Nuclear Physics for and with the National Ignition Facility

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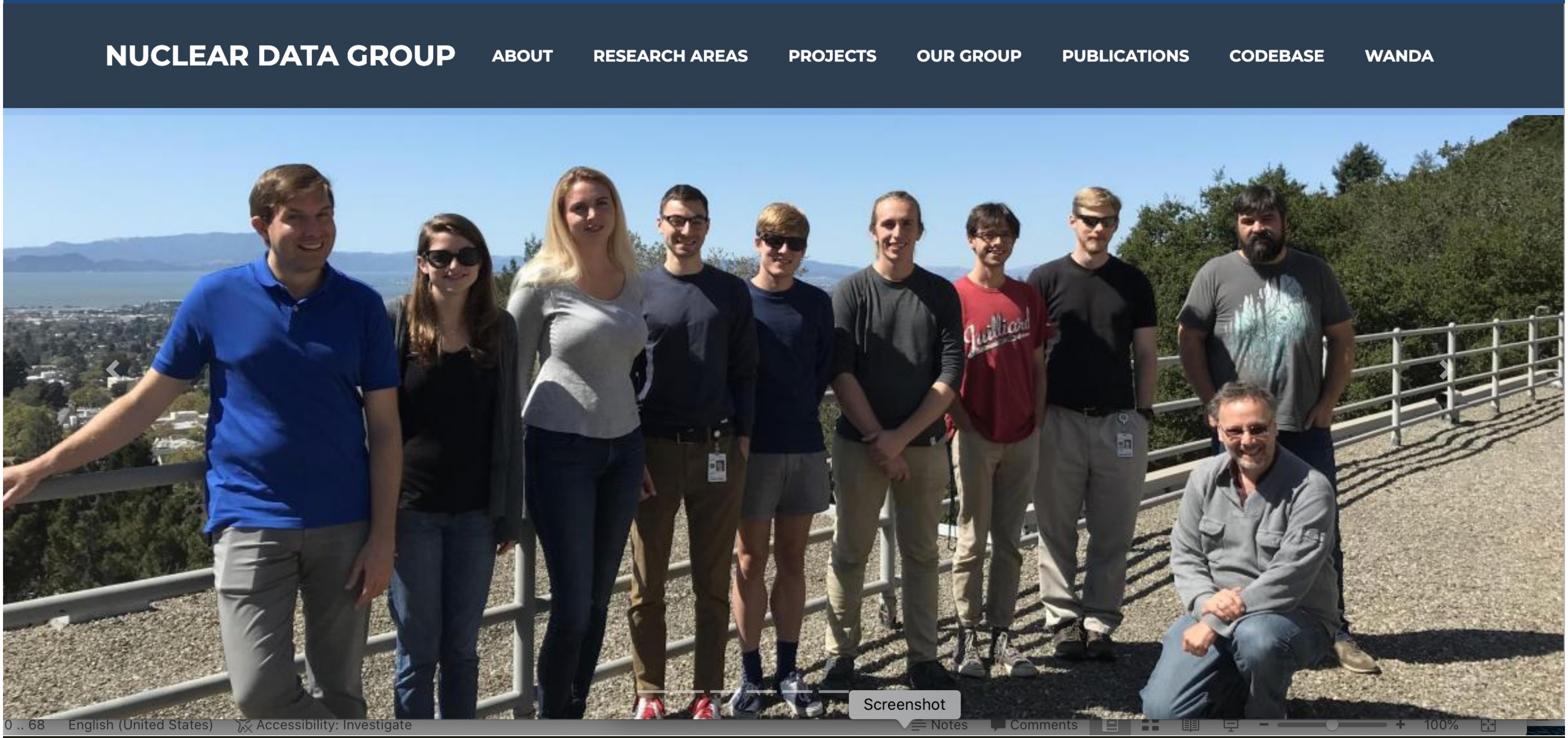
https://nucleardata.berkeley.edu

The Bay Area Nuclear Data (BAND) Group



Our mission is to address the nuclear data needs of the applied and basic nuclear science and engineering community while training the next generation of nuclear scientists and engineers in the process

