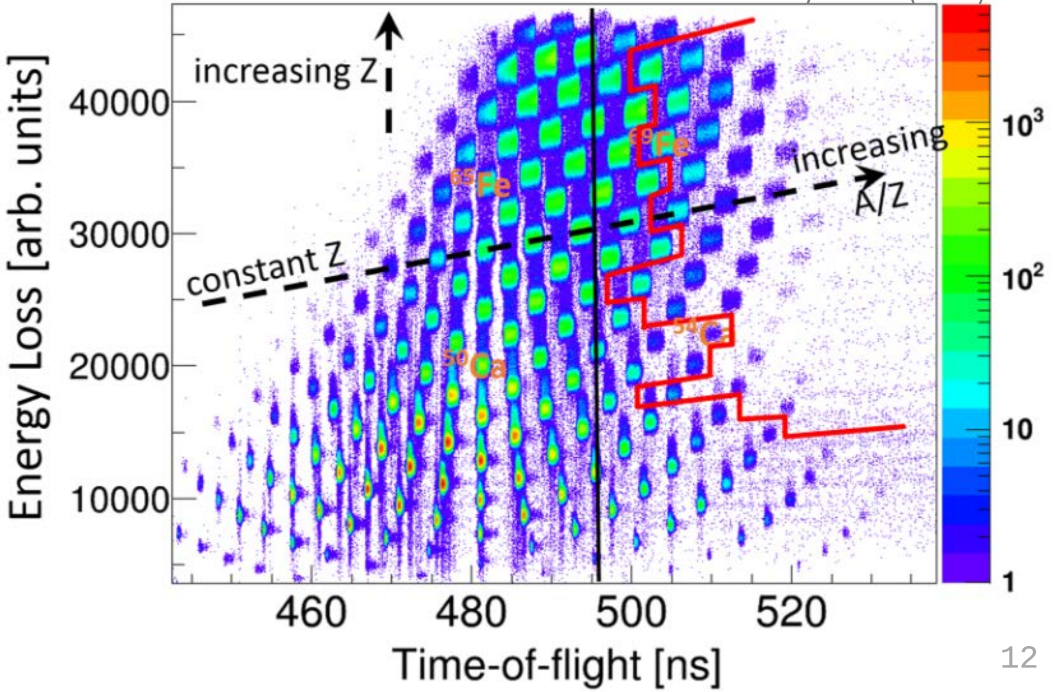
Projectile fragmentation

- The opposite approach is to blast apart a heavy nucleus by bombarding it onto a robust target
- The resulting fragment distribution can be understood in terms of evaporations and intranuclear cascades, as will spallation, or in terms of a macroscopic “abrasion-ablation” model
- For abrasion-ablation, the overlapping region of the beam and target is sheared-off the projectile. The remaining component de-excites statistically.
- Since both models are statistical in nature, the calculation results are largely similar, producing a wide swath of nuclides
- Projectile fragmentation requires an in-flight separation of nuclides, which are forward-focused, but still can have an appreciable angular spread
- Such calculations can be performed with [LISE++]()

Loveland, Morrissey, & Seaborg, Modern Nuclear Chemistry (2006)



140MeV/u ^{82}Se on Be Z.Meisel et al. Phys.Rev.C (2016)

