Experimental Measurement at the NIF of Electron-mediated Nuclear Plasma Interactions

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

February 1st, 2016

LLNL-PRES-681817

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

About half of the elements between Fe and Bi were formed in neutron-induced reactions in HED plasmas

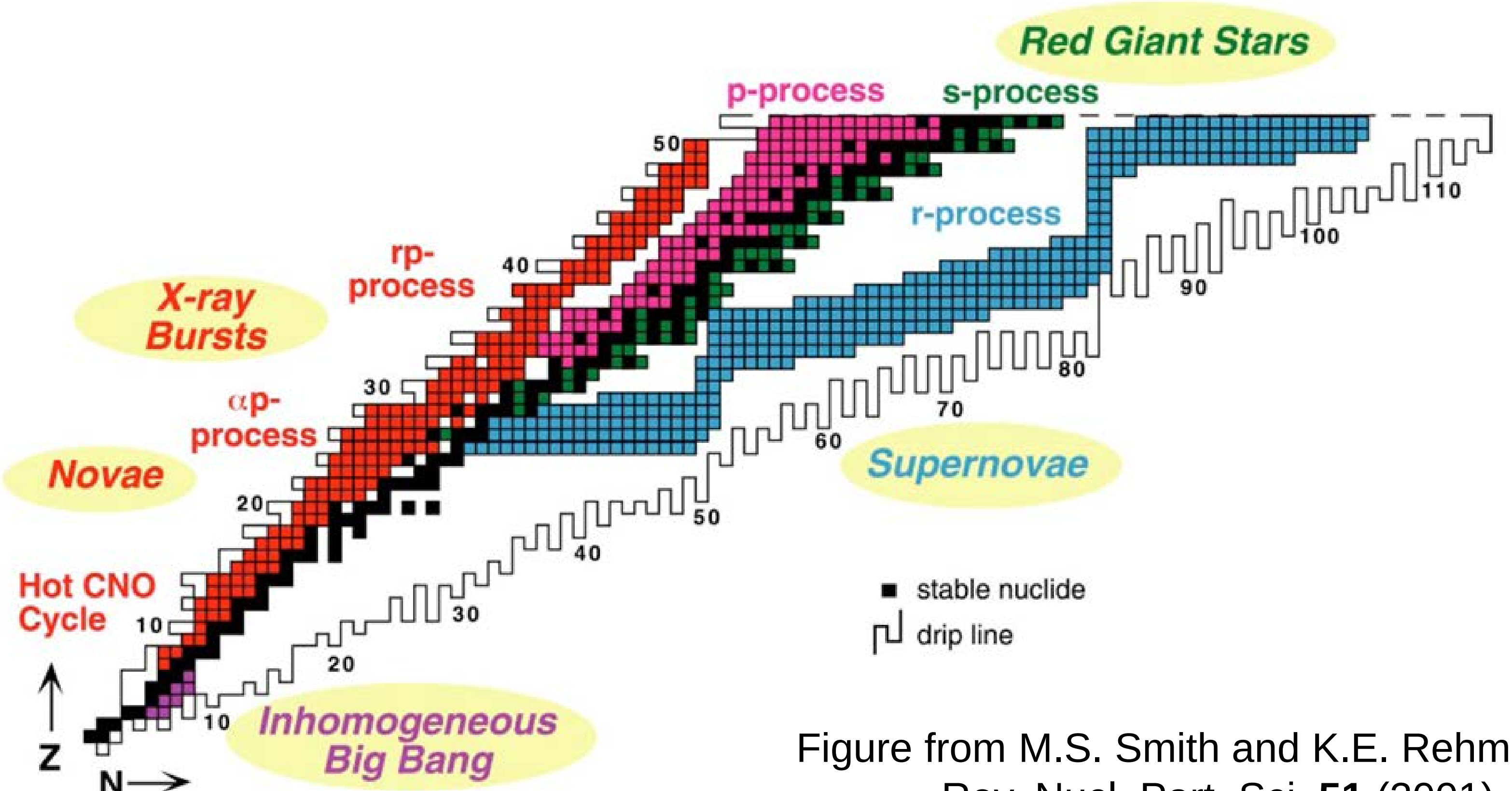
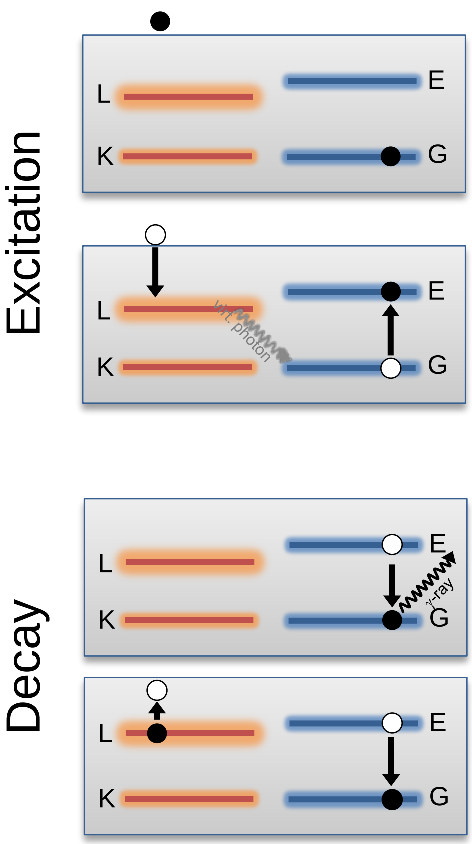


Figure from M.S. Smith and K.E. Rehm, Annu. Rev. Nucl. Part. Sci. **51** (2001)

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.