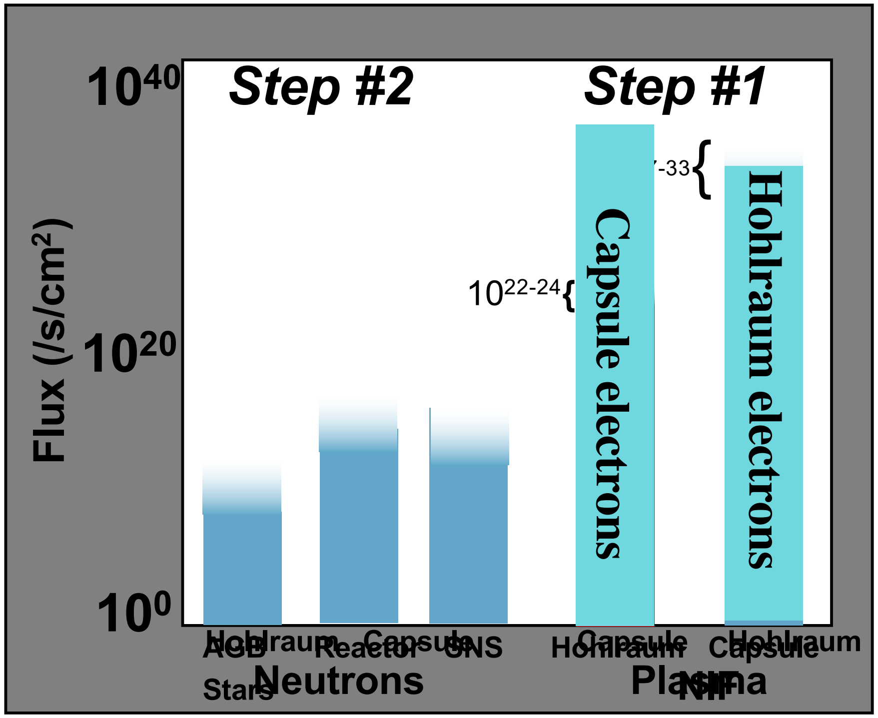
Me in a nutshell

- Rutgers University Ph.D. (1994)
- LLNL Post-doc → Staff (1994-2016)
- Deputy Group Leader for Nuclear Diagnostics at NIF (2008-2013).
- Q-clearance holder (LLNL VSP)
- Joint Faculty Scientist (UC/LBNL) and Nuclear Data Group Leader
- Published 230+ papers in Nuclear Structure, Reactions, Plasma Physics
- Principal advisor to 12 graduate and 3 undergraduate students.
- Nuclear Science & Security Consortium Director for National Labs
- Nuclear Science Advisory Committee member (2021-2023)
    - Nuclear Data Subcommittee Chair (2022-2023)

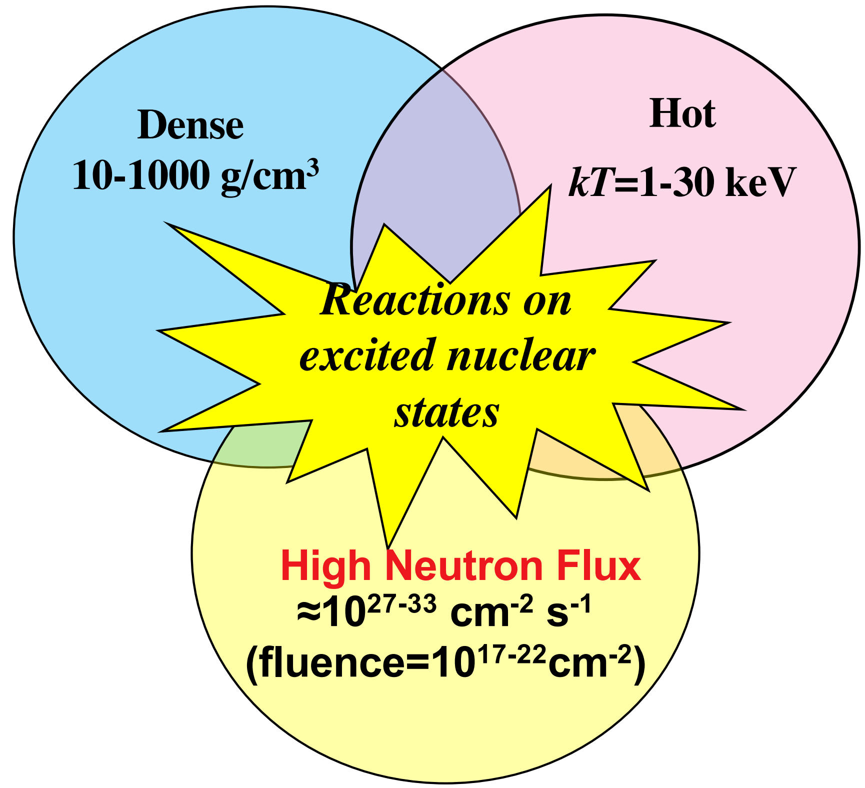
Outline

- Introductions
- What NIF can do for Nuclear Physics
  - Nuclear reactions in HEDP environments
  - Historical example: The wheel experiments
  - Gedanken experiment #1: Using DD capsules to study neutron capture nucleosynthesis in an HEDP
  - Gedanken experiment #2: Using NIF+ARC to study fission in High Energy Density Plasmas
- What Berkeley can do for NIF & LLNL
  - The 88-Inch cyclotron high-intensity neutron source
  - The BELLA petawatt laser-driven HED facility
  - Example: New gamma diagnostic for $E_\gamma < 3$ MeV
- Workforce Development

The high *e, γ and n flux* in an ICF capsule allows us to explore the effects of a HEDP environment on nuclear reaction rates



NIF capsule/hohlraum



Excited State Reaction Possibilities

Nuclei are excited by and HEDP and then capture a neutron

Nuclear-plasma interactions are assumed to cause thermal population of low-lying nuclear states in HED plasmas

