Office of Defense Nuclear Nonproliferation Research and Development

University and Industry Technical Interchange (UITI2014) Review Meeting

Nuclear-Plasma Interactions with Compound Nuclear States

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Nuclear-Plasma Interactions with Compound Nuclear States

- **Nuclear Plasma-Interactions (NPIs)**
  - Calculating the rates of nuclear-plasma interactions.
  - Nuclear-Plasma Interactions with Compound Nuclear States
  - Experimental Signature of the impact of NPIs on Spin.
- **Planned Experimental Measurements**
  - Using the Inertial Confinement Fusion (NIF).
  - Using a Long-Pulse/Short Pulse Laser (GEKKO+LFEX).
  - Using a Beam-Foil Setup (88-Inch Cyclotron at LBNL).
- **Summary and Future Work**

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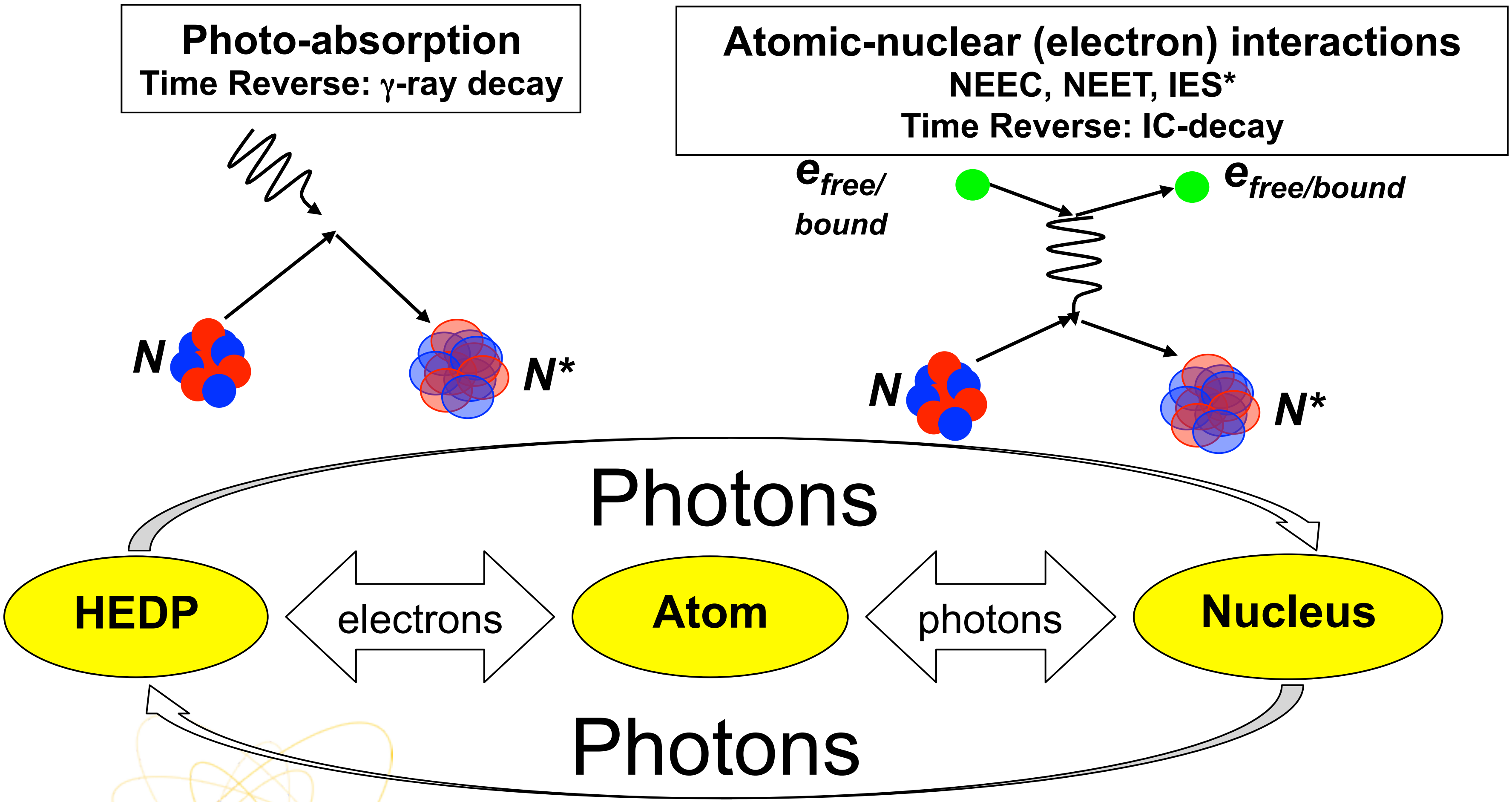
Nuclei can interact with electrons via nuclear-plasma interactions (NPI).



How would these interactions impact compound nuclear states?

In NEEC, a free electron with some energy is captured into a bound state.

$E_r \left|\phi_r\right\rangle$

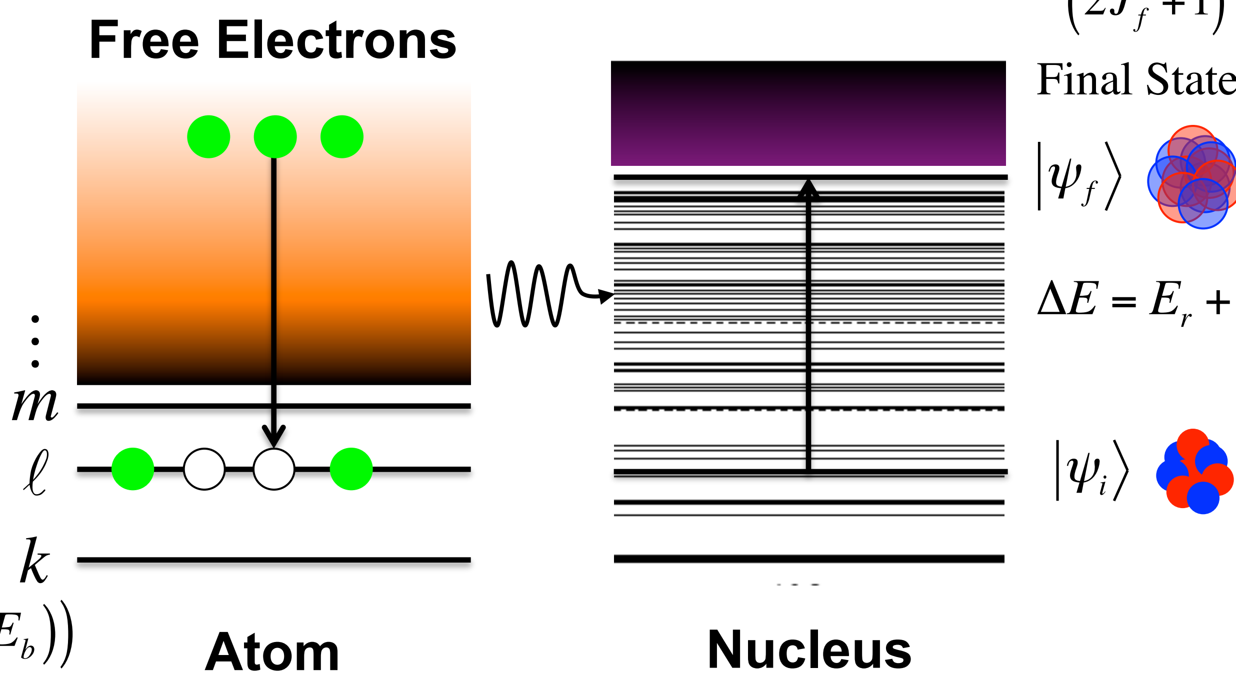
$n(E_r) f_{FD}(E_r)$

Incoming e's

$E_b \left|\phi_b\right\rangle$

$n(E_b)\left(1 - f_{FD}(E_b)\right)$

Empty Orbitals



$(2J_f + 1)$

Final States

$\left|\psi_f\right\rangle$

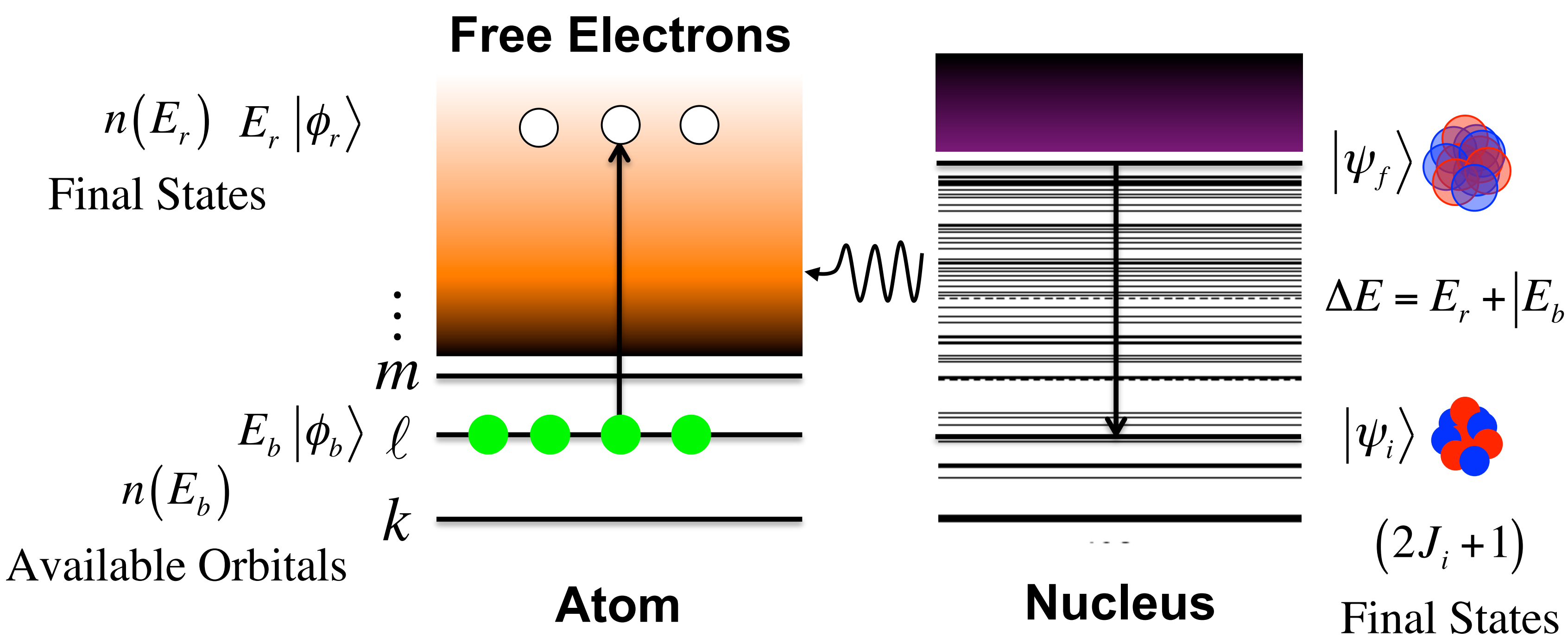
$\Delta E = E_r + |E_b|$

$\left|\psi_i\right\rangle$

$$\lambda_{\text{NEEC}} = \frac{2\pi}{\hbar} \qquad \left|\left\langle \psi_f \phi_b \middle| H \middle| \psi_i \phi_r \right\rangle\right|^2$$

Following the model from G. Gosselin and P. Morel, PRC 70, 064603 (2004).