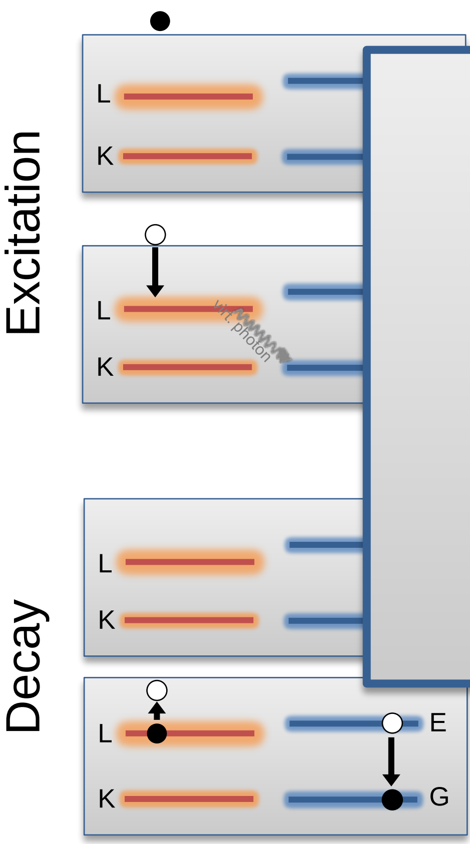
An electron is captured and the nucleus can be excited via the resonate transfer of a virtual photon. **However**, the nuclear transition energy must be well-matched to that of the virtual photon.

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 via

ver, the

to that of

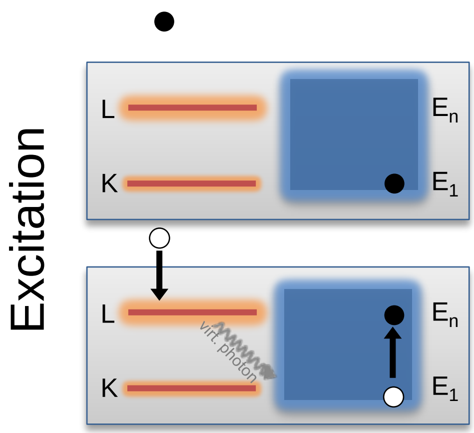
Two Major Challenges:

1. Nuclear transitions are extremely narrow (Γ~1 μeV).

1. HEDPs are noisy! It is difficult (or impossible) to discriminate between the prompt ~few keV γ ray coming from NPI effects and the plasma background.

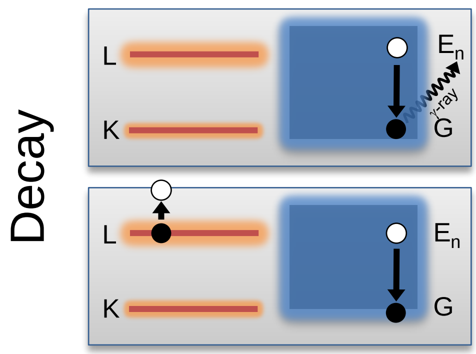
or the nucleus decays via internal conversion.

The NIF can help measure NPIs



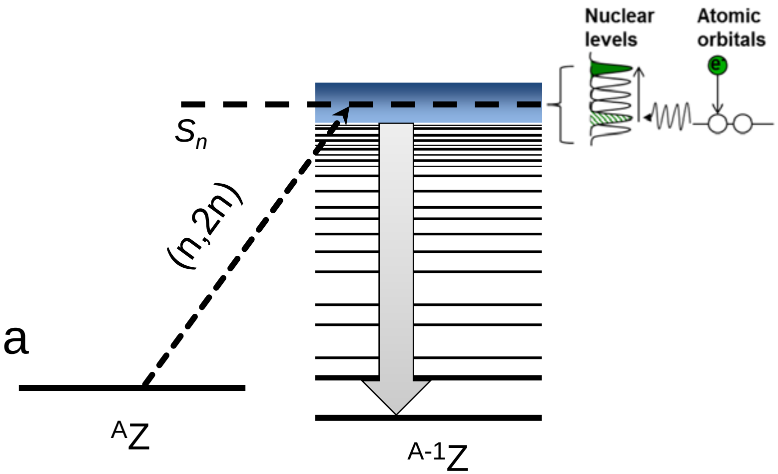
Create an ion in an **excited** state in the **quasi-continuum** in an environment where there are free electrons.

The level density in the quasi-continuum is high, so it is much more likely that there is a nuclear transition with $\Delta E_n = \text{B.E.} + E_{elec}$



Nucleus decays by emitting a γ-ray…

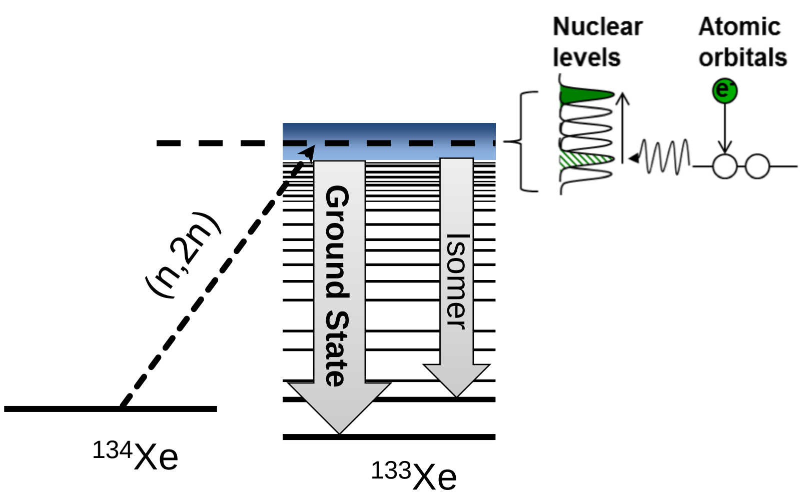
or the nucleus decays via internal conversion