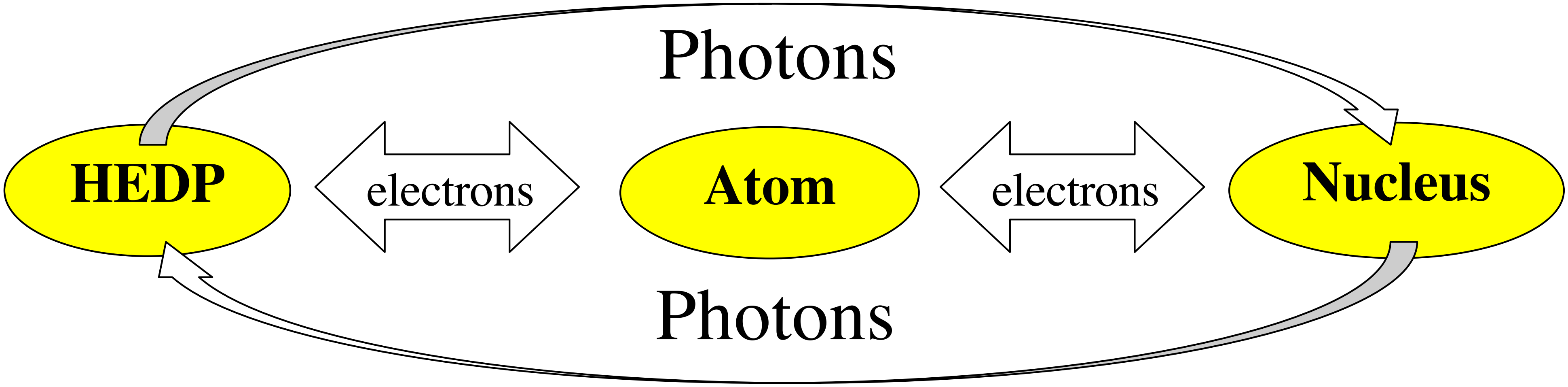
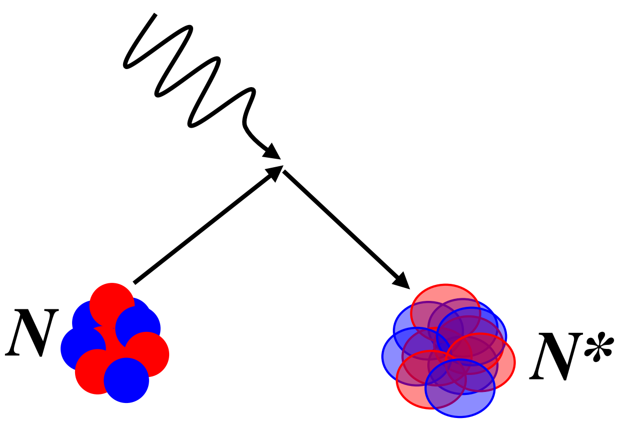
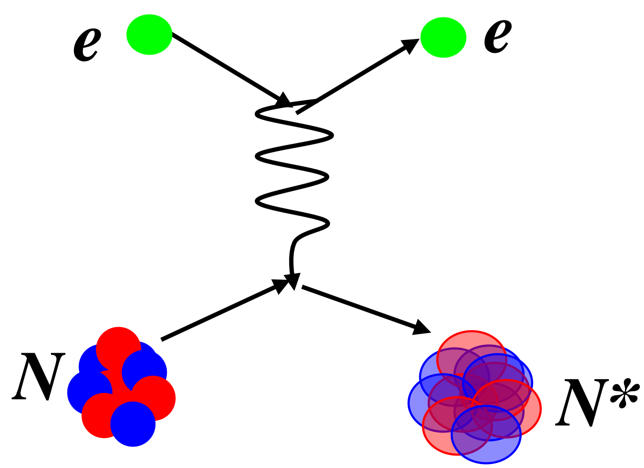


Photo-absorption
Time Reverse: γ-ray decay

Atomic-nuclear (electron) interactions
NEEC, NEET, IES* (Time Reverse: IC, BIC)

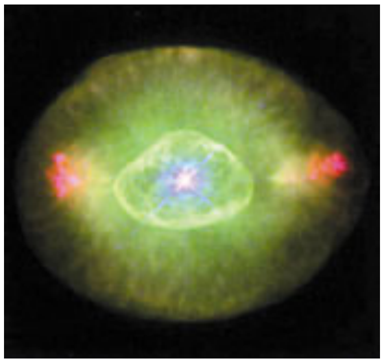




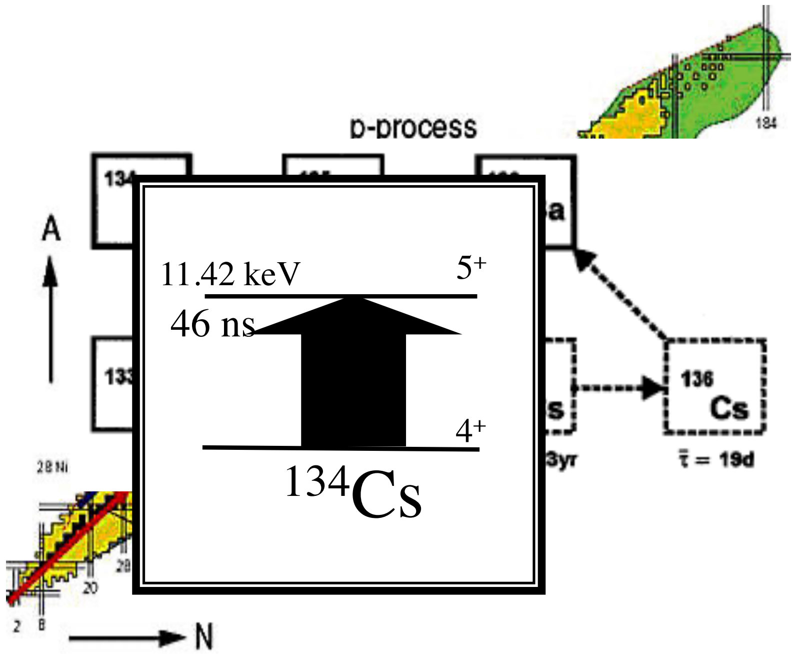
Electron-nuclear rates are likely to be the most important in stars