Many of these same factors appear in the inverse process, internal conversion:

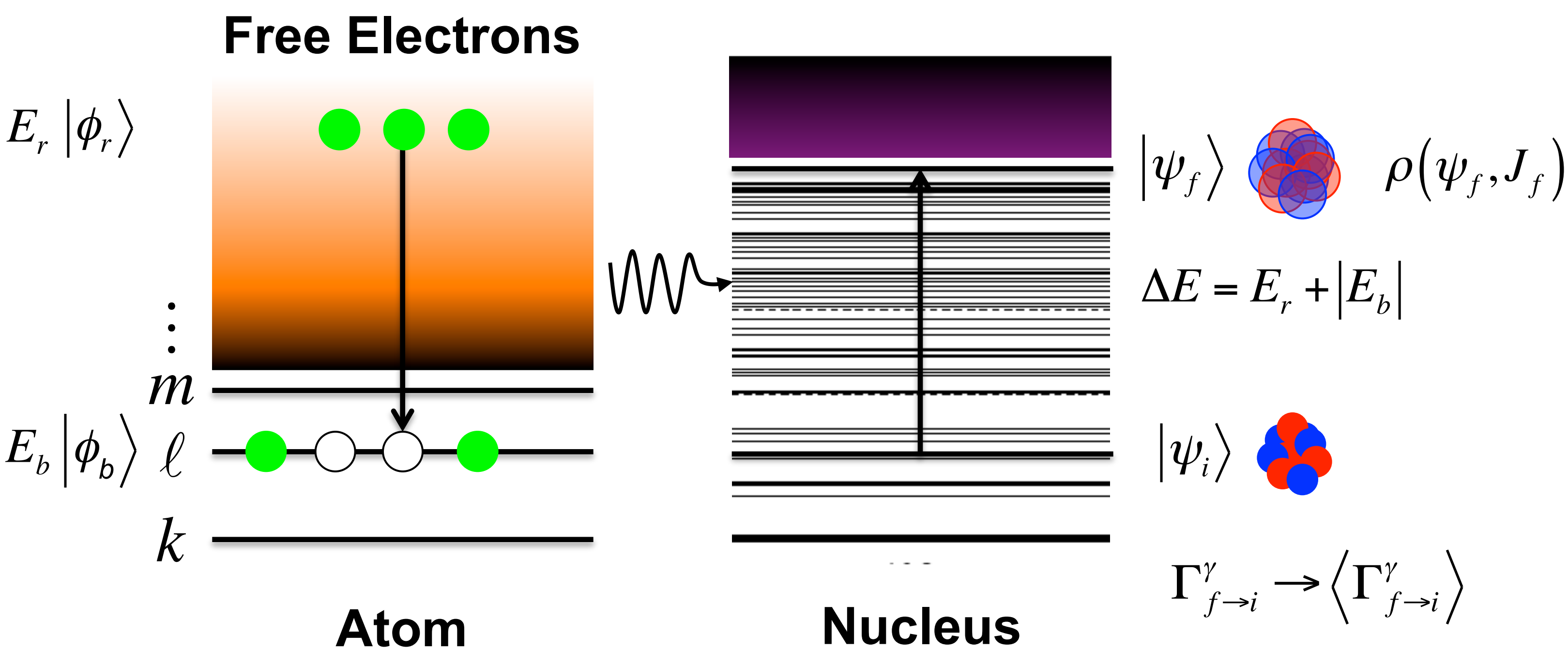


$$\lambda_{\mathrm{IC}} = \frac{2\pi}{\hbar} \left| \langle \psi_i \phi_r | H | \psi_f \phi_b \rangle \right|^2$$

$$\lambda_{\mathrm{NEEC}} = \frac{2\pi}{\hbar} n(E_r) f_{\mathrm{FD}}(E_r) \left| \langle \psi_f \phi_b | H | \psi_i \phi_r \rangle \right|^2 \frac{2J_f+1}{2J_i+1} \left[1 - f_{\mathrm{FD}}(E_b)\right].$$

$$\lambda_{\mathrm{NEEC}} = \frac{\alpha(T_e, E_r)}{\hbar} \Gamma^{\gamma}_{f \to i} (2J_f+1) n(E_b) \left[1 - f_{\mathrm{FD}}(E_b)\right]$$

In the quasi-continuum, there are also multiple final levels:

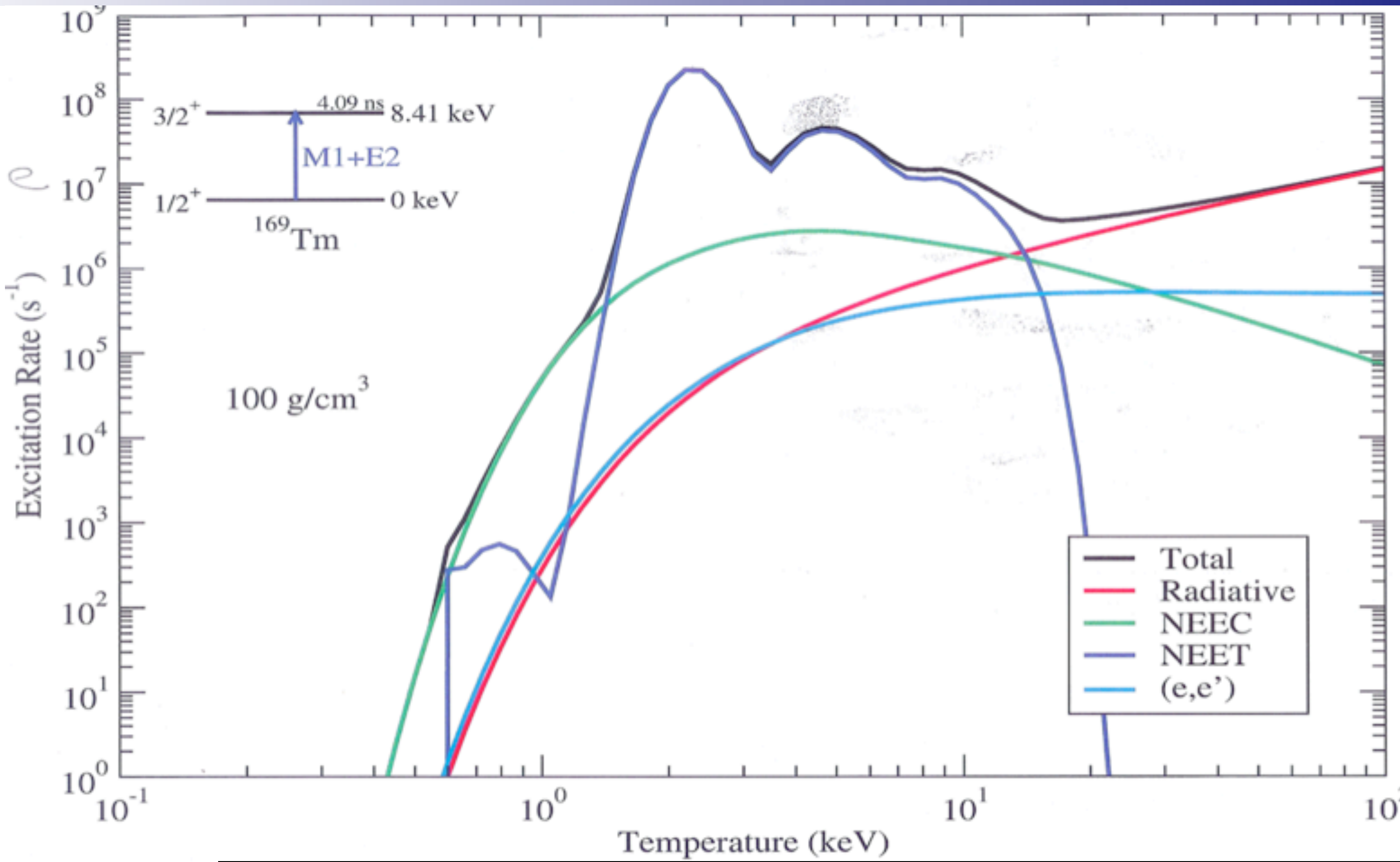


$$\lambda_{\text{NEEC}} = \frac{2J_f + 1}{2J_i + 1} f_{\text{FD}}\left(E_r\right) \frac{\alpha\left(T_e, E_b\right)}{\hbar} \Gamma^{\gamma}_{f\to i} \left[1 - f_{\text{FD}}\left(E_b\right)\right].$$

Similar Arguments apply to NEET :

$$\lambda_{NPI} \propto \left\langle \Gamma^{\gamma}_{f\to i} \right\rangle \times \rho_{Nuclear}\left(\psi_f, J_f\right)$$

If $\Gamma^{\gamma}_{f\rightarrow i}$ is known, all of these factors can be calculated.