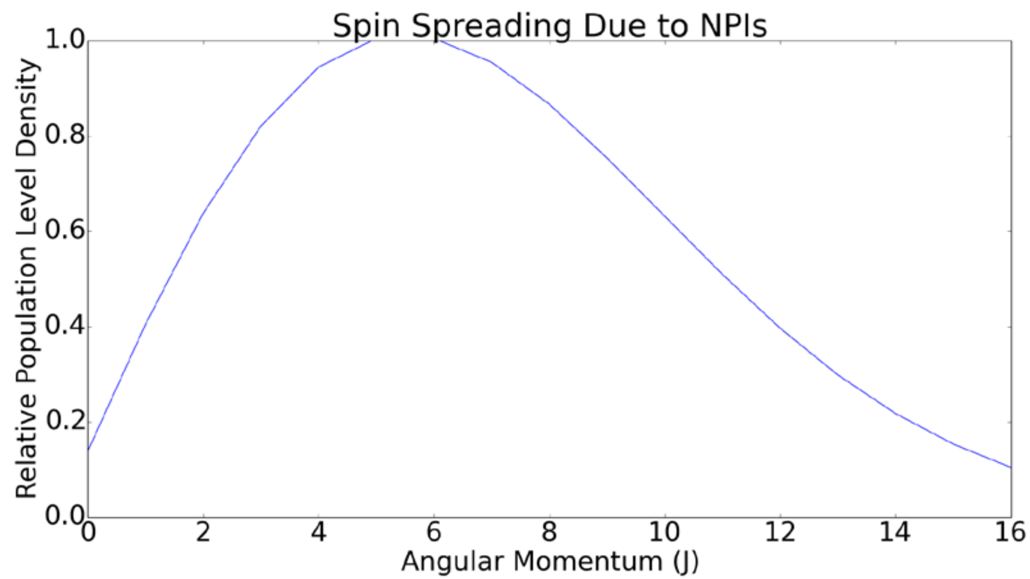


NPIs change spin distributions

- 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.

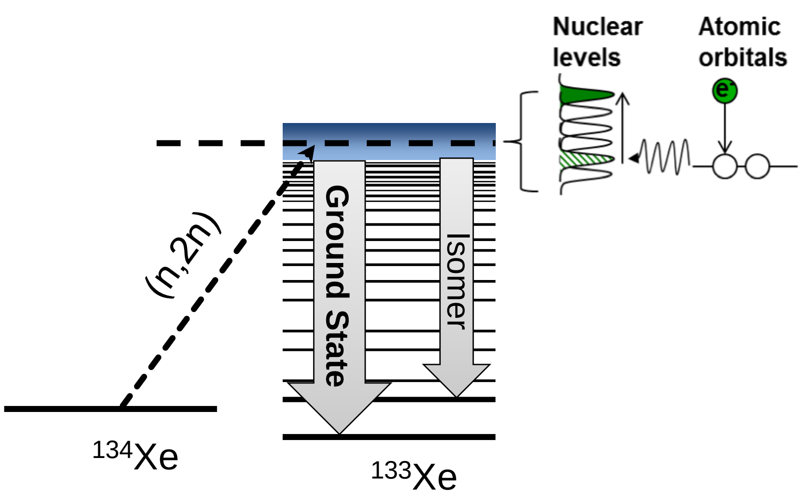


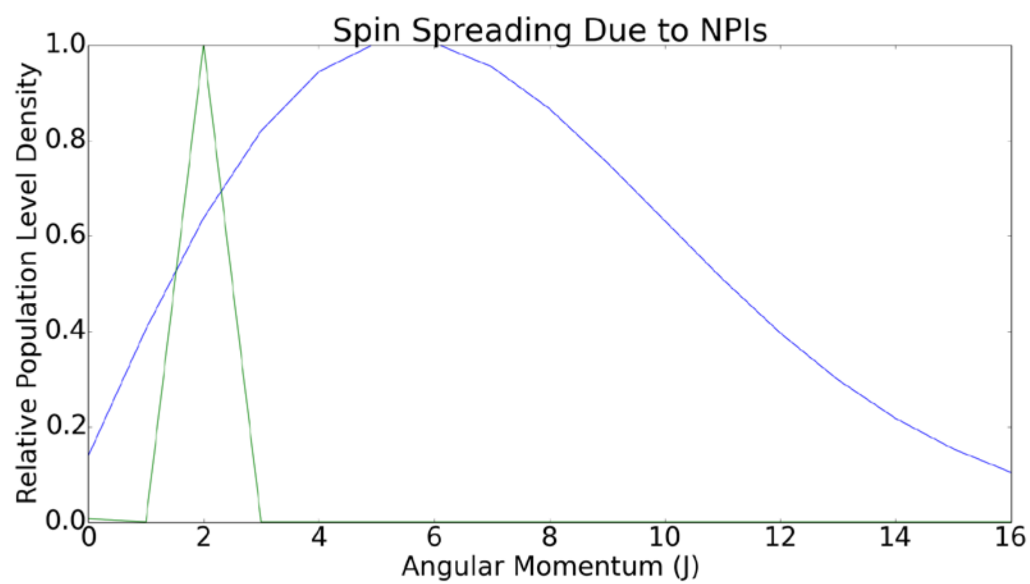


Calculation by Jutta Escher, LLNL

NPIs change spin distributions

- Changes to the entry spin distribution of the compound nucleus can affect both the 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.