Nearly half of the elements are made via neutron capture *in a stellar plasma*

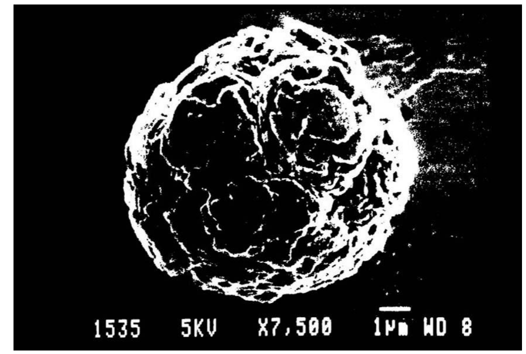
AGB stars ➔ disperse elements



$k_B T \approx 10\text{-}30$ *keV*



Pre-solar grains



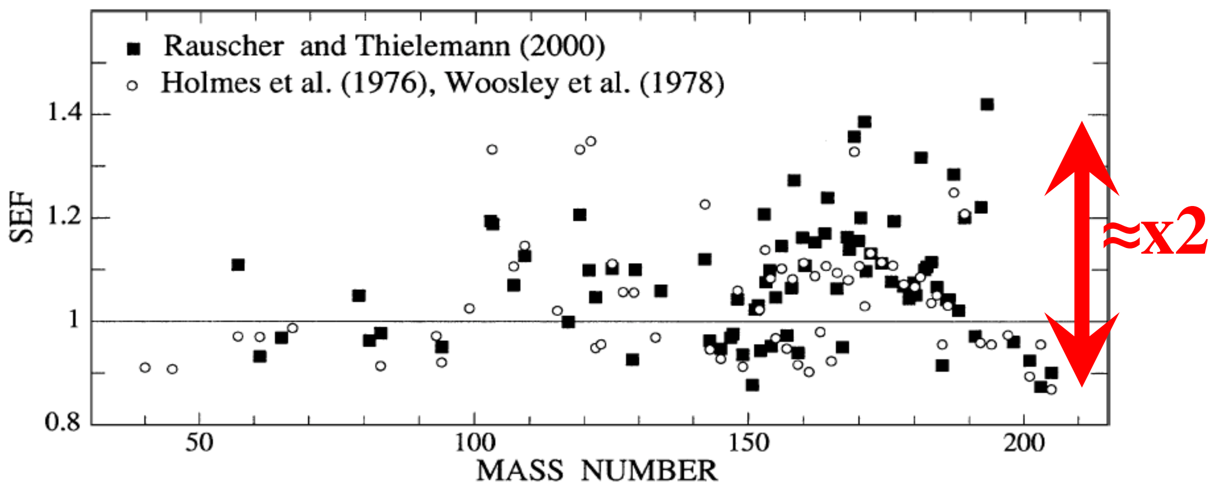
(n,γ) cross section on s-process branch point nuclei allows a "forensic" study of the conditions in a stellar interior

The excitation of these low-lying levels leads to a change in the neutron capture cross sections

S-process (n,γ) cross sections due to excited states*

$$\sigma_{stellar}^{(n,\gamma)} = \sum_i (2J_i + 1) e^{\frac{-E_i}{kT}} \sigma_i^{(n,\gamma)}$$

$$SEF = \frac{\sigma_{stellar}^{(n,\gamma)}}{\sigma_{terrestrial}^{(n,\gamma)}}$$

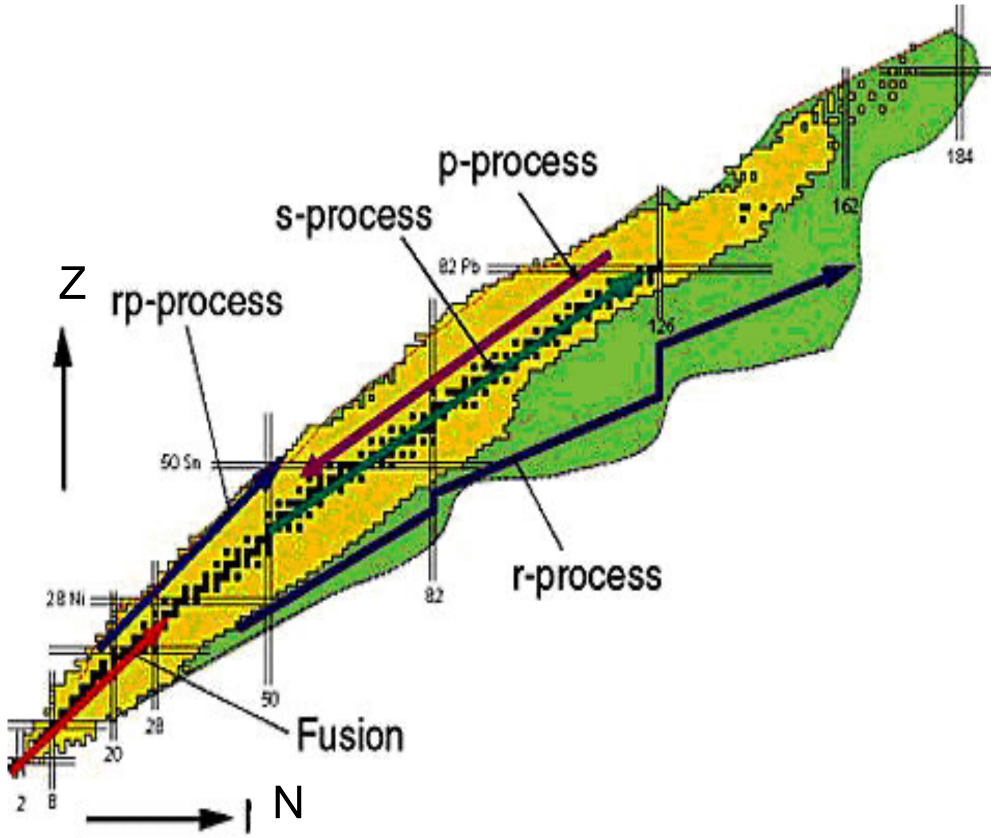


Branch Point	Gnd State J^π	1^{st} Exc. State E_x (keV)	1^{st} Exc. State J^π
^{79}Se	$7/2^+$	95.77	$1/2^-$
^{85}Kr	$9/2^+$	304.871	$1/2^-$
^{147}Pm	$7/2^+$	91.1	$5/2^+$
^{151}Sm	$5/2^-$	4.821	$3/2^-$
^{163}Ho	$7/2^-$	100.03	$9/2^-$
^{170}Tm	1^-	38.7139	2^-
^{171}Tm	**$1/2^+$**	**5.0361**	**$3/2^+$**
^{179}Ta	$7/2^+$	30.7	$9/2^+$
^{204}Tl	2^-	414.1	4^-
^{205}Pb	$5/2^-$	703.3	$7/2^-$
^{185}W	$3/2^-$	23.547	$1/2^-$

