Constraining the low energy limit of the strength function through nuclear-plasma interactions

D.L. Bleuel[1], Andrew Ratkiewicz[1], L. Berzak Hopkins[1], L.A. Bernstein[2], K. van Bibber[2], W.S. Cassata[1], C. Cerjan[1], J.E. Escher[1], B.L. Goldblum[2], R. London[1], D. Meeker[1], S. Siem[3], C.A. Velsko[1], M. Weideking[4], and C. Yeamans[1]

[1]Lawrence Livermore National Laboratory, Livermore CA 94551, USA
[2]University of California, Berkeley CA 94720, USA
[3]University of Oslo, N-0316, Oslo, Norway
[4]iThemba LABS, Somerset West 7129, South Africa

6th Workshop on Nuclear Level Density and Gamma Strength
May 8-12, 2017

LLNL-PRES-727633

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

Why should nuclear physicists care about plasmas, anyway? 🤔

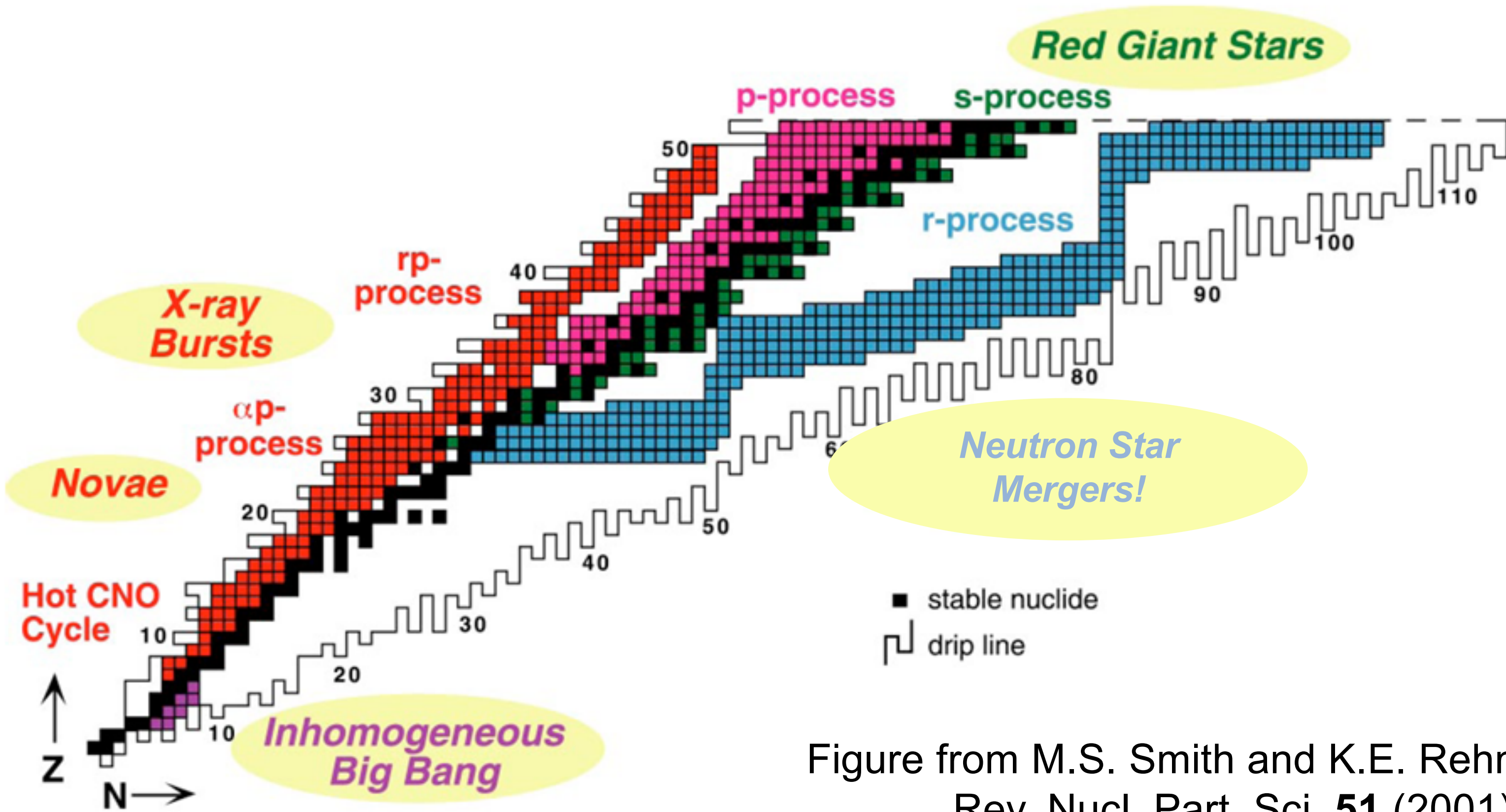
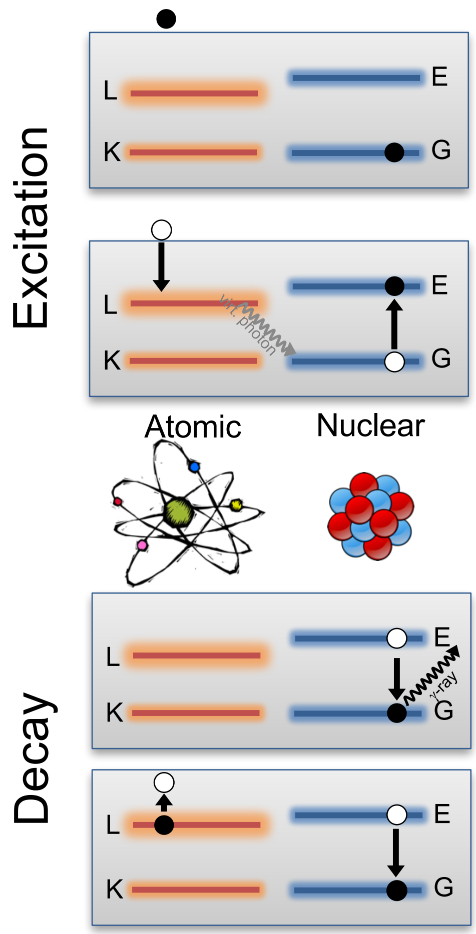


Figure from M.S. Smith and K.E. Rehm, Annu. Rev. Nucl. Part. Sci. **51** (2001)

NPI effects can change reaction cross sections in HED plasmas — consequences for nucleosynthesis, ICF implosions

Challenges in measuring electron mediated NPIs

Traditional Picture of Nuclear Excitation by Electron Capture (NEEC)



System begins with an ion in the ground state and free electrons.