Caclulations from G. Gosselin, CEA

What is $\left\langle \Gamma^{\gamma}_{f\rightarrow i} \right\rangle$ for transitions between compound nuclear states?

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Two estimates: Single-Particle Strength and Photon Strength Function *f*.

Six orders of magnitude difference between estimate.

No experimental data on PSF for relevant atomic energies (*ΔE* < 100 keV) .

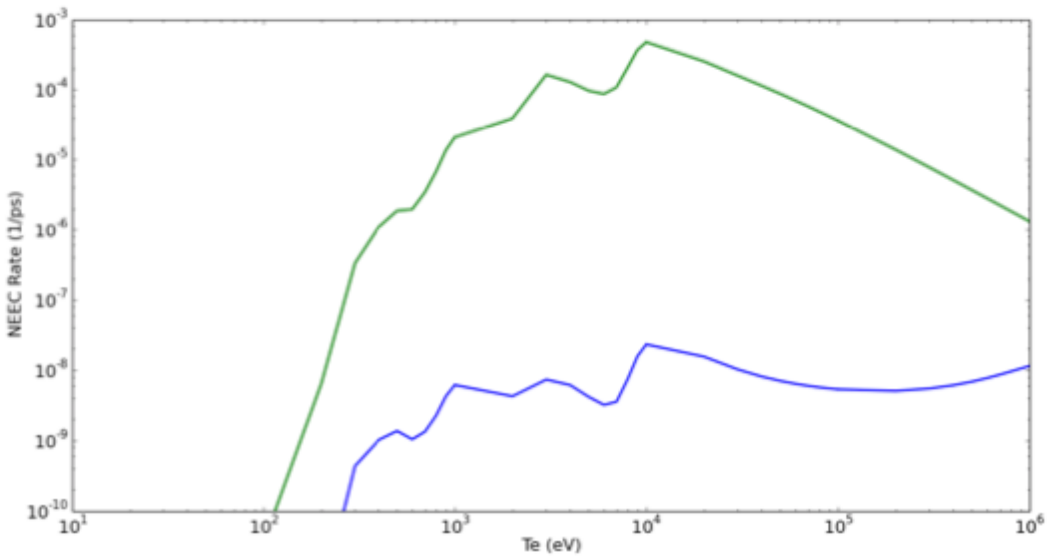
NPI in the quasi-continuum might be the only way to measure this.

What would the impact on neutron capture be?

$$\lambda_{\mathrm{NPI}} \propto \left\langle \Gamma^{\gamma}_{f\to i} \right\rangle \times \rho_{Nuclear}\left(\psi_f, J_f\right)$$

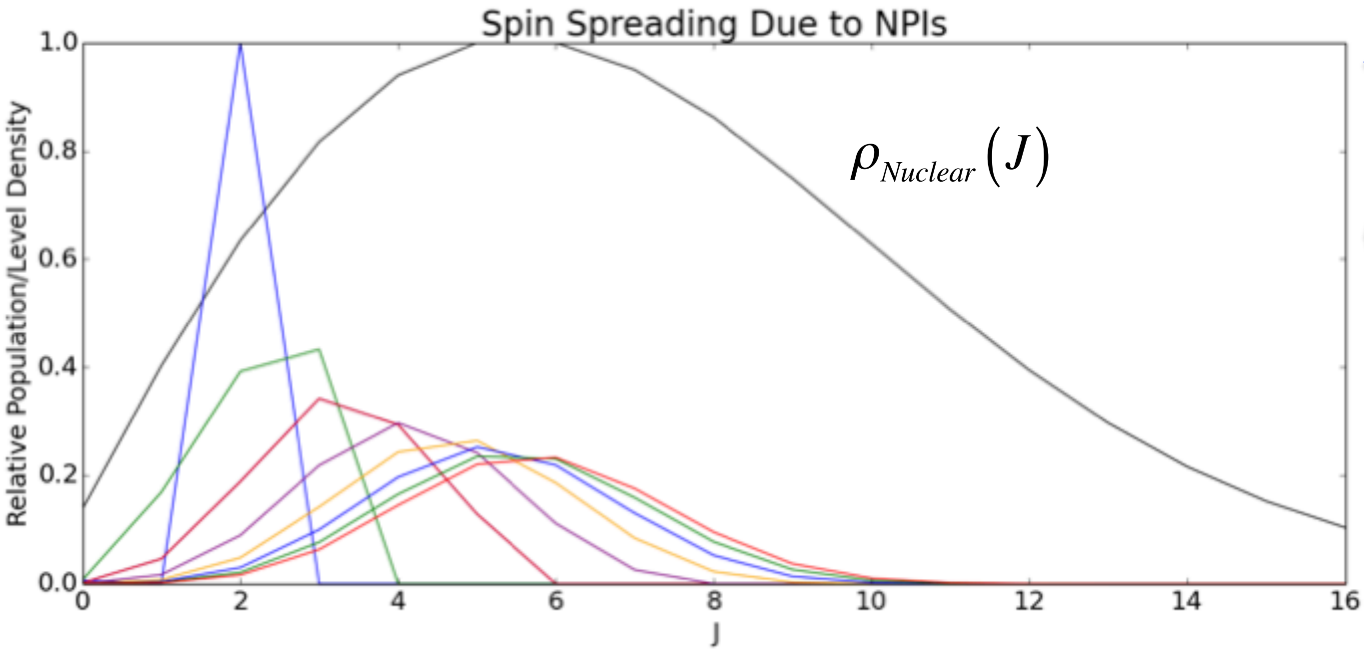
$$\left\langle \Gamma^{\gamma}_{f\to i} \right\rangle \times \rho_{Nuclear}\left(\psi_f, J_f\right) = f_{XL}\left(\Delta E, J_f\right) \times \Delta E^{2L+1}$$

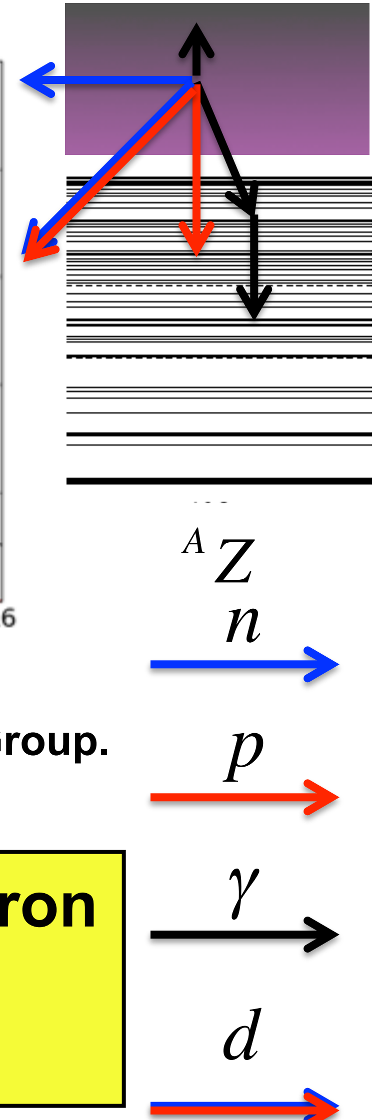
$$\lambda_{\mathrm{NPI}} \propto f_{XL}\left(\Delta E, J_f\right) \times \Delta E^{2L+1}$$



green: single particle; blue: lorentzian PSF. NEEC on ^{198}Au quasi-continuum.

NPIs opens up a new channel, resulting in a “spreading” of the spin distribution.





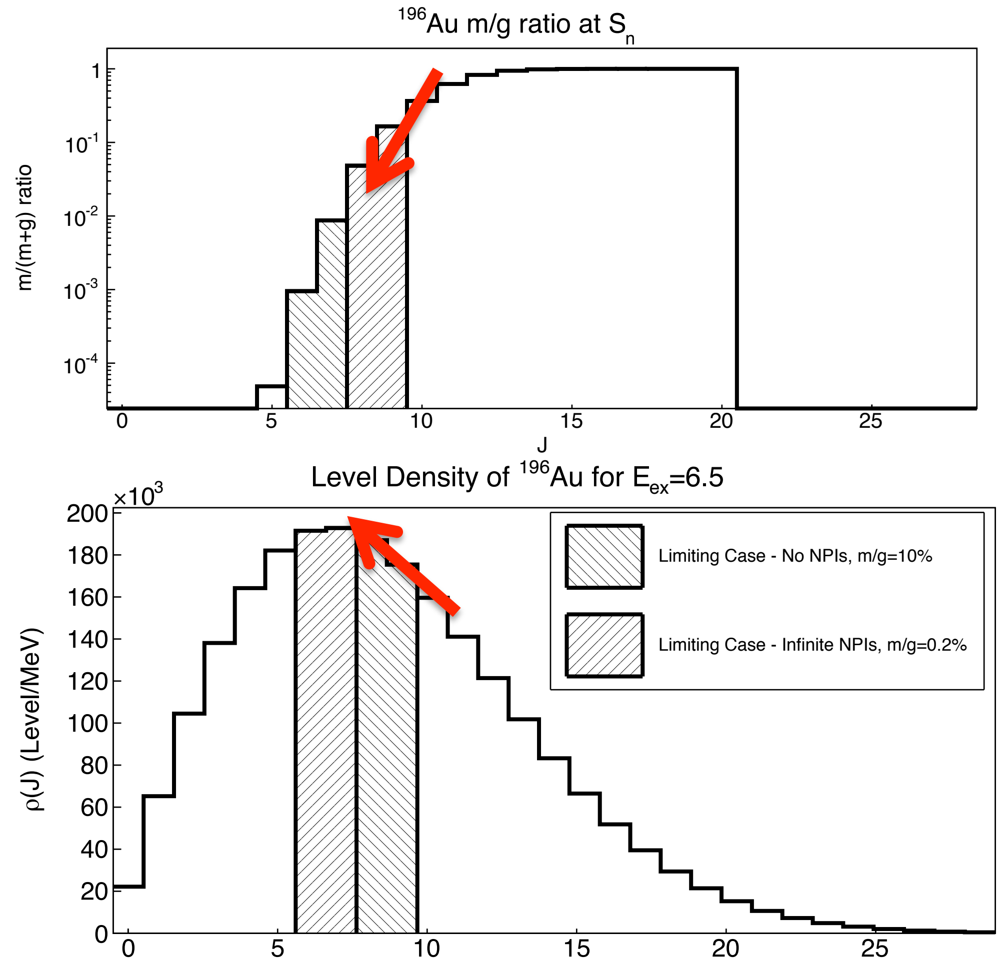
At low spins, even a single NPI can drastically change the spin.
Calculations from Jutta Escher, LLNL Nuclear Theory & Modeling Group.