A neutron-rich HED plasma like NIF is the *only* place where (n,γ) might be measured on a combination of ground & excited states

*Bao & Kappeler At. Dat. Nucl. Dat. Tables **76,** 70–154 (2000)

Using NIF to measure (n,γ) on s-process branch point nuclei was the topic of a 2010 workshop



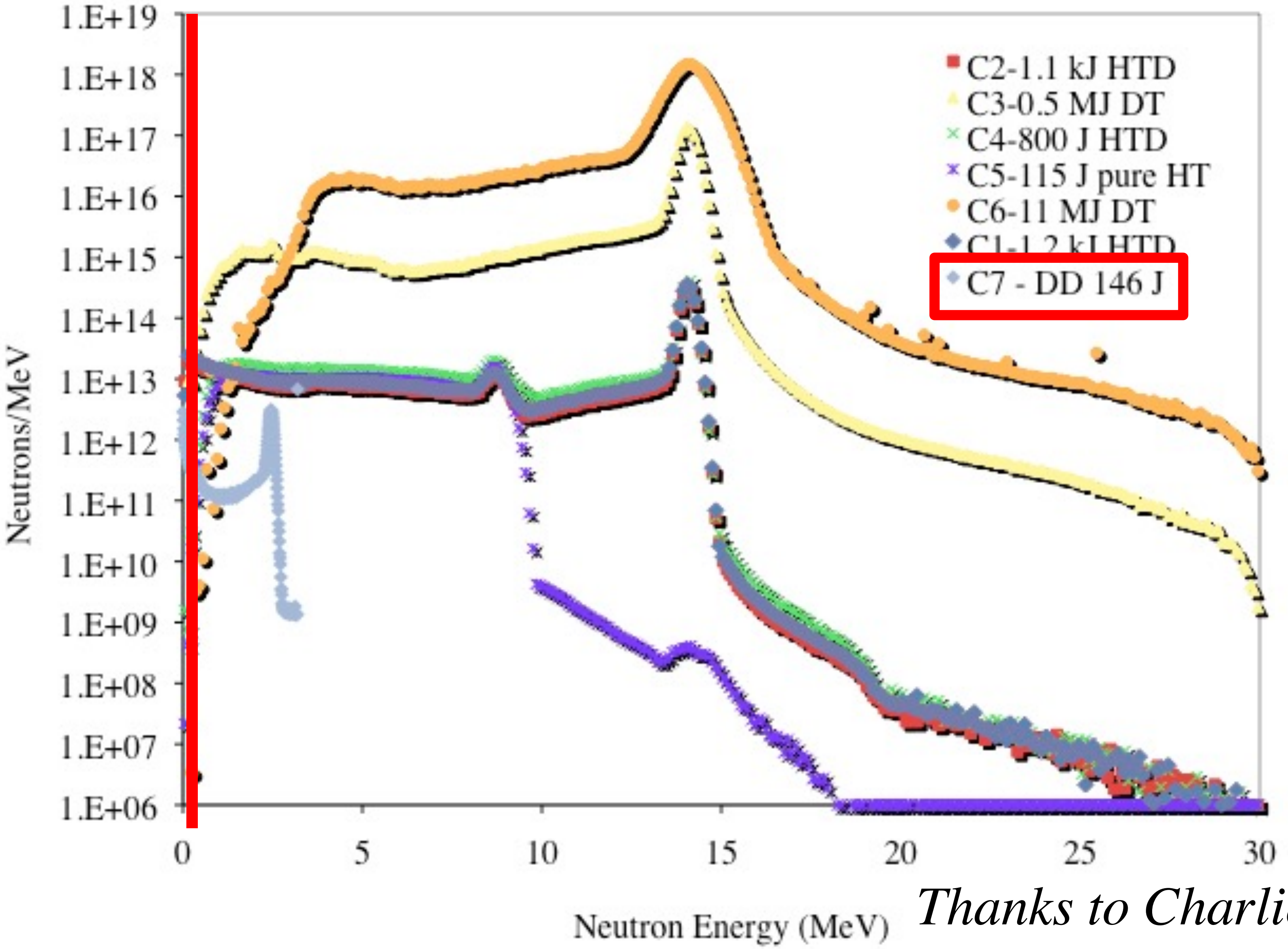
- Held at LBNL, March 2010 (!)
- 35 attendees from 8 institutions
  - LLNL, LBNL, LANL, Ohio Univ., Colorado-Mines, GSI-Darmstadt, Notre Dame, CEA-DAM
- Talks were presented on:
  - NIF diagnostics
  - s-process nucleosynthesis
  - Nuclear-plasma interactions

This program would require DD fuel, target implantation and either sold radchem or Gamma spectroscopy

How would you measure an astrophysical (n,γ) cross section at NIF?

1. Create the correct environment (neutrons, T, ρ)
    - Fuel load and moderation environment
2. Get the material into the capsule
    - Ion-implantation
3. Measure target areal density
    - Energy resolved X-ray imaging
4. Measure the number of reactions and the neutron spectrum
    - Solid Debris Collection
    - Prompt γ-ray detection using Gas Cerenkov Detectors

This type of measurement would require pure deuterium fuel to create the correct neuteron spectrum



Thanks to Charlie Cerjan!