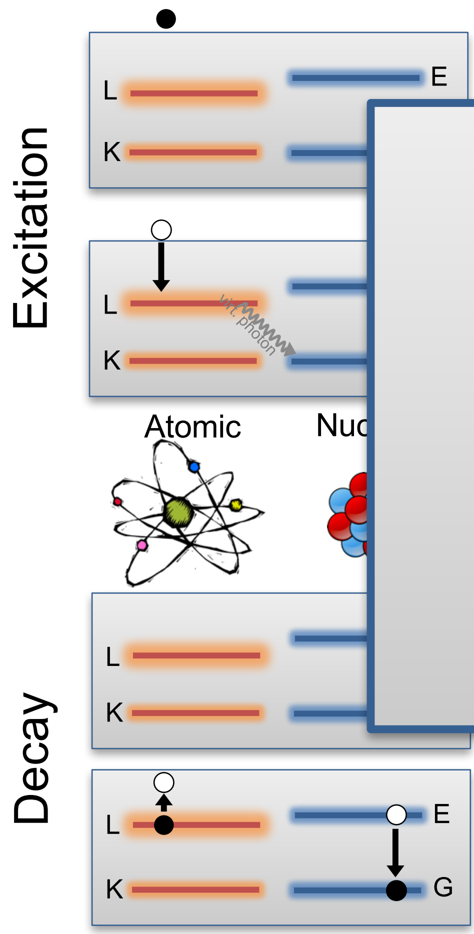
An electron is captured and the nucleus can be excited.
However, $E_\gamma = E_r + |E_b|$

Nucleus decays by emitting a γ-ray...

or the nucleus decays via internal conversion.

Challenges in measuring electron mediated NPIs

Traditional Picture of Nuclear Excitation by Electron Capture (NEEC)



System begins with an ion in the ground state and free

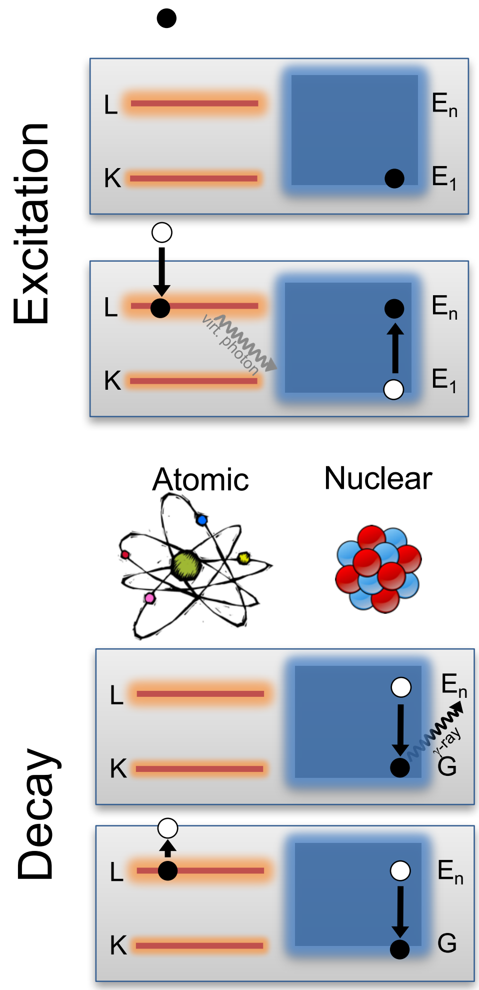
excited.

Two Major Challenges:

- Nuclear transitions are extremely narrow (Γ~1 μeV).
- HEDPs are noisy!

or the nucleus decays via internal conversion.

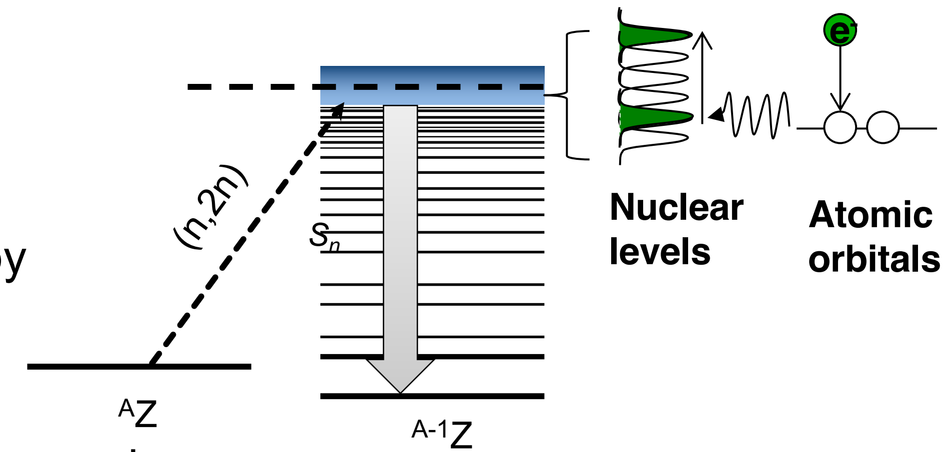
Solution: NPIs in the quasi-continuum



Create an ion in an **excited** state in the **quasi-continuum** in an environment where there are free electrons.