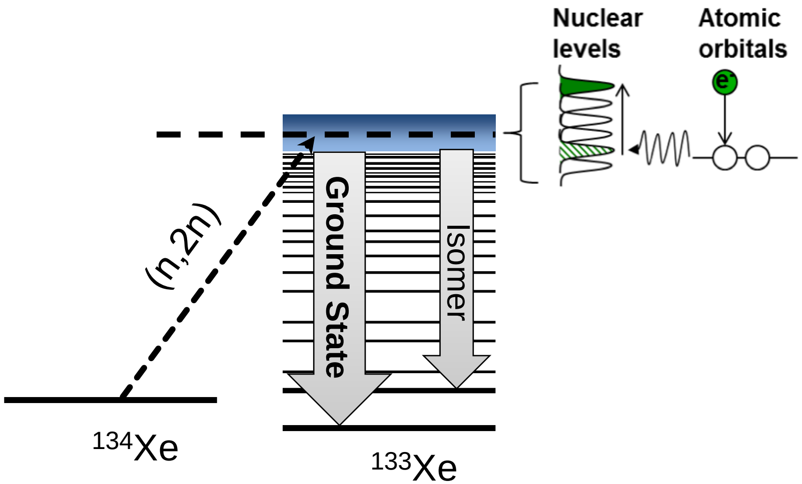


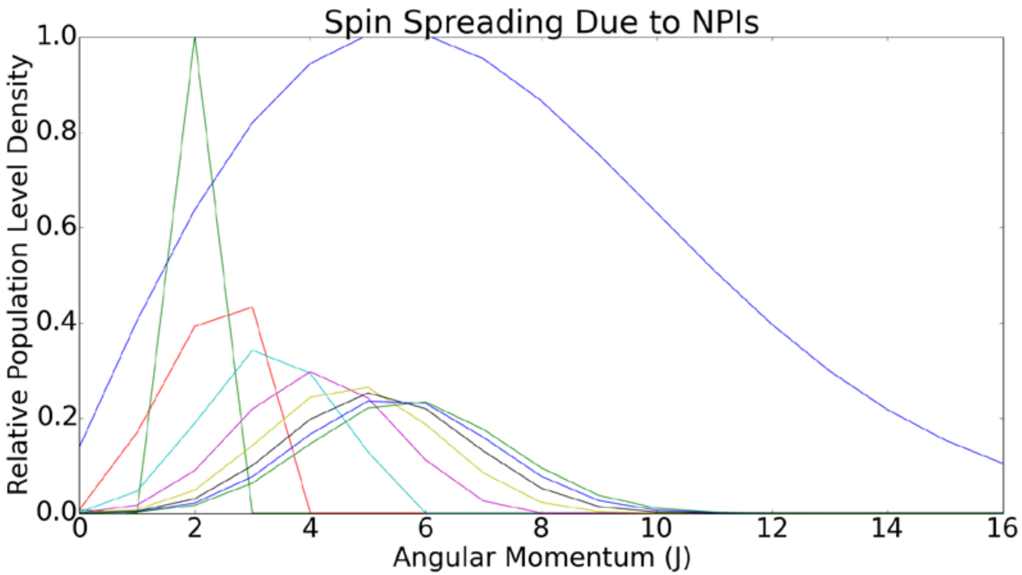
Calculation by Jutta Escher, LLNL

NPIs change spin distributions

- Changes to the entry spin distribution of the compound nucleus can affect both the 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

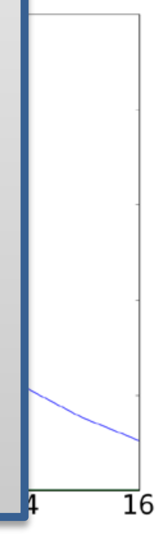
NPIs change spin distributions

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

Two Major Challenges:

1. *Nuclear transitions are extremely narrow.*
   → **Level density in the quasi-continuum is extremely high (ρ~1/eV)**

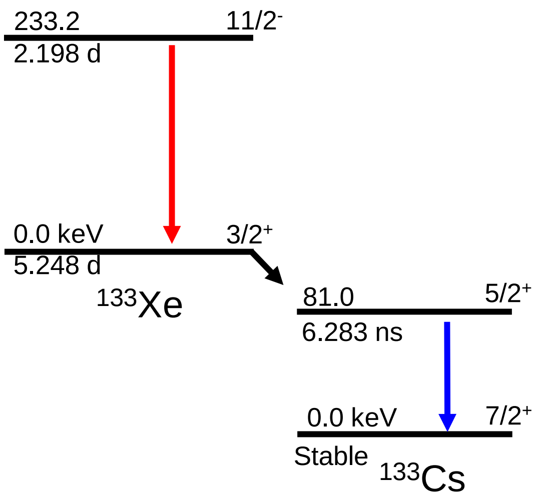
1. *HEDPs are noisy! It is difficult (or impossible) to discriminate between the prompt ~few keV γ ray from NPI effects and background.*
   → **Select a target which will produce a radioactive nucleus with a ~few day, ~few 100-keV isomer, probe the strength of NPI effects by measuring the relative population of the isomer and ground state.**



Calculation by Jutta Escher, LLNL

Isomeric decay as an experimental signature of NPIs

- The Double Isomer to Ground State (DIGS) ratio represents the differential population of a high-spin isomer to the ground state of a nucleus [1].
- 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.