(Modeling courtesy of C. Cerjan)

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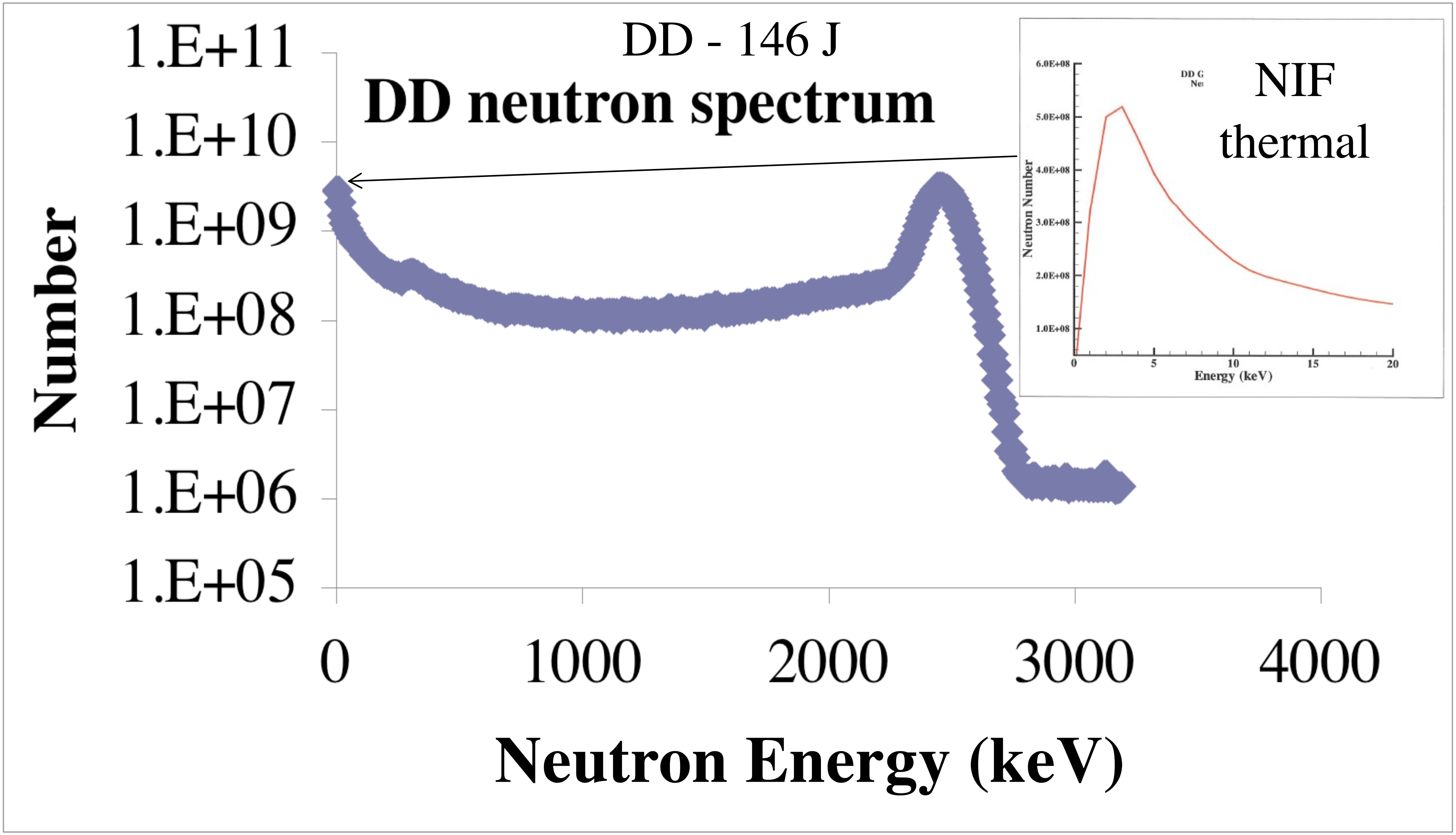
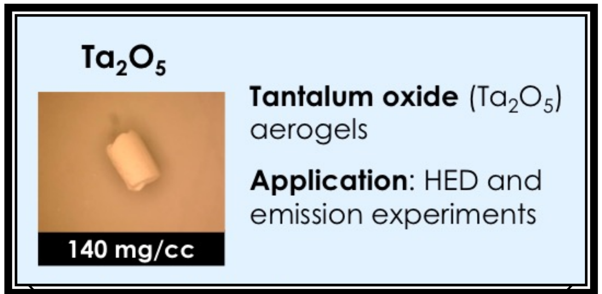
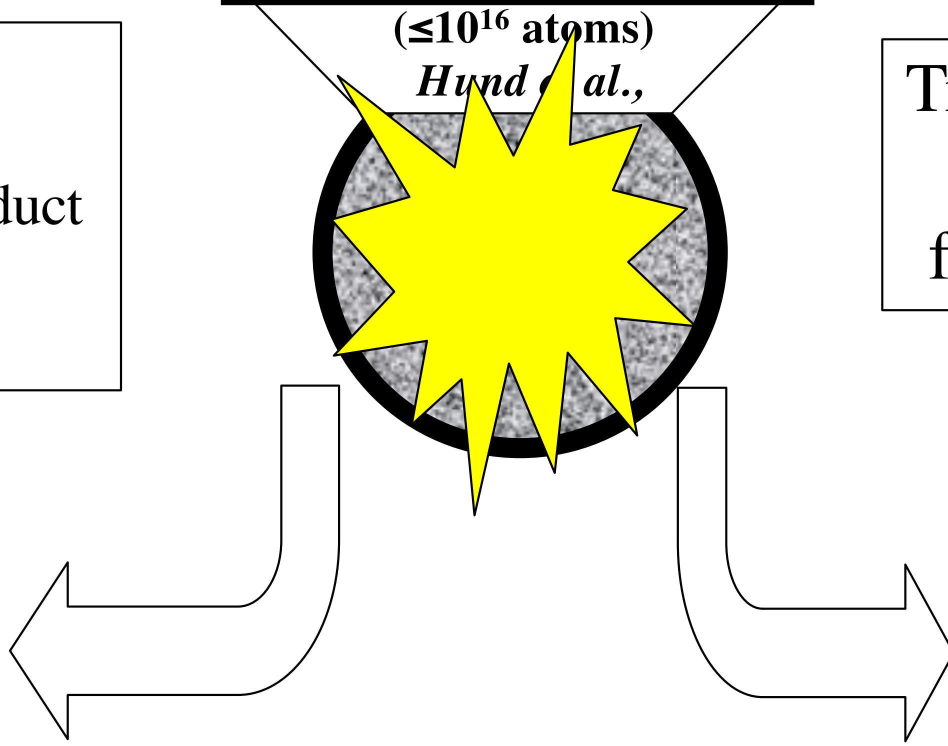