The level density in the quasi-continuum is high, so it is much more likely that there is a nuclear transition with
$$E_\gamma = E_r + |E_b|$$

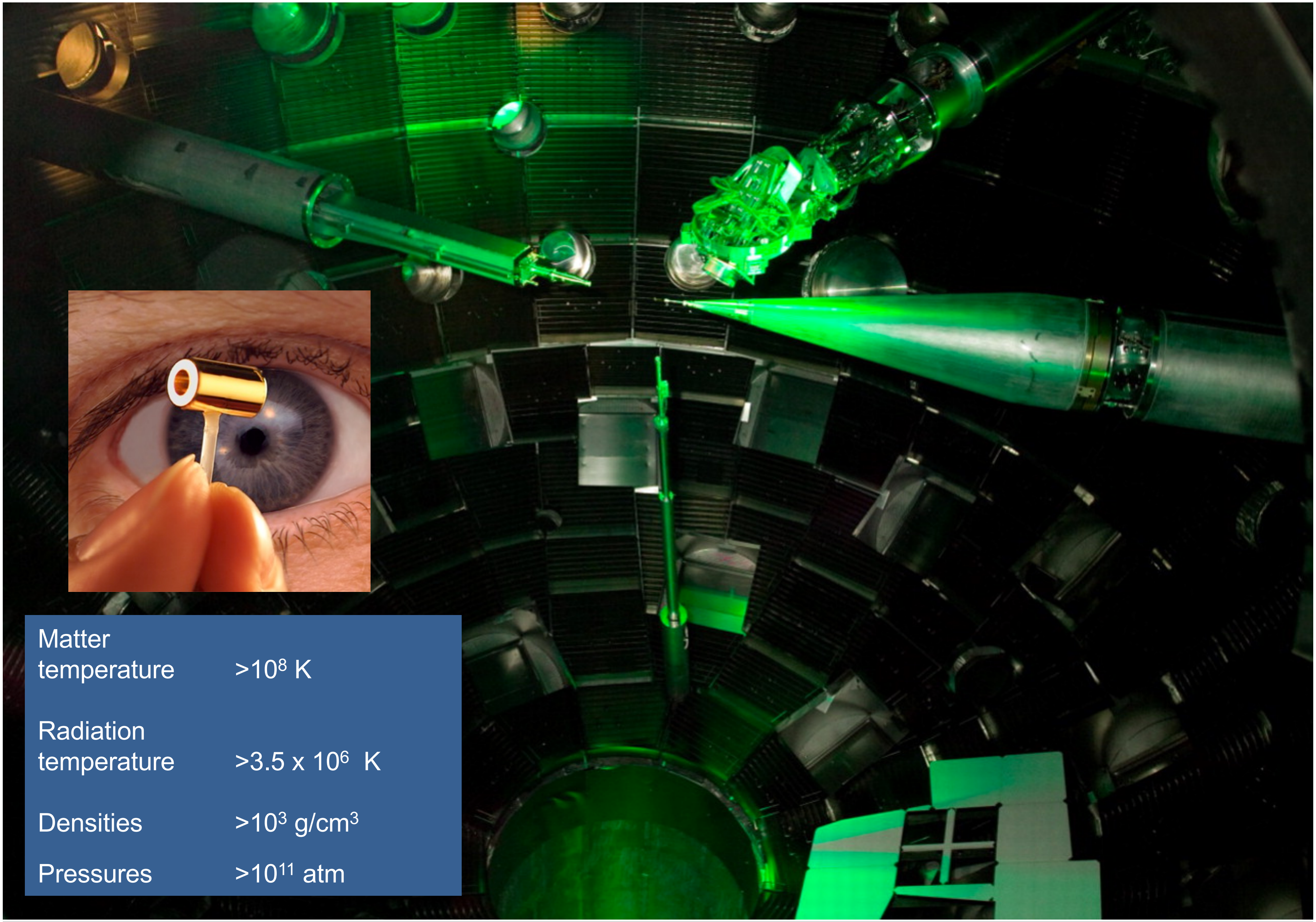
Nucleus decays by emitting a γ-ray…



or the nucleus decays via internal conversion

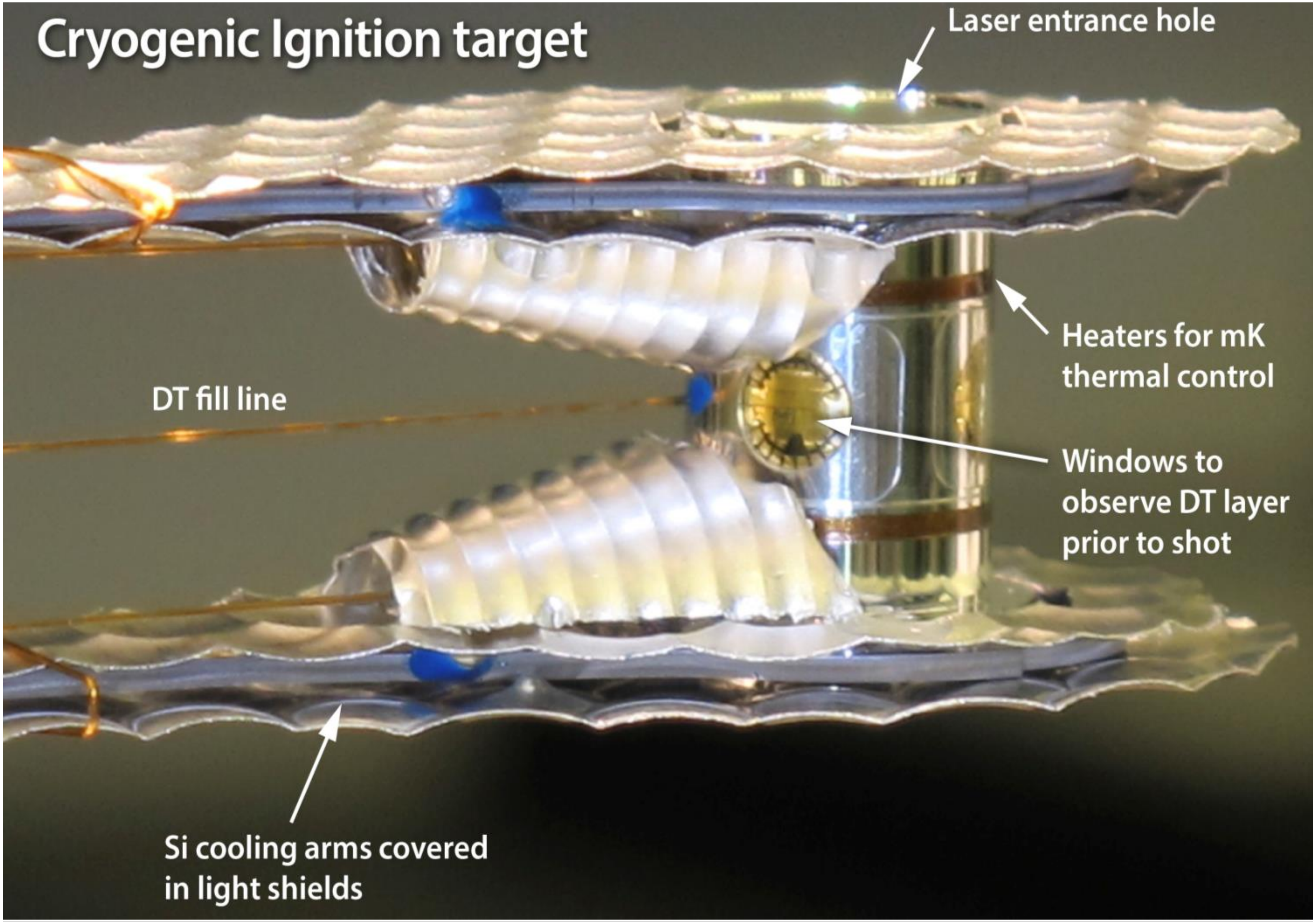
But where can we achieve these conditions?