Increase in spin will enhance neutron retention following low energy neutron capture.

Measuring Neutron Capture in a Plasma will be difficult.

- **Population of Spin-Trap isomers following a nuclear reaction depends strongly on the initial spin.**

- **^{198}Au, ^{196}Au, and ^{134}Xe all have long lived spin trap isomers and radioactive ground states, so relative changes in isomer population can be measured using radiochemistry.**



By measuring m/g ratio in and out of plasmas, can observe the impact of NPIs.

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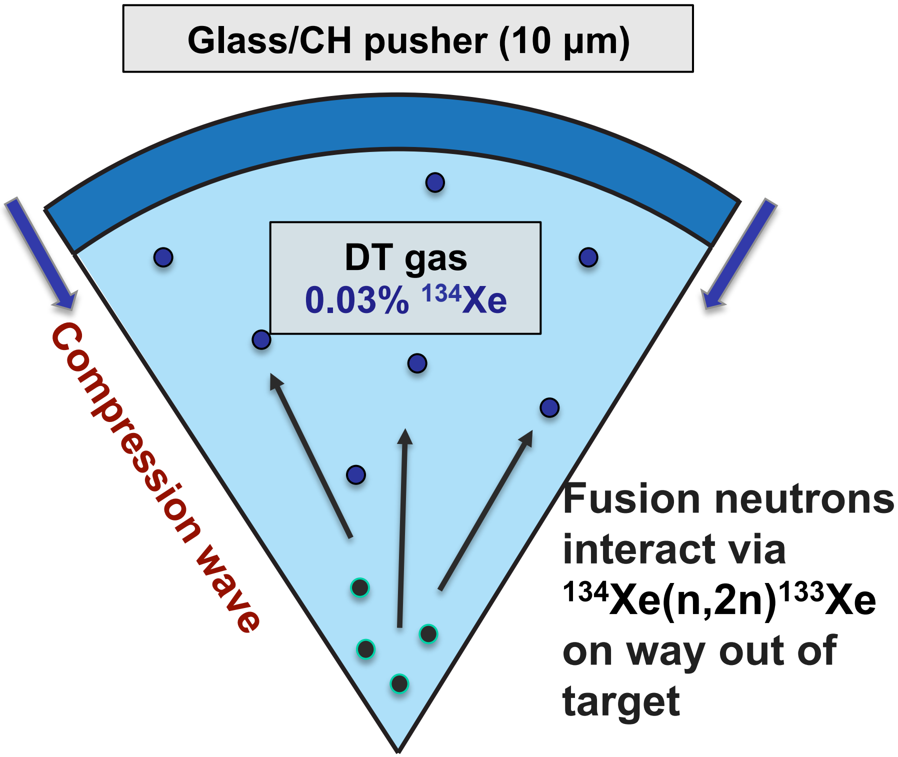
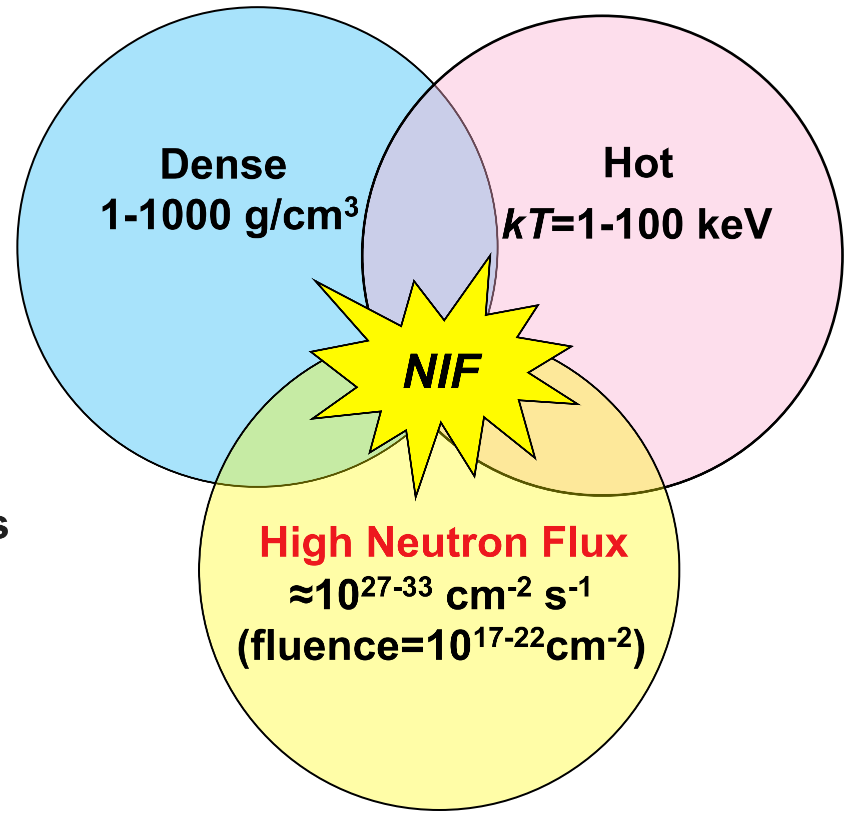
Using the Inertial Confinement Fusion (NIF)

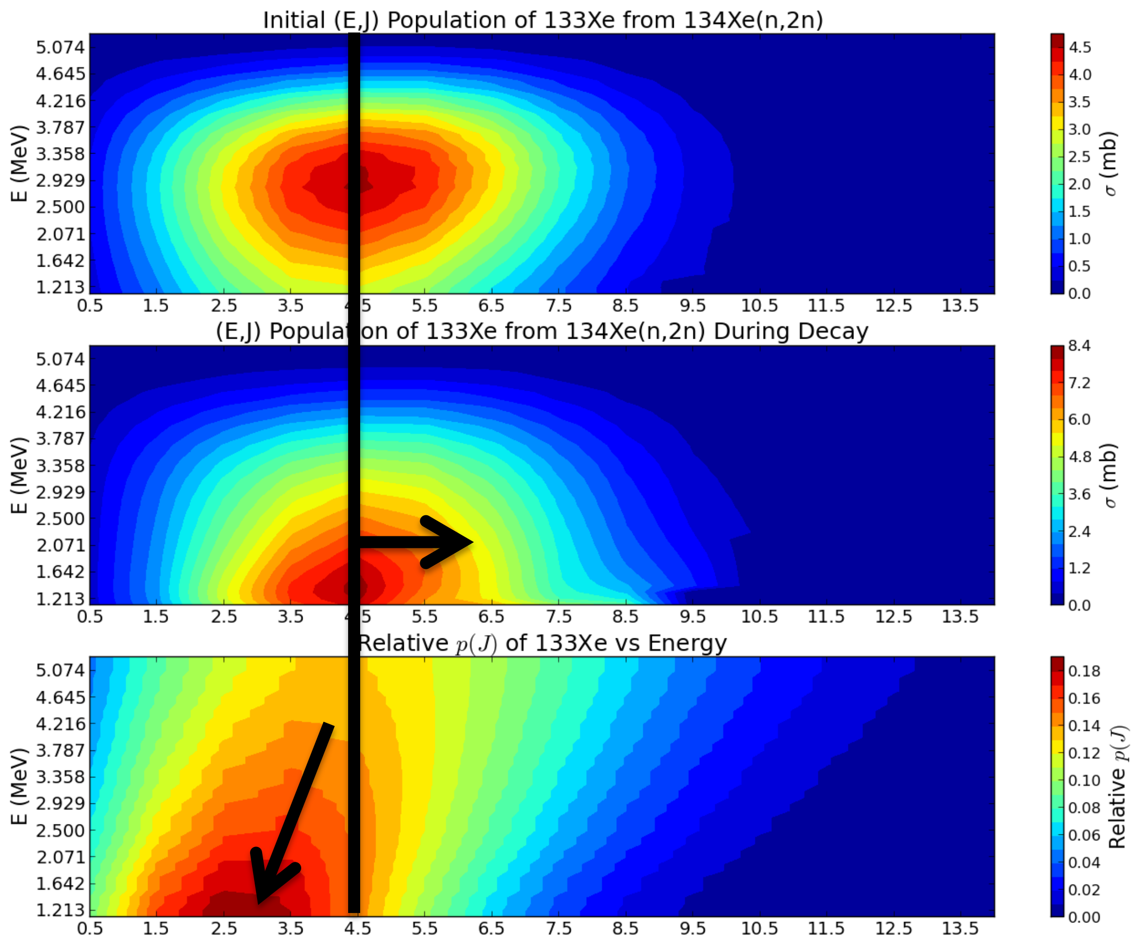




Maximize neutron flux and plasma density by placing a ^{134}Xe dopant in an ICF target.

$^{134}Xe(n,2n)^{133}Xe$ sits on an ideal spot for testing NPIs on compound states:

- **Peak of residual spin distribution at J=4.5.**
- **Isomer is strongly fed for J>4.5, effectively 0 feeding below 4.5.**
- **Peak of residual spin distribution falls on highest slope of ρ(E,J).**



Single-Particle Transition estimate yields up to 5-10% decrease in DIGS.