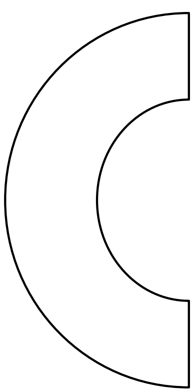
(Modeling courtesy of C. Cerjan)

The neutron capture reaction products could be measured either by prompt gamma signal or solid/gaseous radchem

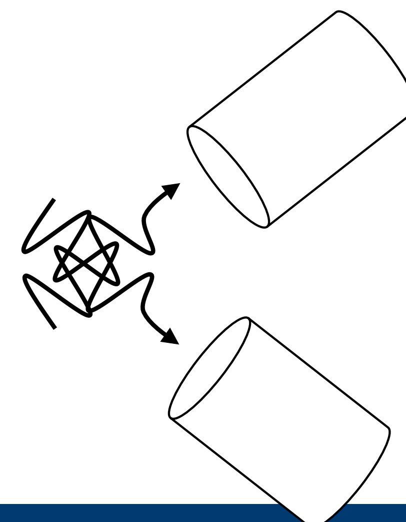




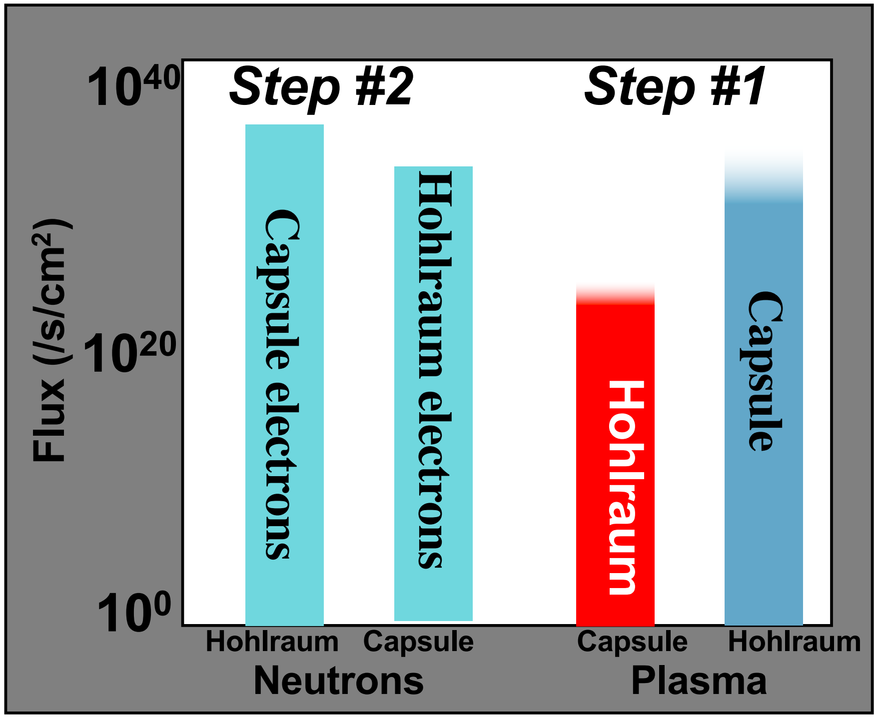
Collect "debris" and count-
Tough if stable product
(Shaughnessy, Grim, Greife…)