The National Ignition Facility: a football stadium-sized facility generates MJ of energy into 192 laser beams and concentrates that energy into a mm^3

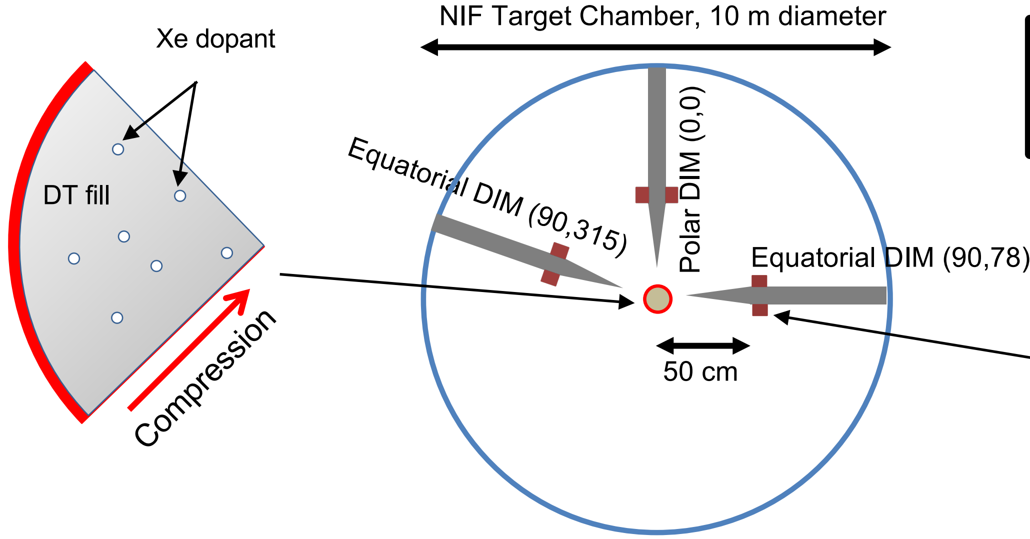


Matter temperature	$>10^8$ K
Radiation temperature	$>3.5 \times 10^6$ K
Densities	$>10^3$ g/cm^3
Pressures	$>10^{11}$ atm

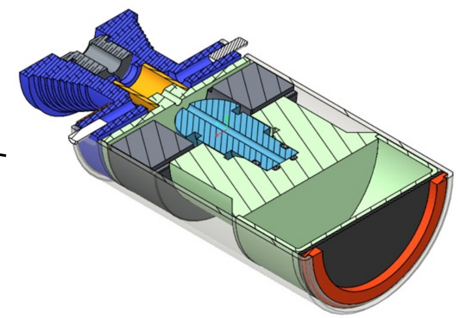
Cryogenic Ignition target



NIF can create highly-excited nuclei in a high energy density plasma



But how do we **detect** NPIs in such a chaotic environment?



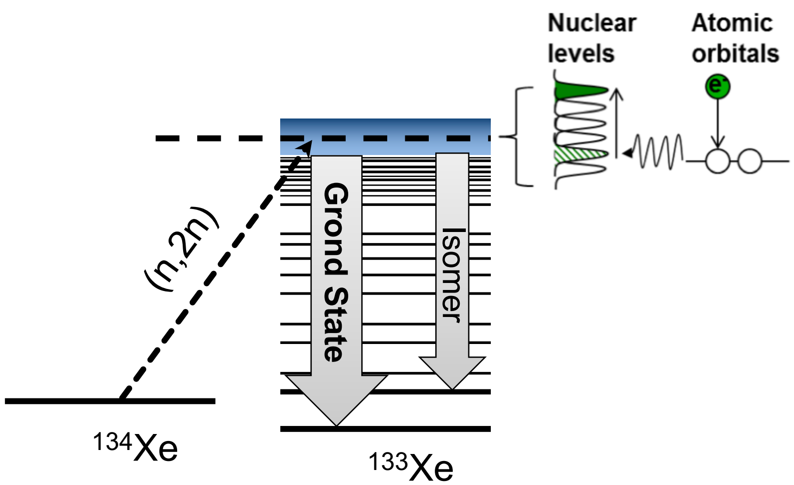
- **Target**: IDEP (indirect drive, exploding pusher) filled with 10 atm DT, doped with 0.01 atm ^{134}Xe.
- Sees neutrons, plasma.
- Post-shot, gaseous products collected by RAGS.
- Sample counted at LLNL NCF.