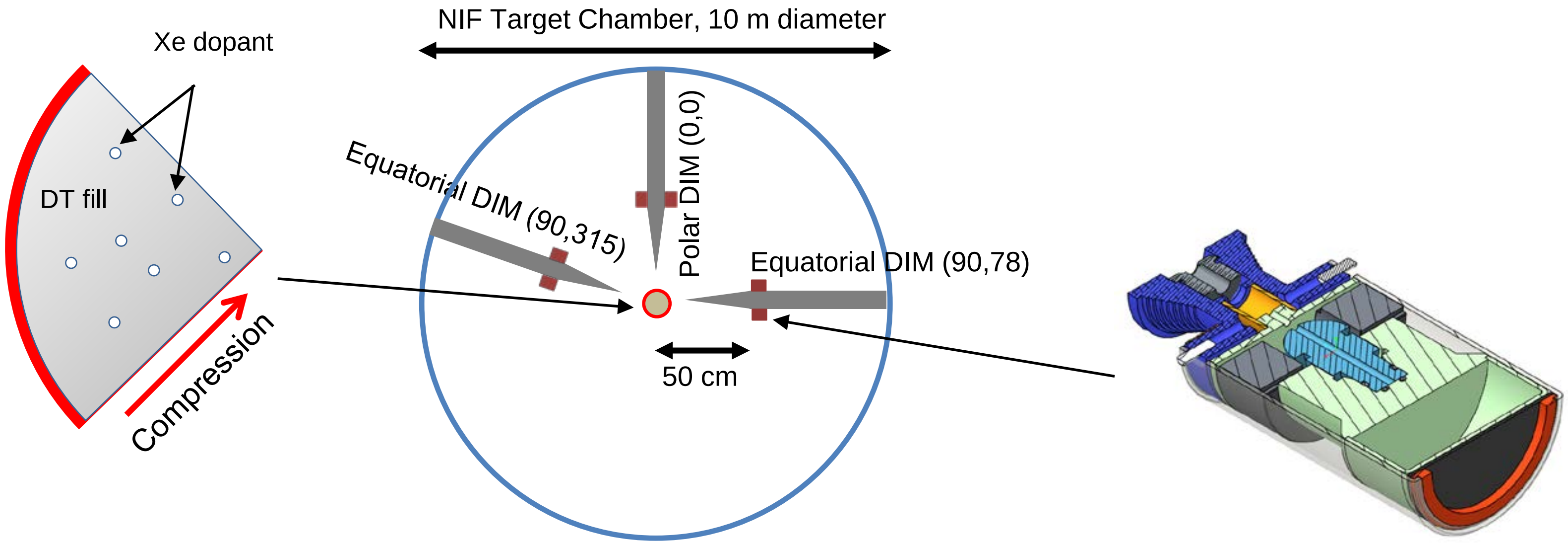


$$R_{DIGS} = \frac{N_{plasma}^{Xe-133m} / N_{plasma}^{Xe-133g}}{N_{control}^{Xe-133m} / N_{control}^{Xe-133g}}$$

- 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] D.L. Bleuel *et al.*, to be published in Plasma Fusion Res. (2016).

Measuring electron-mediated NPIs at the NIF

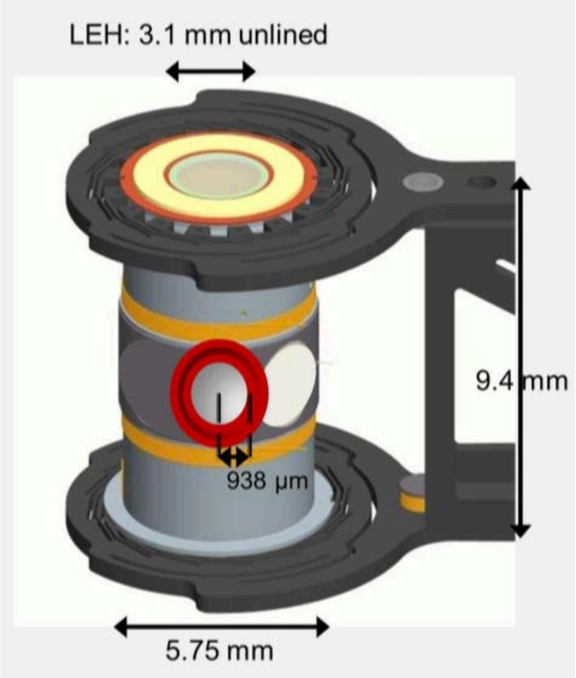


- **Target**: IDEP (indirect drive, exploding pusher) filled with 10 atm DT, doped with 0.3 atm ^{134}Xe.
- Sees neutrons, plasma.
- Post-shot, gaseous products collected by RAGS.
- Sample counted at LLNL NCF.

- **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.

The IDEP platform has been design and qualified

- This platform is designed [2] for use with low laser energies, no damage to optics.
- Targets use standard “off the shelf” NIF hohlraum components.
- Capsule is NIF-standard CH with graded Si dopant, 940 μm inner radius, with 120 μm ablator thickness.
- Platform has been successfully fielded 7 times to date.
  - Capsule and hohlraum performance well-matched by standard radiation hydrodynamics codes.
  - Shots demonstrated excellent implosion symmetry and high neutron yield (5×10^{14} neutrons).
  - The platform causes minimal downscattering of the neutron spectrum.



Slide courtesy L. Berzak Hopkins

[2] S. LePape, Phys. Rev. Lett. 112, 225002 (2014).