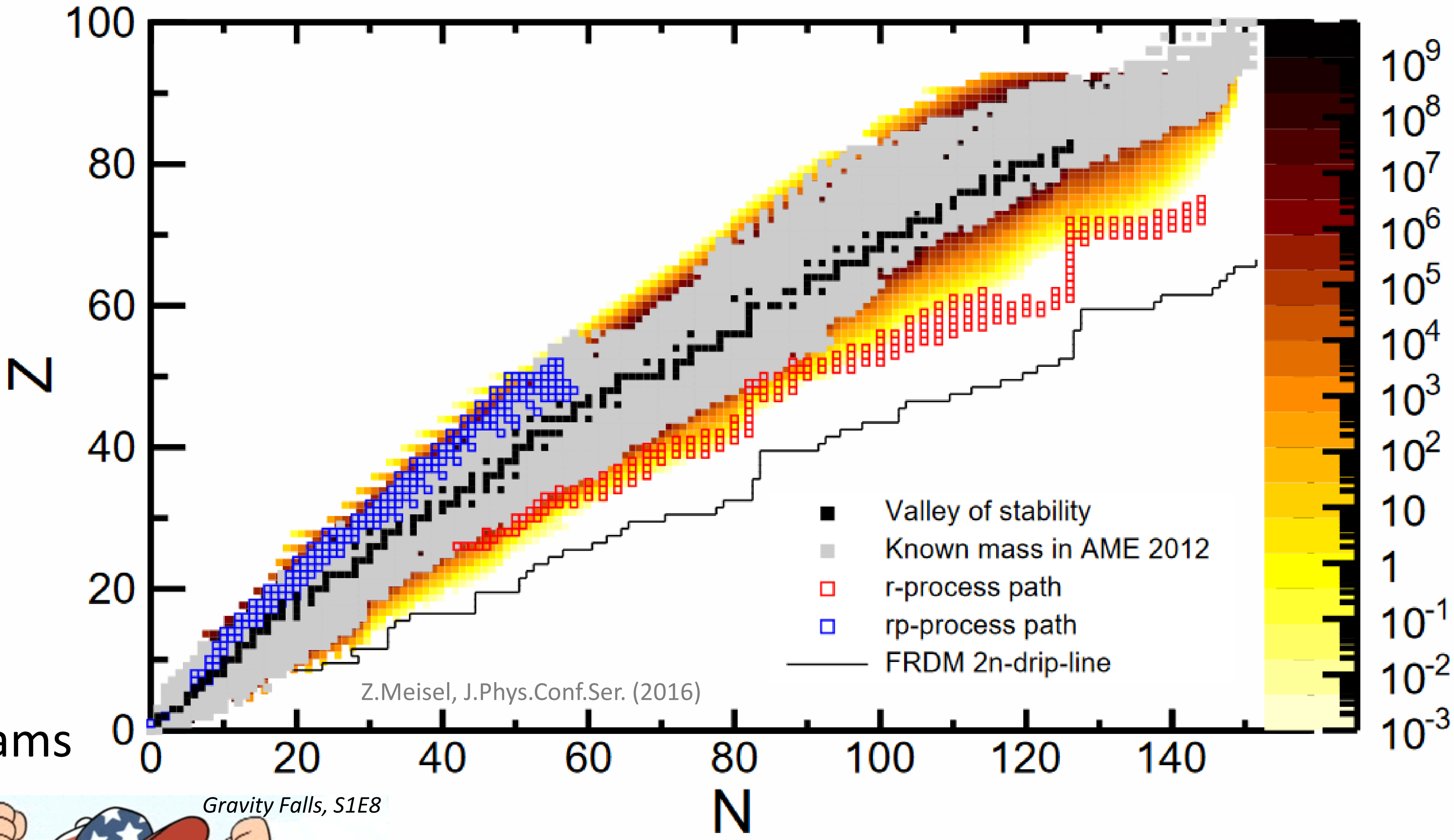


Propaganda:

- One nice feature of projectile-fragmentation is that more exotic nuclides can be made if you can just have projectile-target collisions more often
- Some additional gains are made by increasing the beam energy
- This is the idea behind the Facility for Rare Isotope Beams (FRIB)

which is being constructed in the polar north (Michigan)

FRIB predicted production rate [particles per second]



Z.Meisel, J.Phys.Conf.Ser. (2016)

Gravity Falls, S1E8

Further Reading

- Chapter 10: Modern Nuclear Chemistry (Loveland, Morrissey, Seaborg)
- Chapter 11: Introductory Nuclear Physics (K.S. Krane)
- Chapters 2 & 3: Nuclear Physics of Stars (C. Iliadis)
- Chapters 3 & 4: Talys User Manual (Koning, Hilaire, & Goriely)
- Lecture Notes, Euroschool on Exotic Beams