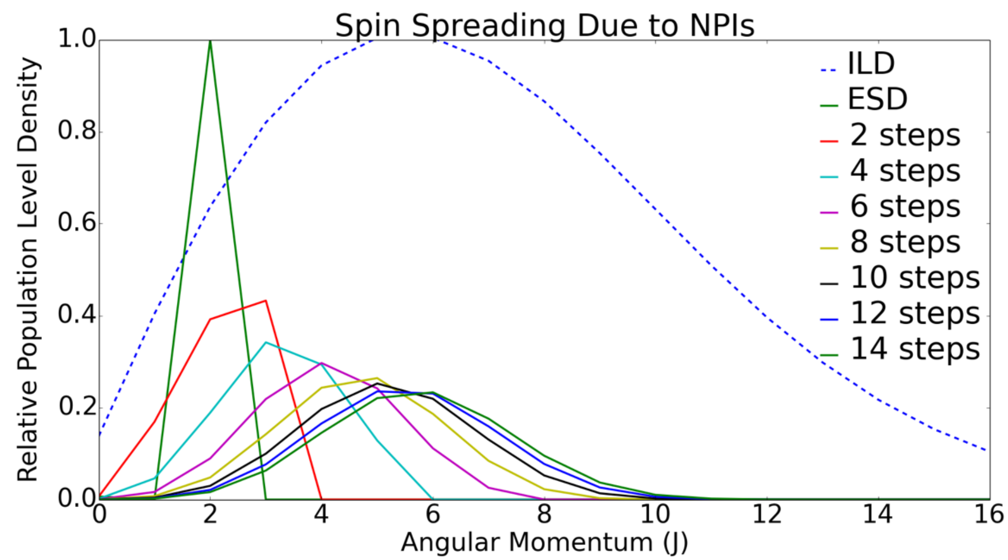
- **Control**: up to 12 gas cells filled with ~1 atm of isotopically pure (>99%) ^{134}Xe.
- Sees only neutrons.
- Post-shot, cell collected by technician.
- Sample counted at LLNL NCF.

NPIs change spin distributions

- Changes to the entry spin distribution of the compound nucleus can affect both the probability of γ decay relative to neutron emission *and* the γ-decay branching ratios

- Select a target which will produce a radioactive nucleus with a long-lived, low-energy, isomer allowing the quantification of this effect.





Calculation by Jutta Escher, LLNL

NPIs change spin distributions

- Changes to the entry spin distribution of the compound nucleus can affect both the prob … ios
- Sele … ergy, isom …

Two Major Challenges:

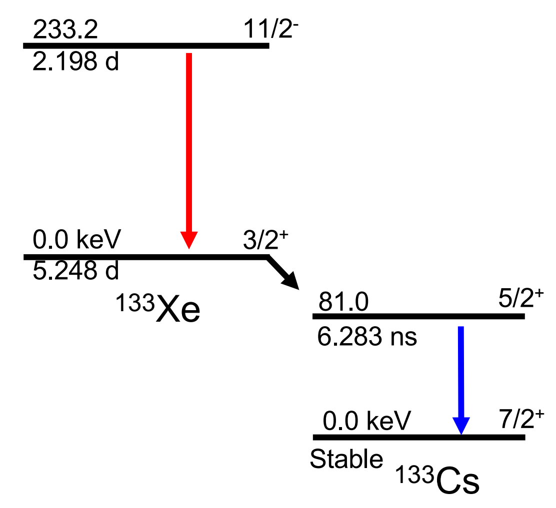
- *Nuclear transitions are extremely narrow.*
  → **Level density in the quasi-continuum is extremely high (ρ~1/eV)**
- *HEDPs are noisy!*
  → **Use relative population of long-lived isomer, ground state to record CN spin change.**

Calculation by Jutta Escher, LLNL

The DIGS (double isomer to ground state) ratio is our experimental signature of NPIs

- Extracting the DIGS ratio requires two independent samples:
  - The *plasma* sample, which is exposed both to plasma and to neutrons.
  - The *control* sample, which is exposed only to the neutrons.

$$R_{DIGS} = \frac{N^{Xe-133m}_{plasma} / N^{Xe-133g}_{plasma}}{N^{Xe-133m}_{control} / N^{Xe-133g}_{control}}$$



Decay of ^{133}Xe

(gammas measured in HPGe)

- A value of $R_{DIGS} \neq 1$ could indicate NPI effects.
- A value of $R_{DIGS} = 1$ would help constrain low-energy photon transition strength in the quasi-continuum [1].

[1] D.L. Bleuel *et al.*, *Plasma Fusion Res.* **11** 3401075 (2016).

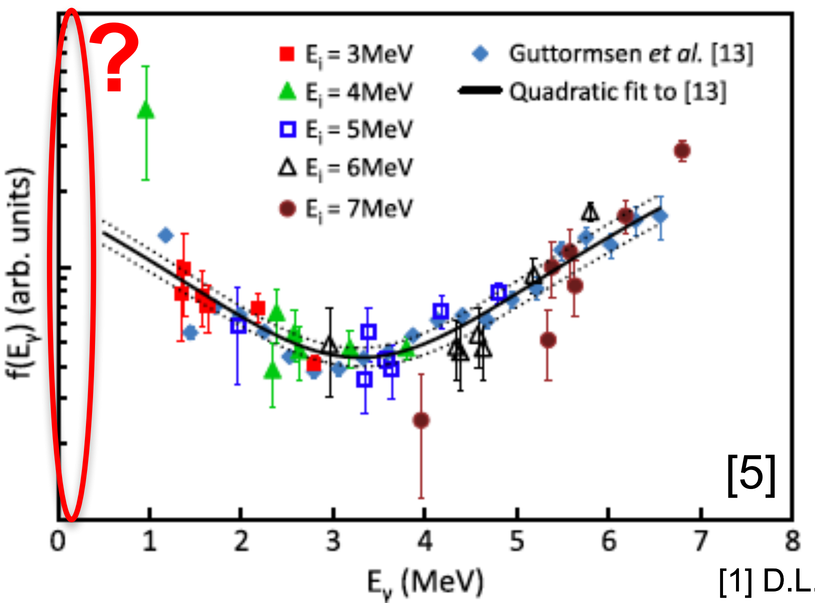
Everything depends on the level density and strength function at low (keV) energies