Collecting chamber gas with RAGS

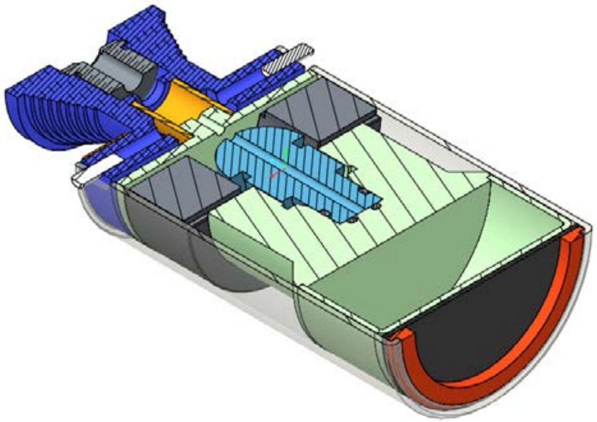
- The target will be destroyed in the shot. The Radiochemical Analysis of Gaseous Samples apparatus (RAGS) [1] will collect the gaseous residue from the chamber minutes after the shot has concluded.
- The collection efficiency of RAGS has been measured at ~90% [3].
- Chamber gas is first pumped through a filter cart, which removes water and reactive gasses.
- The gas is then fractioned in the xenon cart, where the xenon will be collected in a cryotrap, transferred to a sample bottle, and removed for analysis.
  - The contents of the sample bottle will be counted at the LLNL NCF.

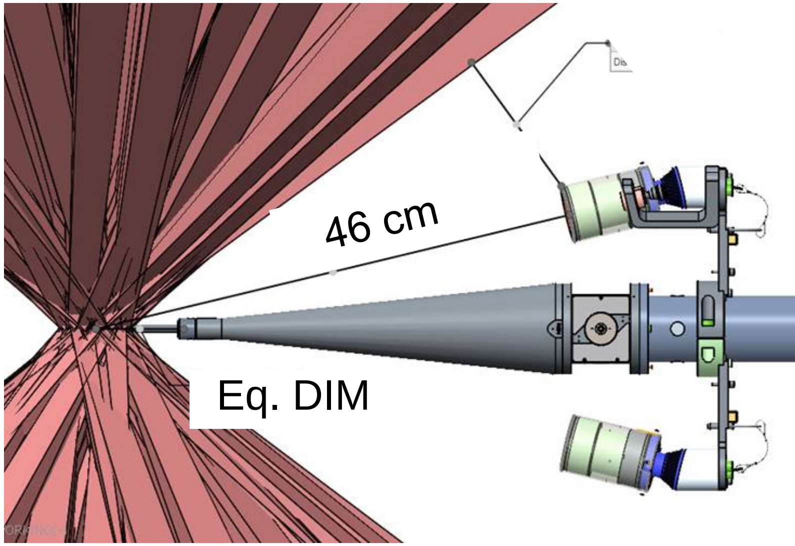
Figure from [1]

[3] D. A. Shaughnessy *et al.*, Rev. Sci. Instrum. **83**, 10D917 (2012).

A new diagnostic has been designed and qualified

- The gas cells are mounted in-chamber, recoverable, and reusable.
- **New** design to support larger volumes (34.3 cm^3) of gas.
- Up to twelve cells can be simultaneously fielded at different locations around the target.
- Diagnostic qualified in two ride-along shots to date:
  - N151105-002: 5 cells with ^{124}Xe:^{136}Xe at 4:1, 1 cell with ^{134}Xe
  - N151228-001: two ^{nat}Xe cells
  - Also used for a Xe activation measurement at LBNL.
  - Additionally, Xe-implanted Al foils can be attached to the outside of the target to provide independent measurement of NPI effects.
  - This diagnostic has also been modified to allow the assessment of the effect of high neutron fluence on active electronic device test objects.