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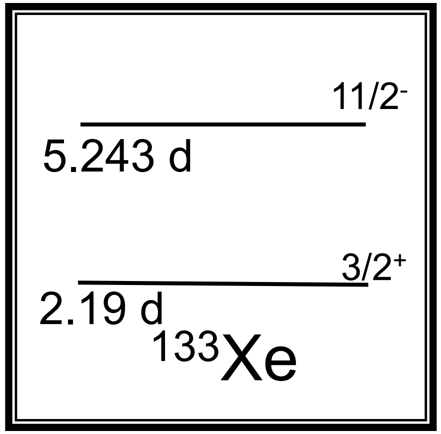
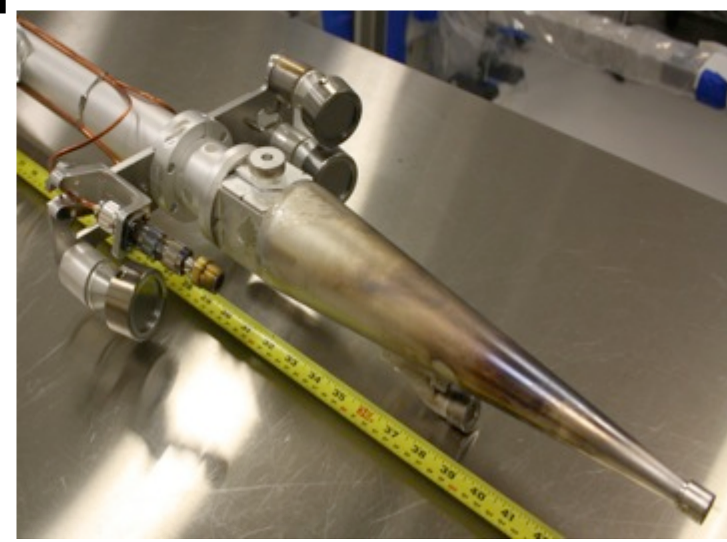
NIF

“Exploding Pusher” capsules consist of DT gas in SiO_2 shell, typically achieve T_{Ion}=8-10 keV.

Very small amount of Xe dopant will minimize impact on plasma conditions while still yielding significant statistics.



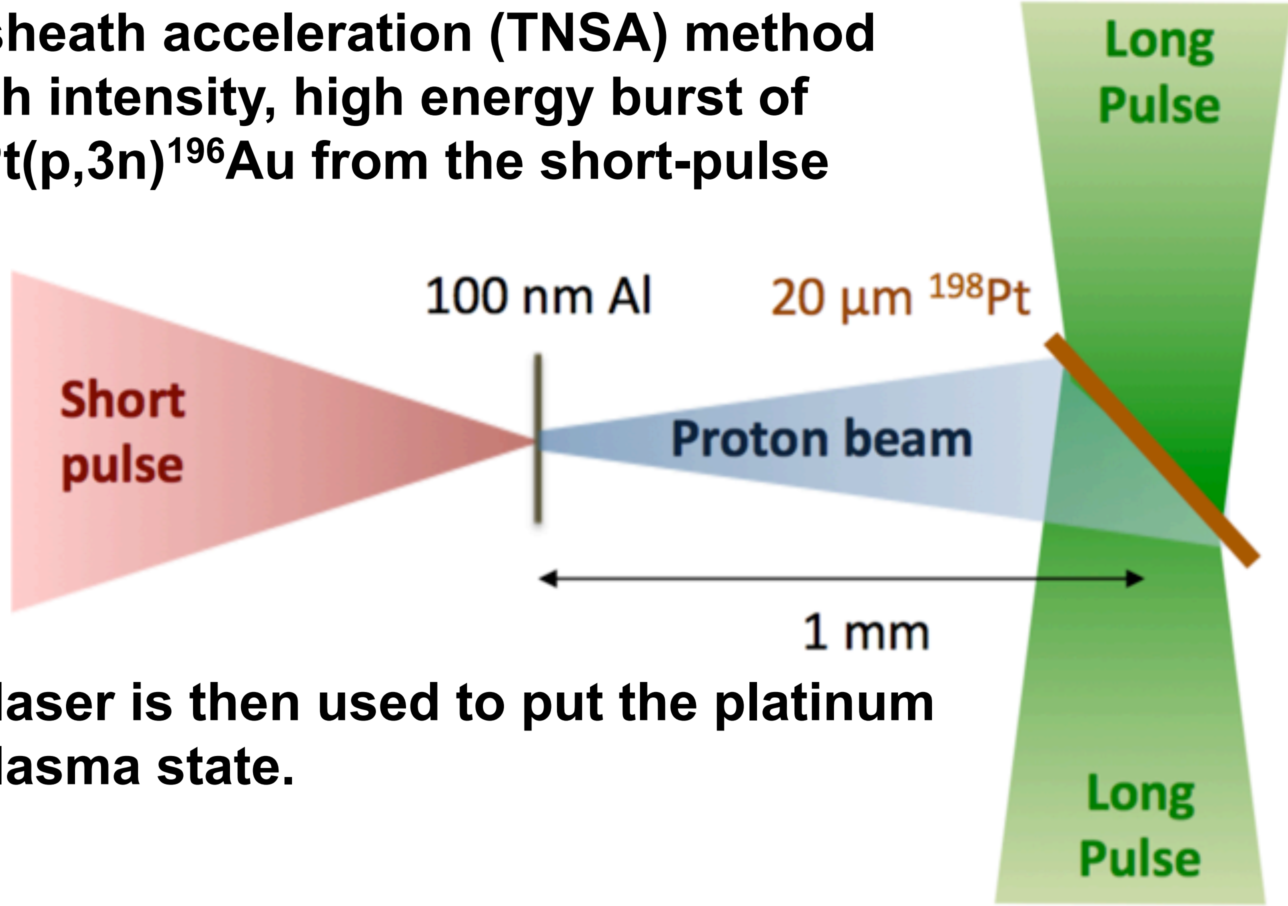
Control sample is placed outside the plasma in a sample positioner on a snout 50cm from the target.



Shot tentatively planned for FY2015.

Using a Long-Pulse/Short Pulse Laser (GEKKO+LFEX)

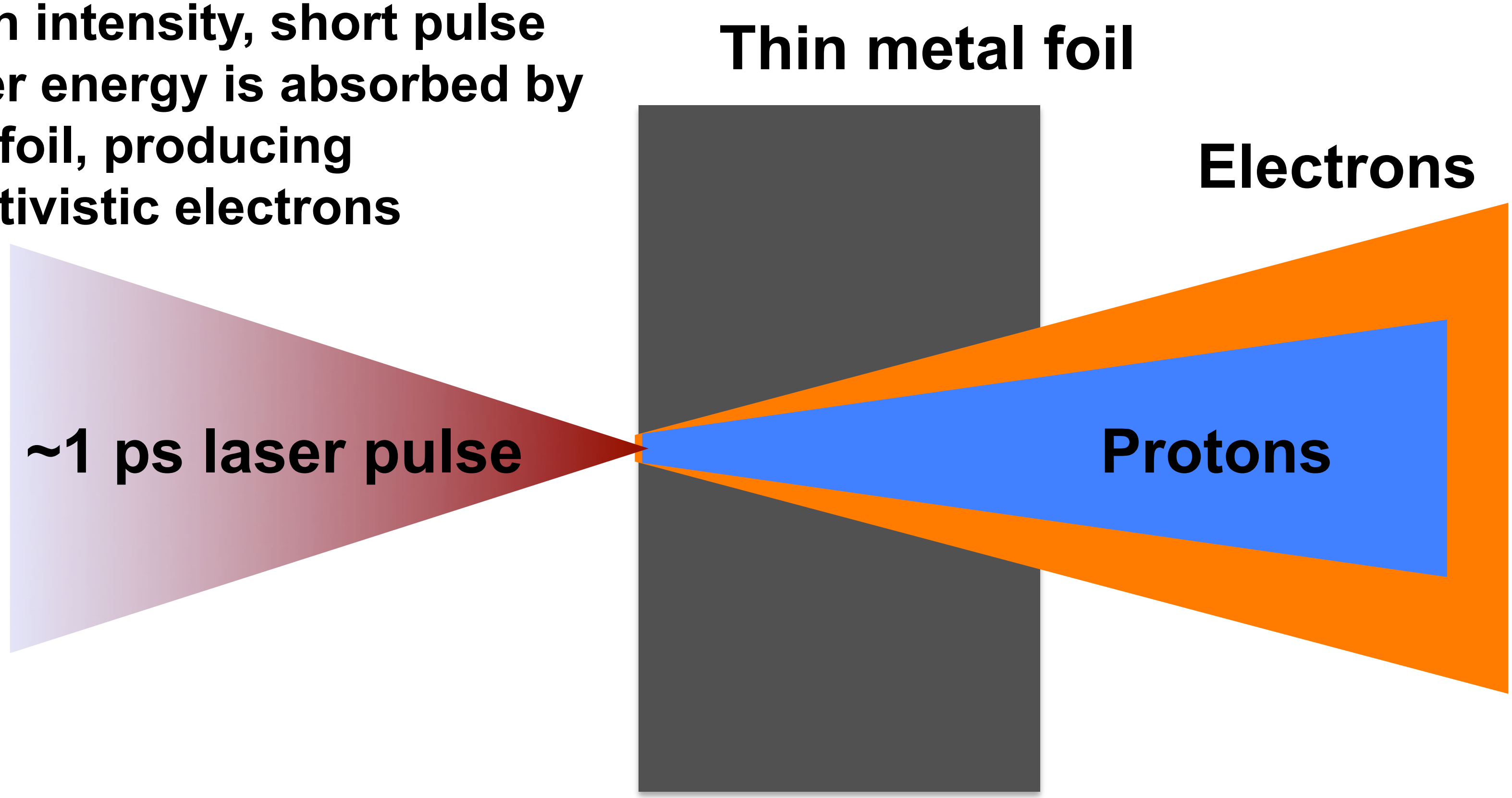
Target normal sheath acceleration (TNSA) method generates a high intensity, high energy burst of protons for $^{198}Pt(p,3n)^{196}Au$ from the short-pulse laser.



Long-pulse laser is then used to put the platinum target in a plasma state.