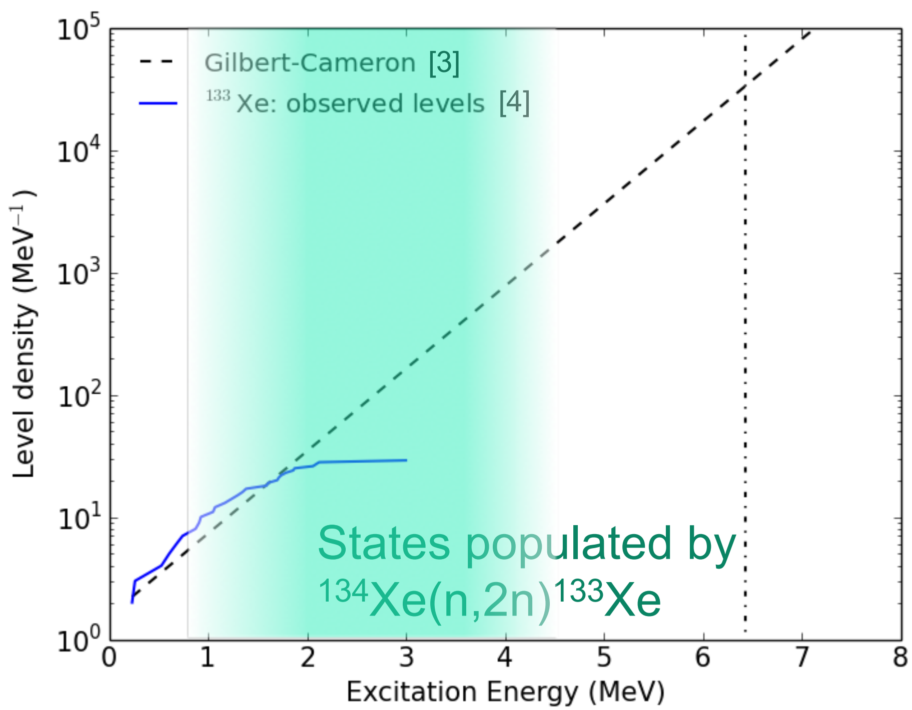
NEEC rate:

$$\lambda_d^{NEEC} = \int dE_r \frac{d\Phi(E_r)}{dE_r} \sum_{all\ b} \frac{2J_f+1}{2J_i+1} \frac{\alpha(T_e)\ln(2)E_\gamma^3}{\hbar} S(E_\gamma) f_{FD}(E_b)(1-f_{FD}(E_r))$$ [1,2]

Photon strength function:

$$S(E_\gamma) = \frac{\hbar}{2} \frac{\rho\left(E_i + E_\gamma, J_f\right)}{\langle T^\gamma_{i\to f}\rangle E_\gamma^3}$$