Diagnostic qualification shots show isotopes of interest

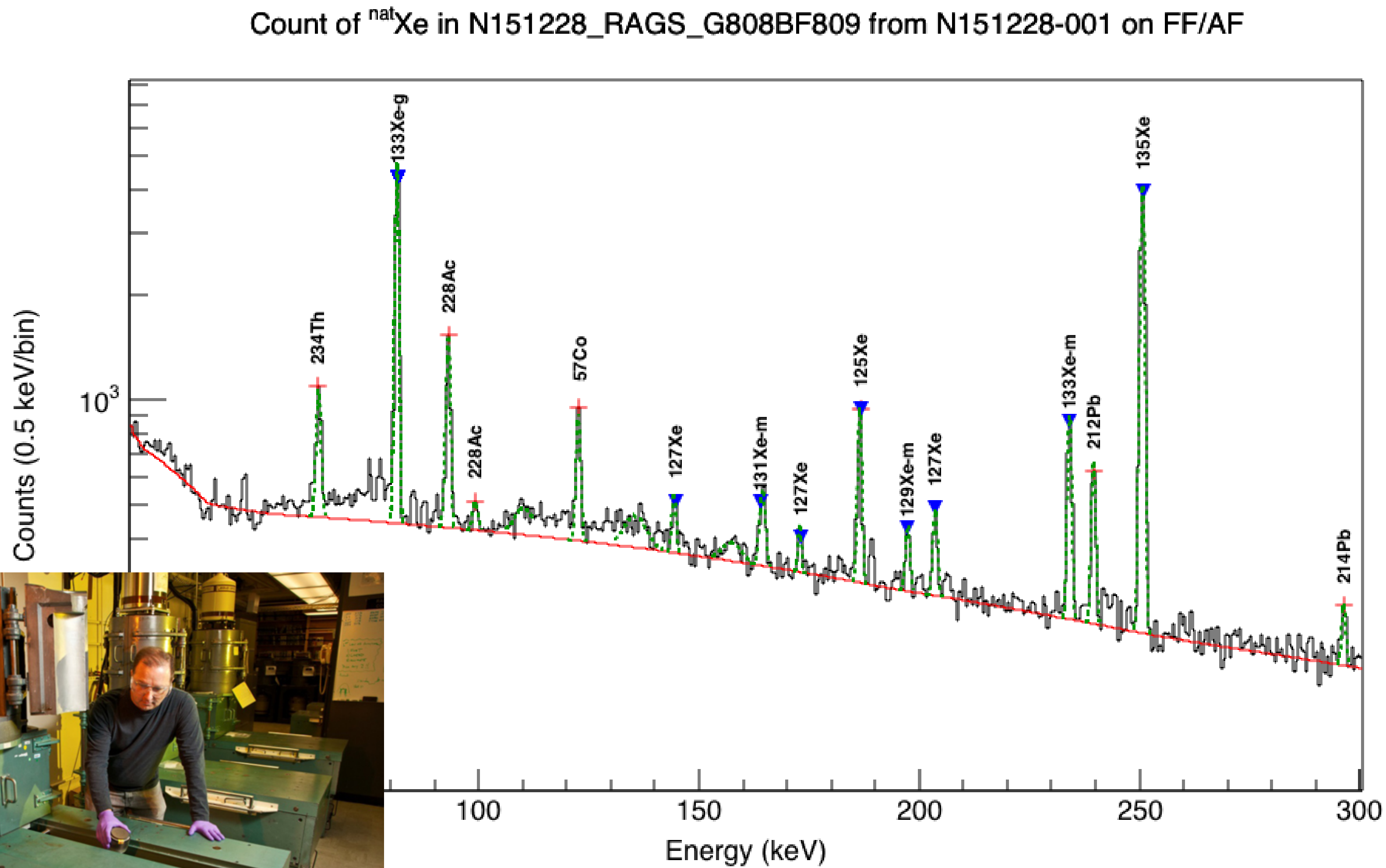
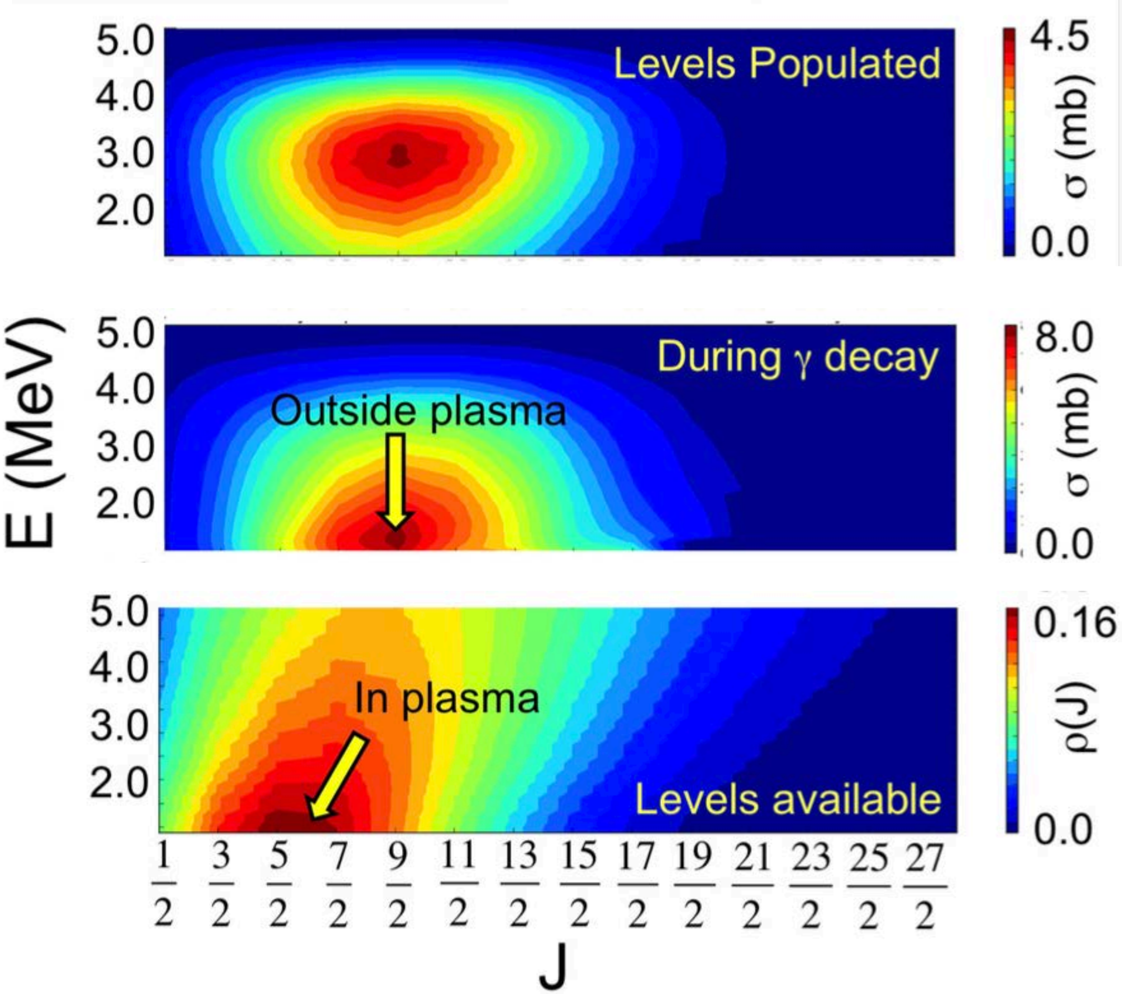


Photo from https://pls.llnl.gov/people/divisions/nuclear-and-chemical-sciences-

TALYS

a coupled-channels code for simulating nuclear physics experiments [4]

- 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** calculations indicate that this effect leads to a ~5% reduction in the isomer to ground state ratio [1].