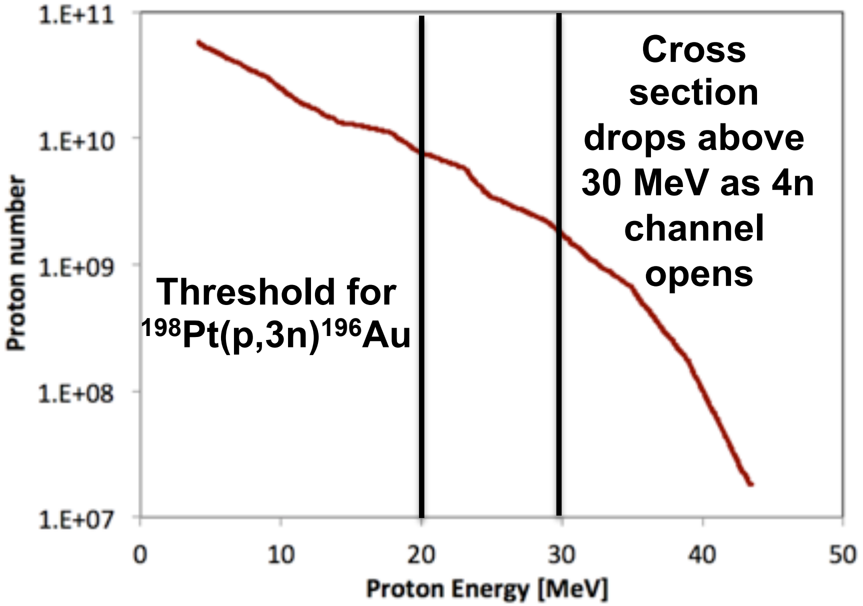
Target-Normal Sheath Acceleration (TNSA) Proton Beams

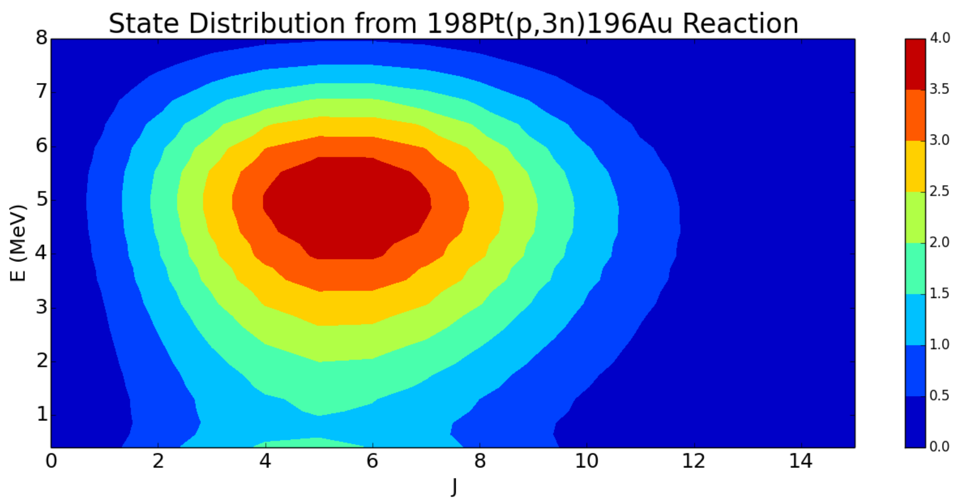
High intensity, short pulse laser energy is absorbed by the foil, producing relativistic electrons



Electrons generate a space charge field with a magnitude of 10^{12} V/m. This field accelerates protons (from CH contamination) to energies of up to 40 MeV.

Compound nuclear state distribution from TALYS predicts long tail at high spin (E_p=25 MeV).





Total isomer to ground state ratio for the integrated TNSA spectrum is calculated at 8.6% (with no plasma).

Due to unknown level structure above the isomer, it is difficult to estimate the change in DIGS.

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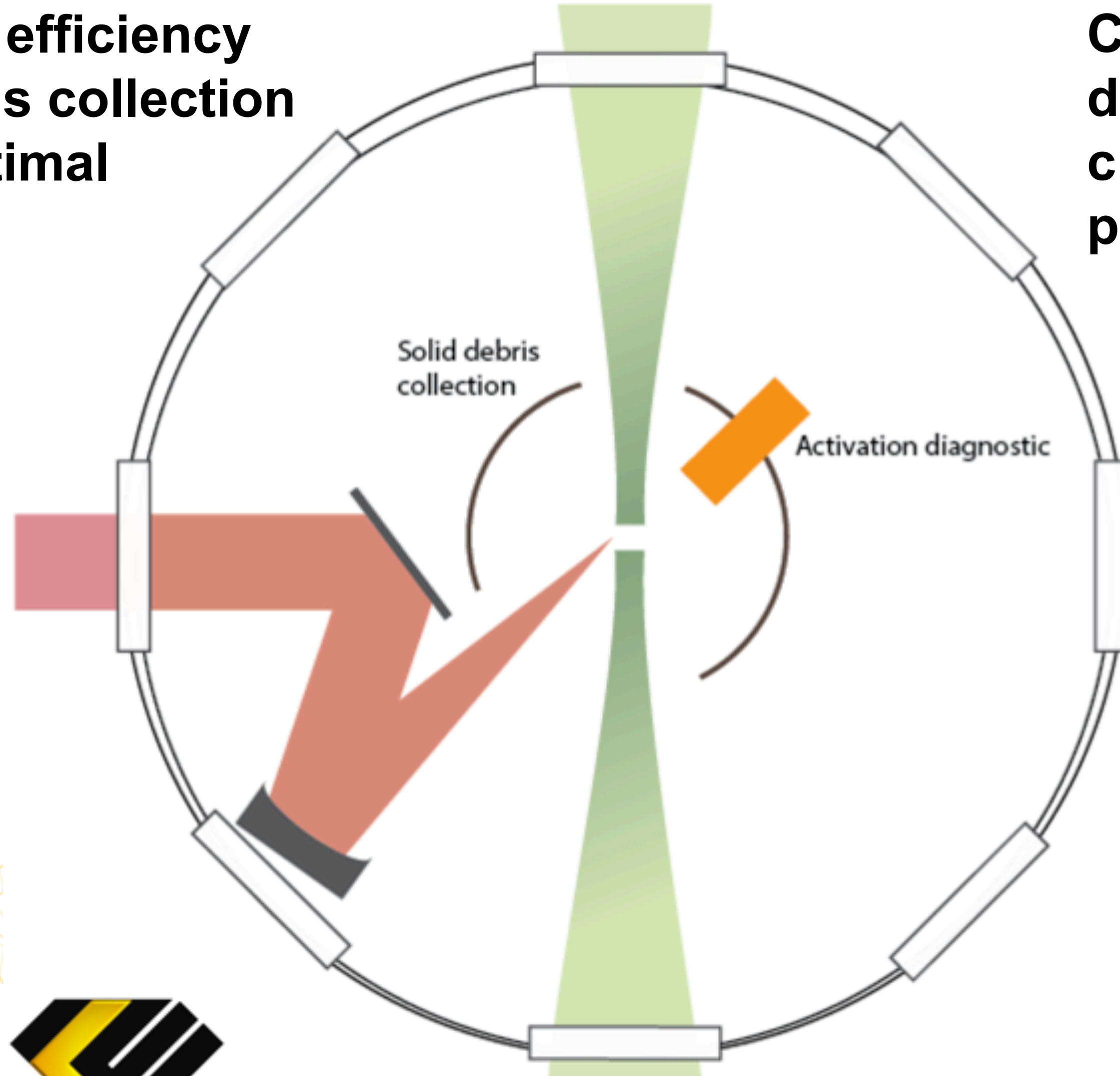
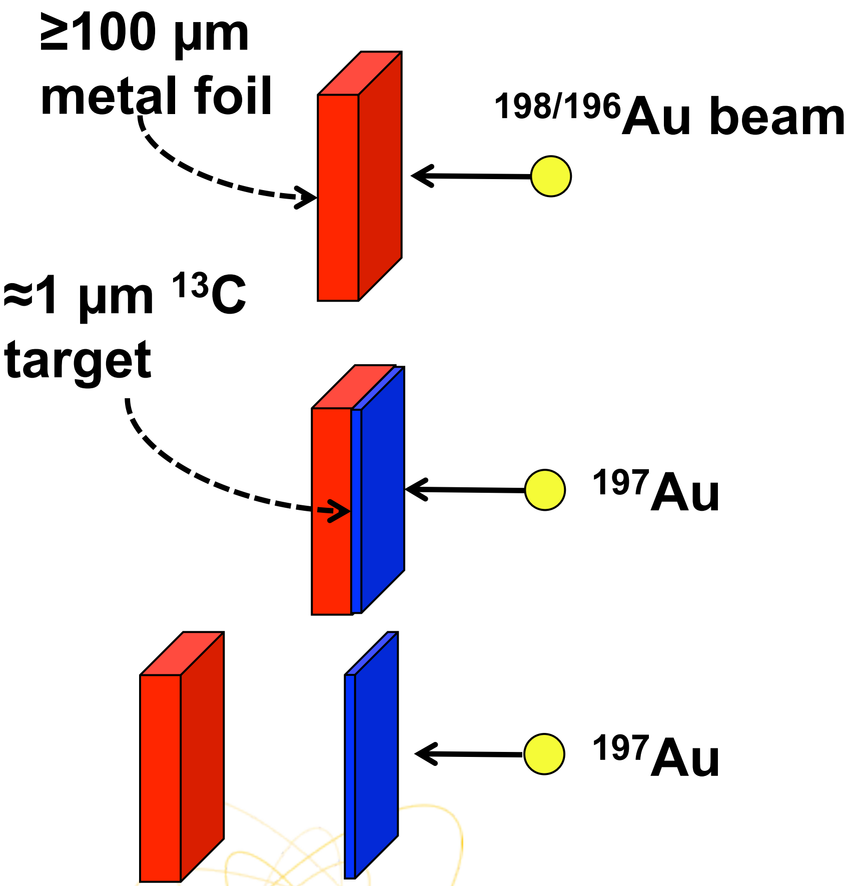
First experiment will be focused on development of solid debris collection.

Need high efficiency solid debris collection to give optimal statistics.

Cu activation diagnostics will characterize the proton beam.