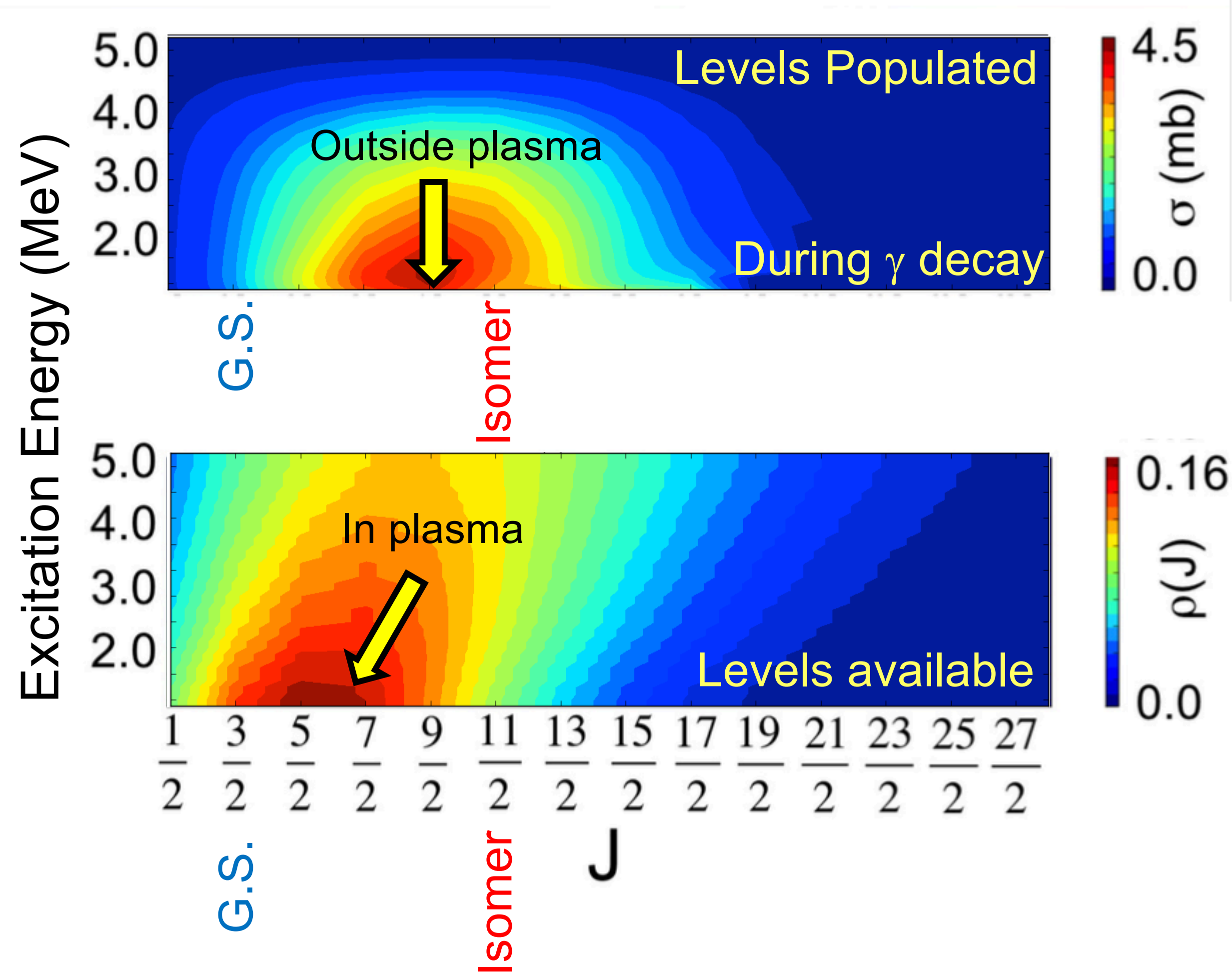




[1] D.L. Bleuel *et al.*, *Plasma Fusion Res.* **11** 3401075 (2016).
[2] Gosselin and Morel, PRC **70**, 064603 (2004).
[3] A. Gilbert and A. G. W. Cameron, *Canadian J. Phys.* **43** (1965) 1446
[4] NNDC
[5] Wiedeking et al., PRL **108**, 162503 (2012)

Hauser-Feshbach calculations are done with TALYS

- Predicts the entry spin distribution of the compound nucleus (peaked at J = 9/2)
- The strength feeding the (J = 11/2) isomer mostly comes from CN states with J ≥ 9/2
- NPIs will shift the angular momentum distribution towards the available level distribution.
- Preliminary Monte Carlo estimates indicate possible ~5-10% effect on DIGS (single particle γSF model).

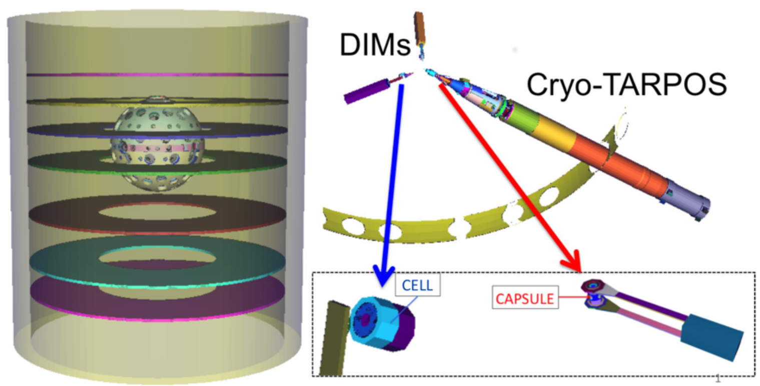


[4] A.J. Koning, S. Hilaire and M.C. Duijvestijn, *Proc. ND2007*, (2008).
[1] D.L. Bleuel *et al.*, *Plasma Fusion Res.* **11** 3401075 (2016).

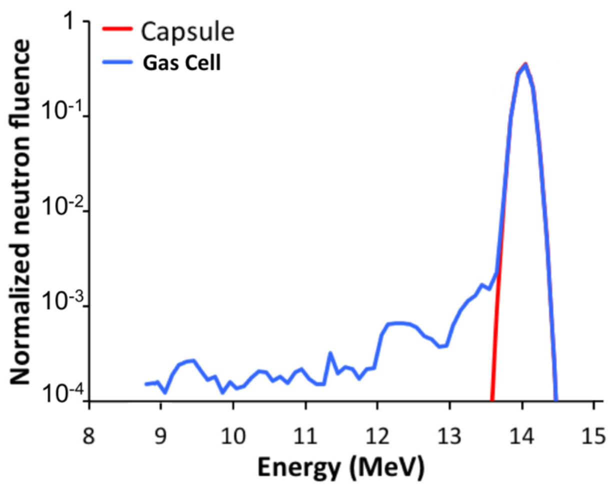
MCNP

(Monte Carlo N-Particle) code was used to simulate neutron transport

- Neutron scattering off of chamber components can contribute to the uncertainty in the DIGS ratio.
  - The (n,2n) reaction cross section is energy-dependent. Downscattering neutrons will increase the DIGS ratio.
- The NIF chamber and its internal components have been modeled with MCNP to determine the effect of neutron downscattering [1].
  - The simulated difference between the neutron spectrum seen by the gas cell and in the capsule leads to a 0.22% increase in the DIGS ratio.

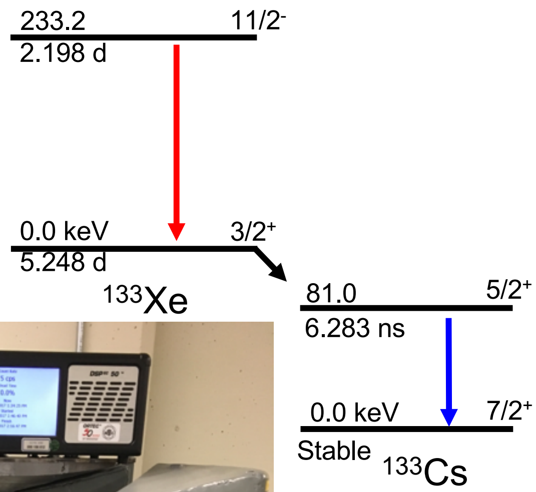


Simulation components by H. Khater, C. Hagmann, J. Hall, C. Brand, and D. Bleuel



[1] D.L. Bleuel *et al.*, *Plasma Fusion Res.* **11** 3401075 (2016).