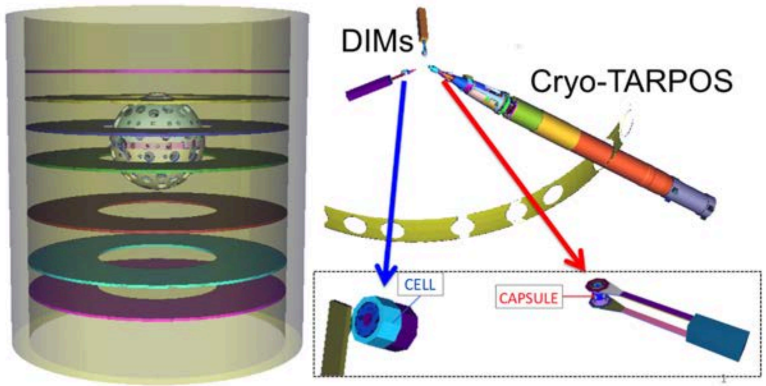


[4] A.J. Koning, S. Hilaire and M.C. Duijvestijn, Proc. ND2007, (2008).
[1] D.L. Bleuel *et al.*, to be published in Plasma Fusion Res. (2016).

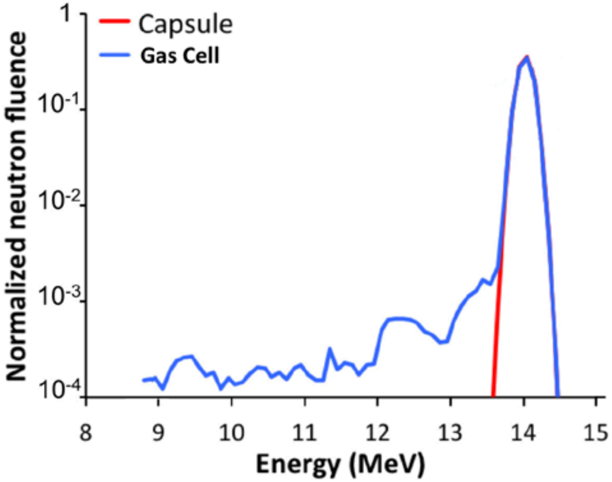
MCNP

(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.



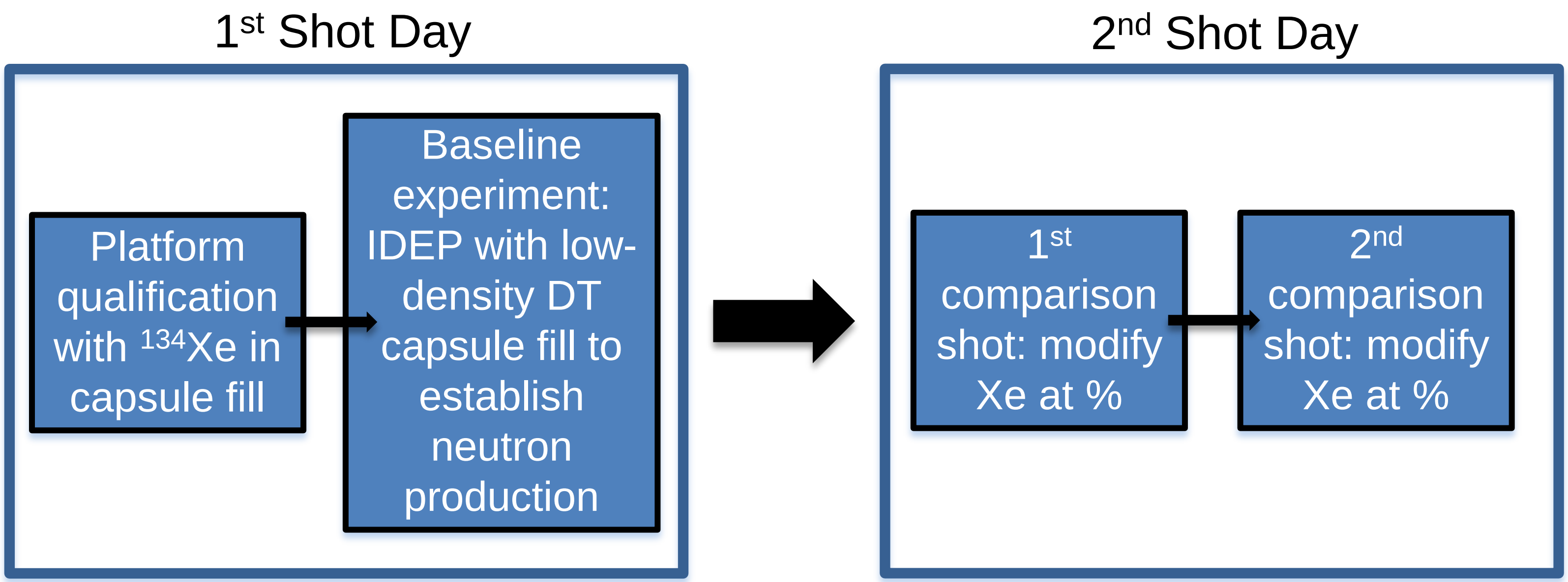
Simulation componets by H. Khater, C. Hagmann, J. Hall, C. Brand, and D. Bleuel



[1] D.L. Bleuel *et al.*, to be published in Plasma Fusion Res. (2016).

Two shot days, with two shots per day allocated through Discovery Science.

- Field gas cells with all shots.



- We plan to execute these shots in FY17.

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 will 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.**
- We have designed and qualified a new platform and diagnostic to conduct these measurements.
- We have quantified the effect of neutron scattering on the isomer and ground state population using an MCNP model of the NIF chamber and its components.
- Calculations to predict NPI rates are on-going.
- The first measurements of NPIs at NIF are planned to occur in FY17!

Thank you for your attention!

Lawrence Livermore
National Laboratory