Using a Beam-Foil Setup (88" Inch Cyclotron at LBNL)



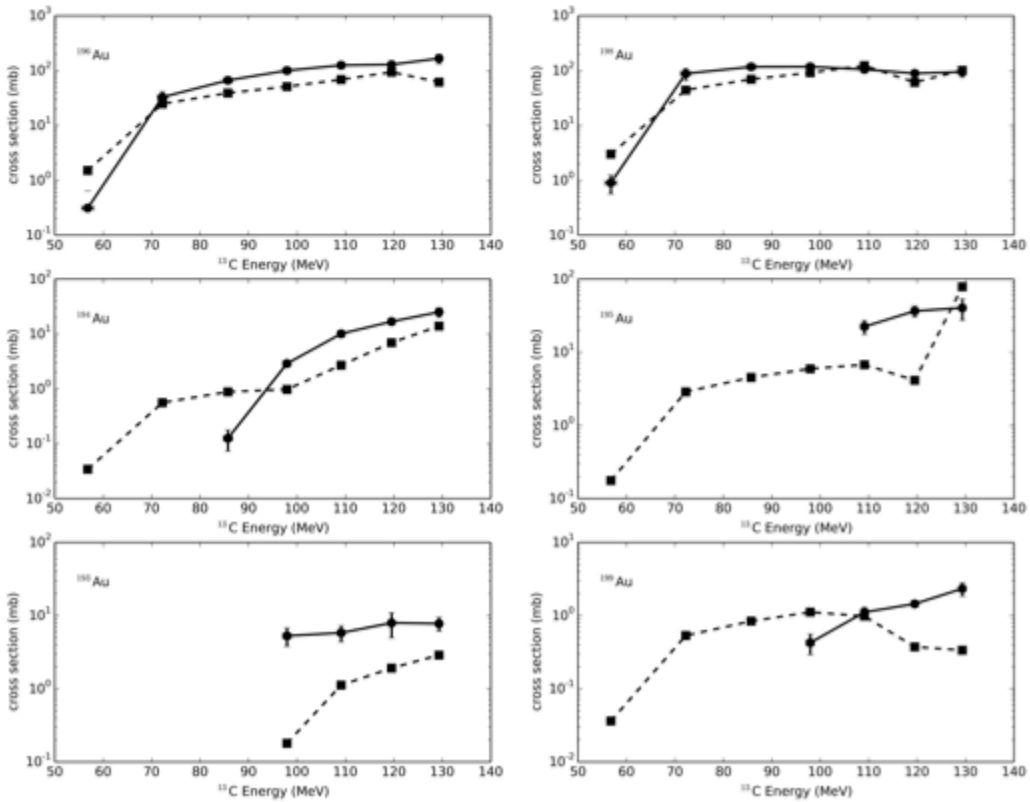
When the highly ionized Au beam encounters the electrons in the foil, NEEC is possible.

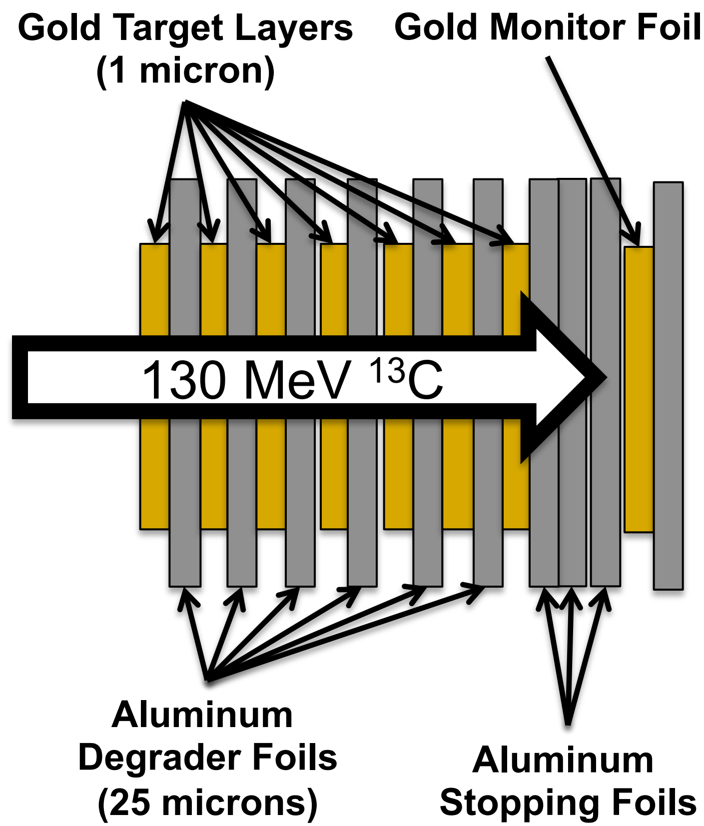
Generate excited $^{198/196}$Au beam via neutron transfer from ^{13}C.

In the "close" target, Au is still excited, and can NEEC.

In the "far" target, Au has decayed to ground state or isomer, and no states available for NEEC.

Inverting the Problem: Designing a ^{13}C Beam Experiment





Transfer cross sections are well explained by binary l-matching model.

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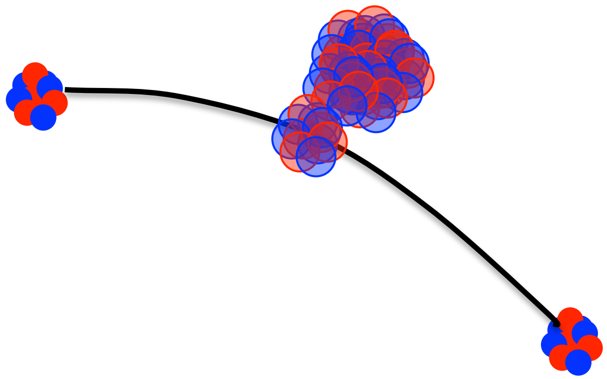

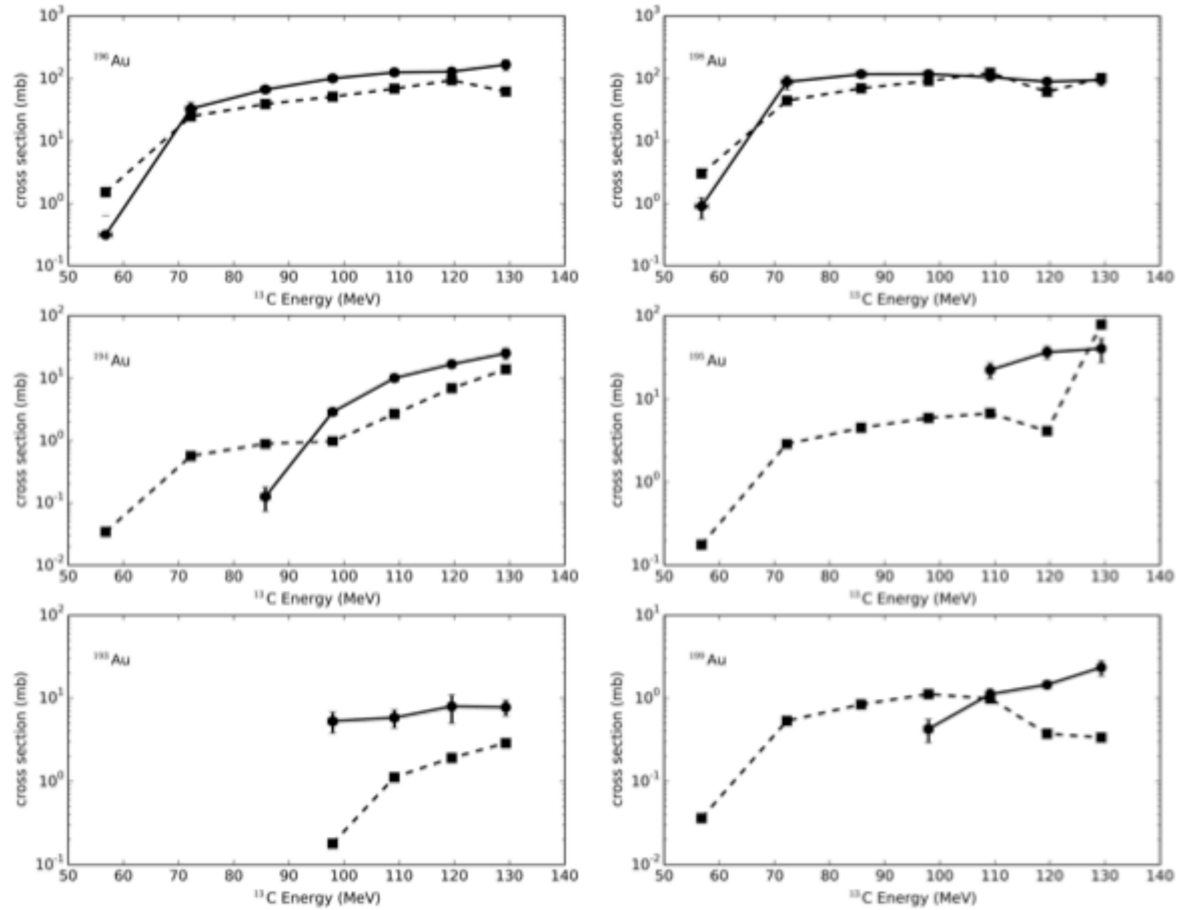

J. Wilczynski, K. Siwek-Wilczynska, J. V. Driel, S. Gonggrijp, D. Hageman, R. Janssens, J. Ukasiak, R. Siemssen, and S. V. D. Werf, Nuclear Physics A 373, 109 (1982)