Measure the decay of ^{133}Xe at the Nuclear Counting Facility



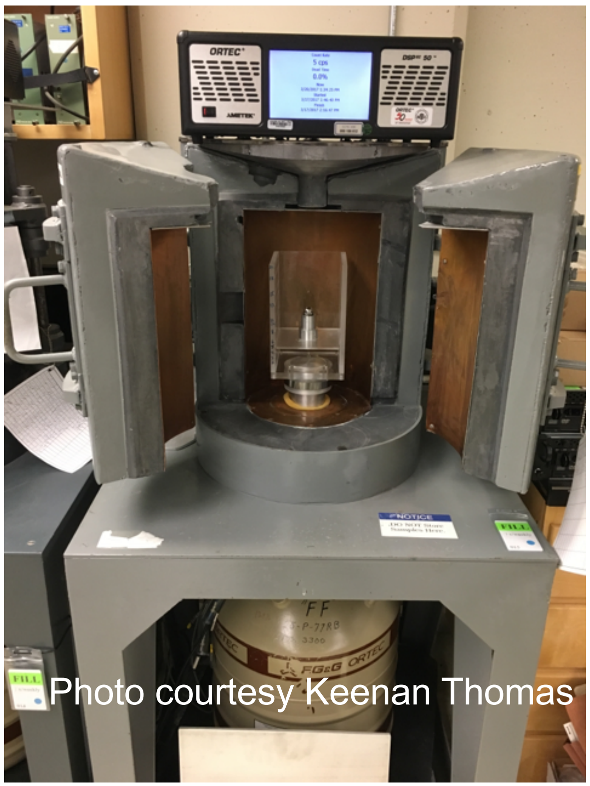
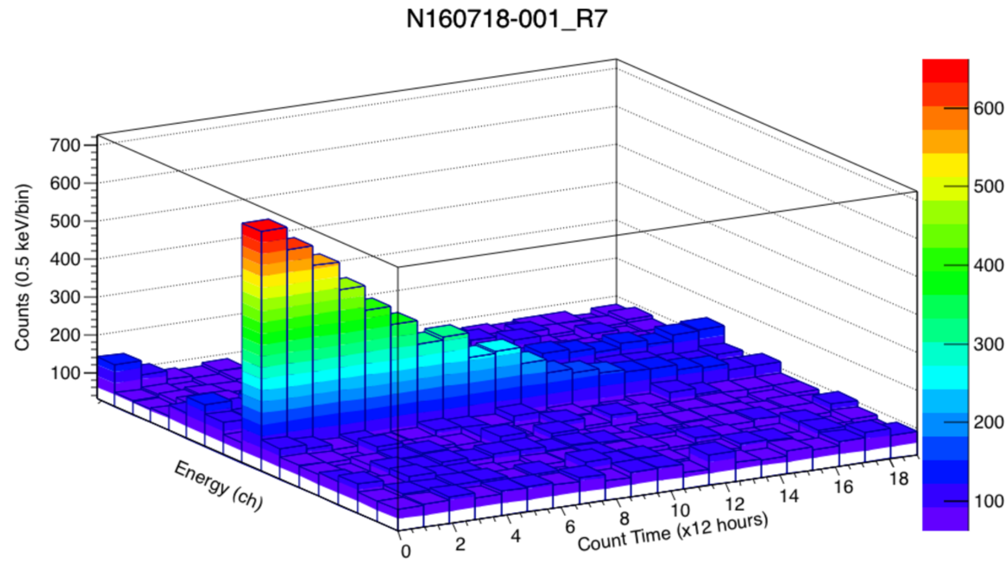
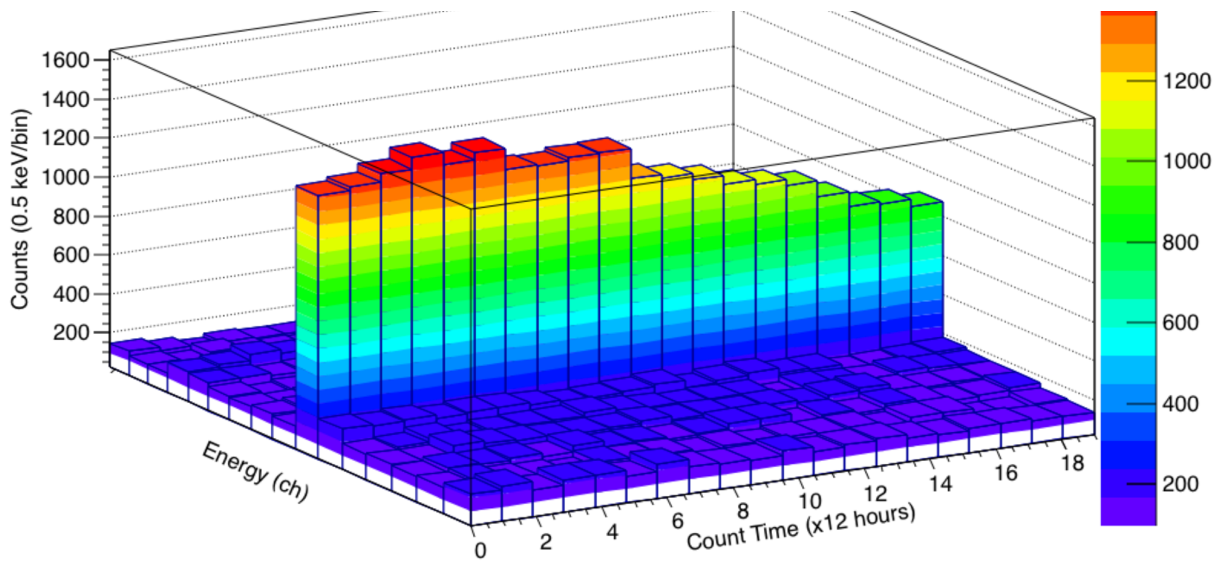


Photo courtesy Keenan Thomas





Extracting the (D)IGS ratios

Next shot: May 2017! (>3x the statistics?)

Preliminary – but intriguing!

NPIs can change reaction cross sections in HED plasmas, are of interest to ICF implosions and nucleosynthesis

- Past attempts to measure NEEC have been hampered by the narrowness of the nuclear transitions thought to participate and the noisiness of the plasma environment.

  - **We address these challenges by inducing NEEC on an excited nucleus and by using the relative populations of the isomer to the ground state in ^{133}Xe to assess NPI effects.**

- The first NIF measurements probing the strength of NPIs occurred in early FY17.

  - **Preliminary results are not inconsistent with a weak NPI effect.**
  - **Even no measured effect can constrain the strength function at keV energy!**

- Follow-on shots to increase statistics are planned for mid and late FY17.

Thank you for your attention!

Lawrence Livermore National Laboratory