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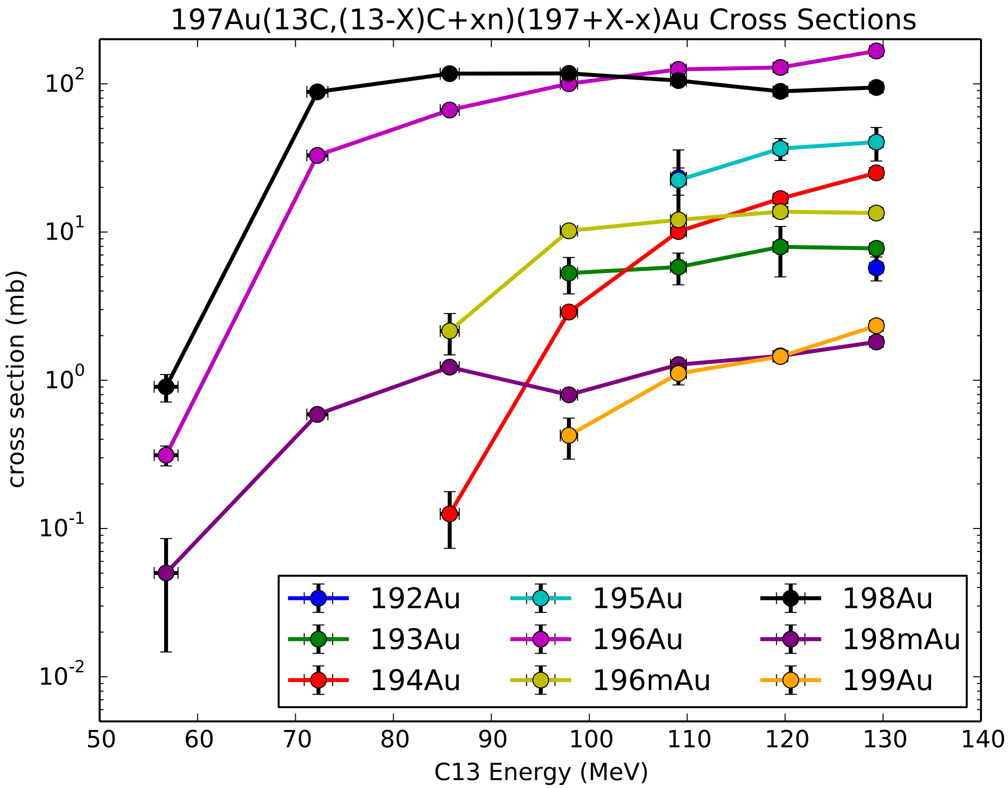
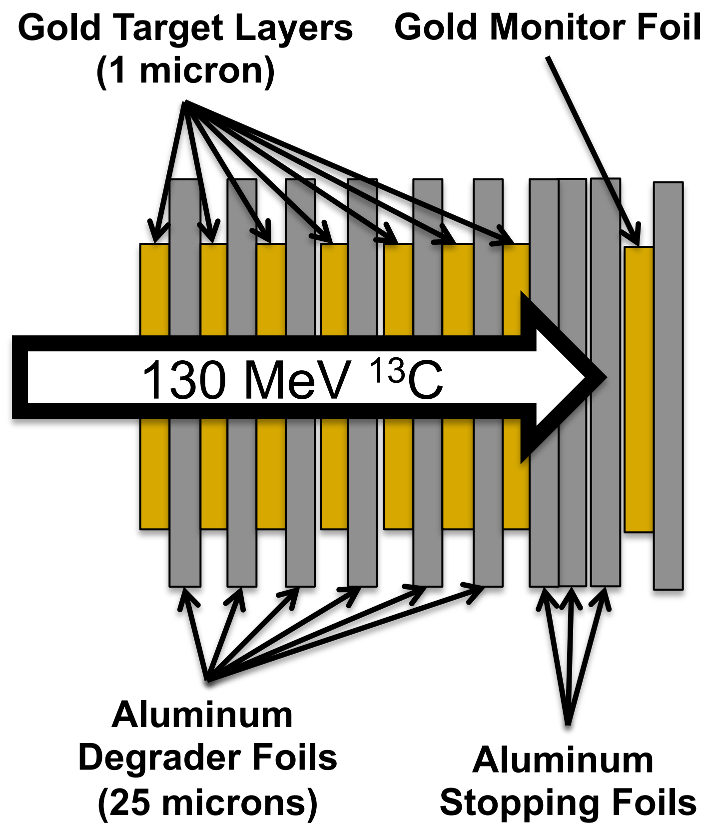
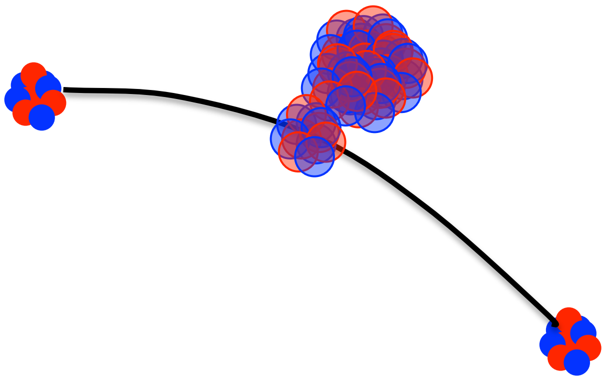




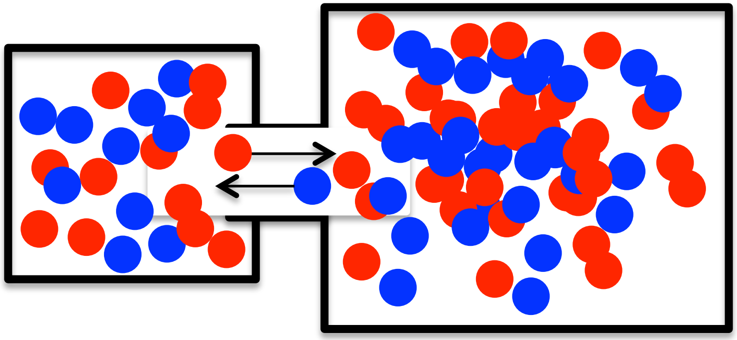
Maximum m/g ratio occurs at 8.5 MeV/nucleon.
What is the spin/energy distribution?

Determine compound E/J Distribution with Fermi-Gas Diffusion Model.

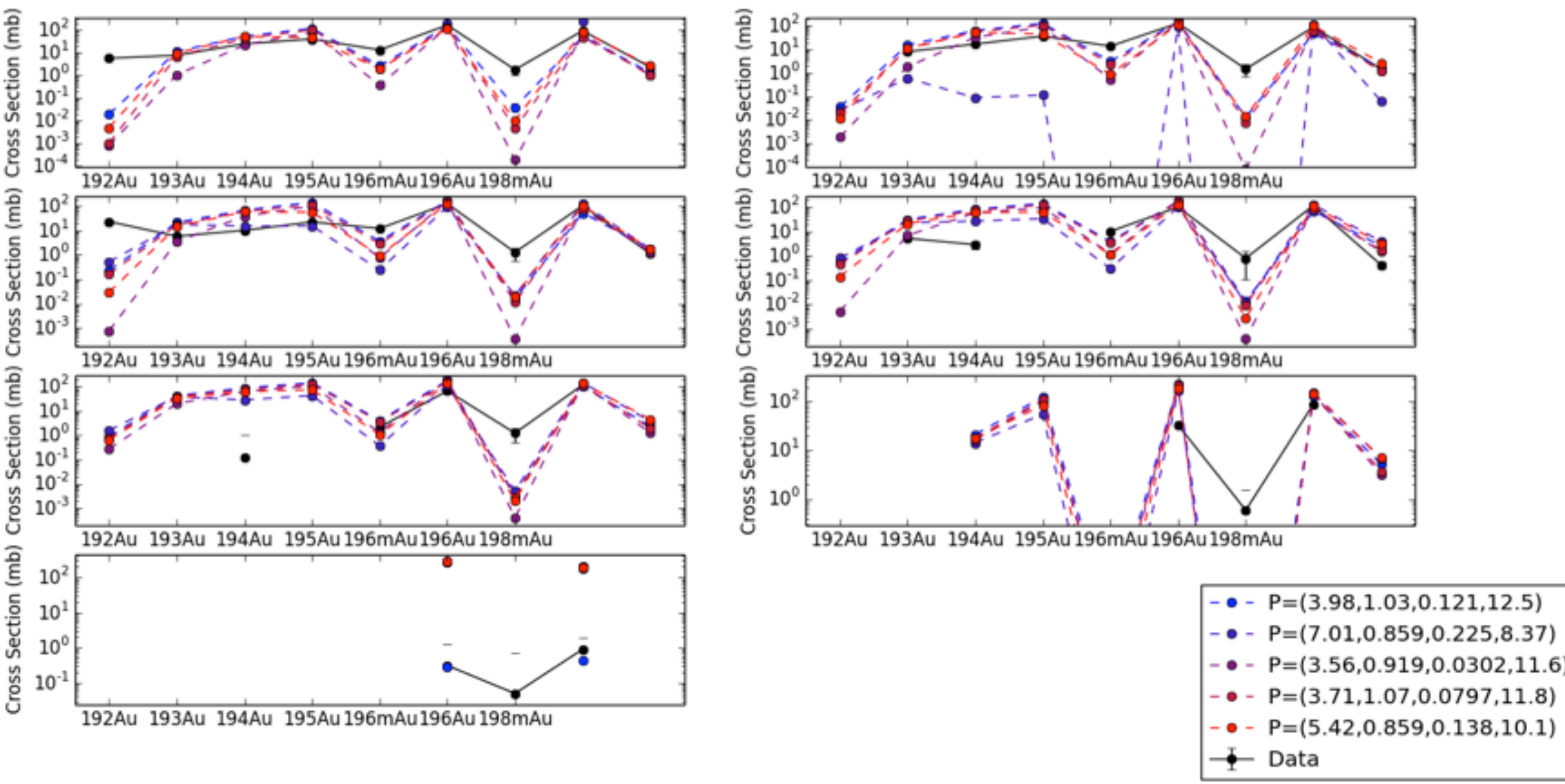


At these energies, heavy ions follow largely classical trajectories driven by coulomb and nuclear forces.

Introduce diffusion terms to allow exchange of particles, angular momentum, and energy, and calculate residual nuclei with hauser-feshbach models.



It still cannot fully predict relatively large single-nucleon transfer cross sections



Analysis ongoing.
Final experiment scheduled for Fall 2014

Summary and Future Work

- Potential for modified neutron capture cross sections in a plasma environment is important for post-detonation forensics, astrophysics, and ICF energy.
- Three planned experiments in the upcoming year to attempt to measure it.
- Xe Doped Exploding Pusher shot tentatively planned at NIF during FY2015.
- Initial experiment planned at GECKO+LFEX to test solid debris collection for TNSA proton beam experiment.
- Beam-Foil based experiment at the 88-Inch Cyclotron at LBNL scheduled for October 2014.