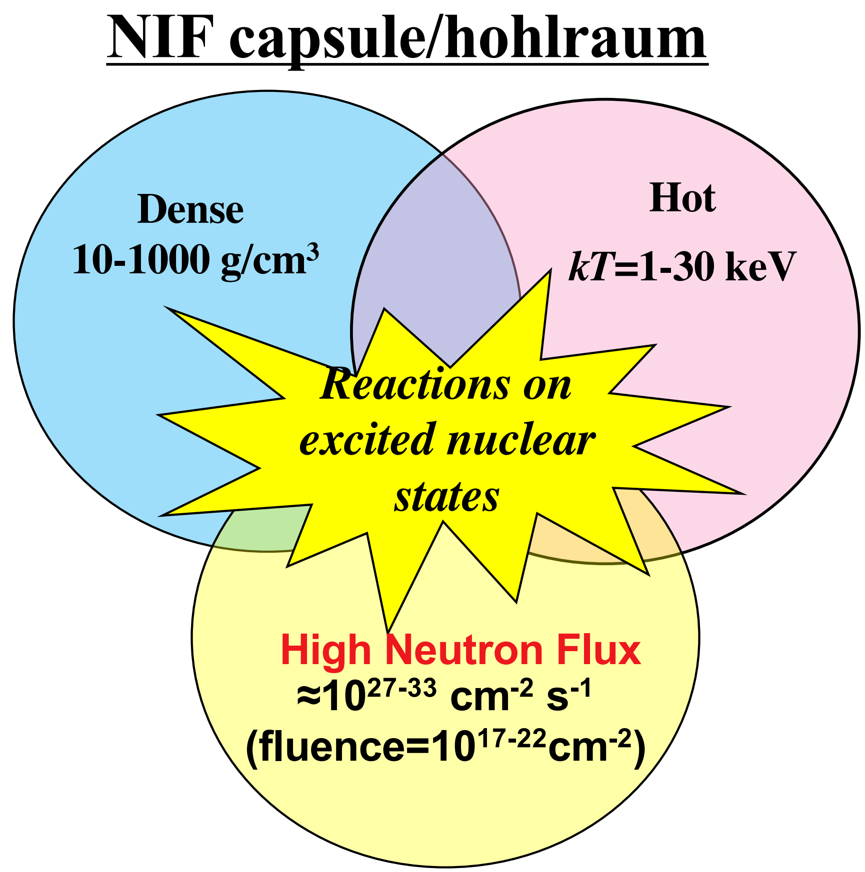


Try to measure the prompt γ-rays following capture



The high *e, γ and n flux* in an ICF capsule allows us to explore the effects of a HEDP environment on nuclear reaction rates



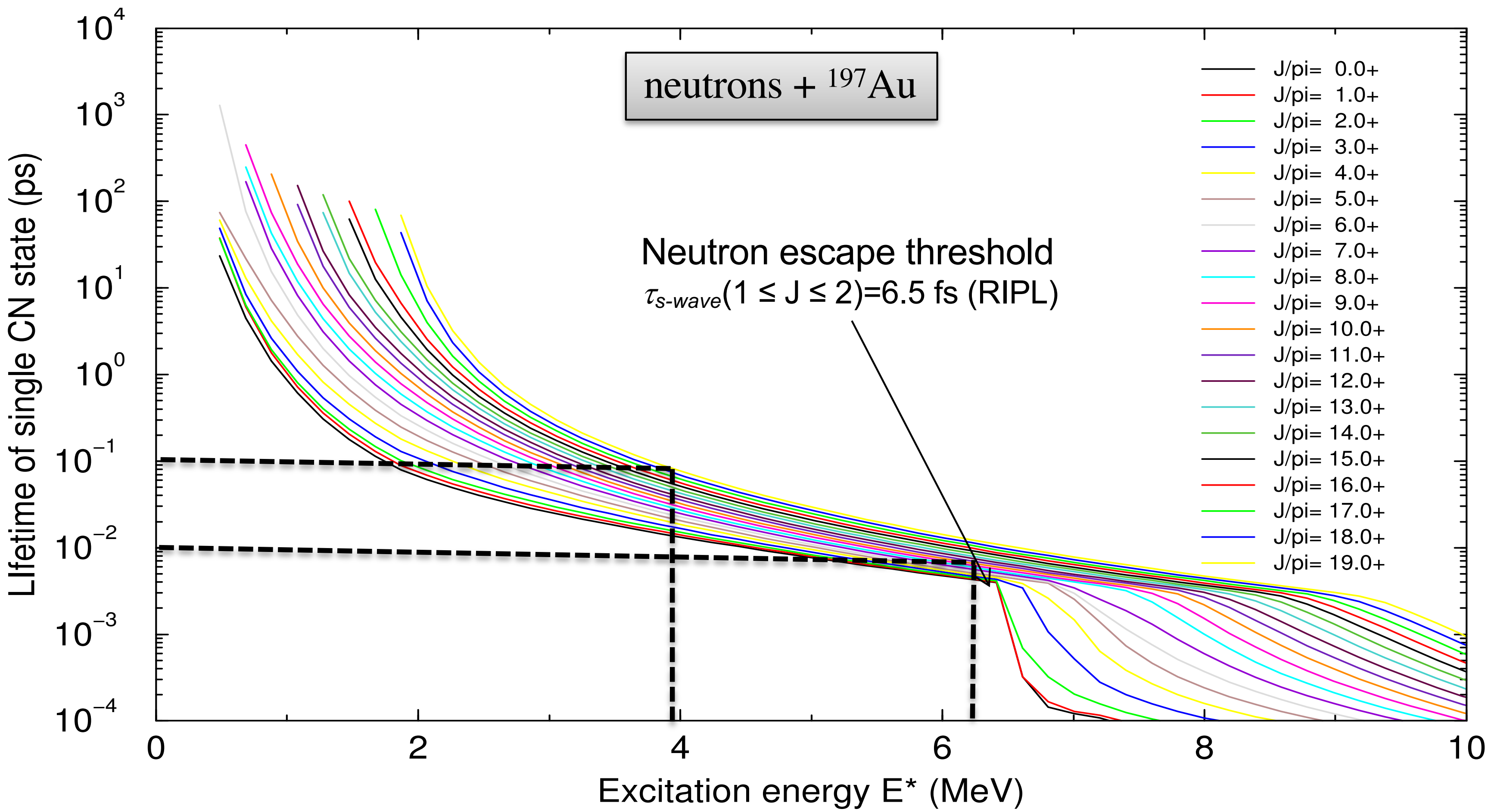


Excited State Reaction Possibilities

Nuclei are excited by an HEDP and then capture a neutron

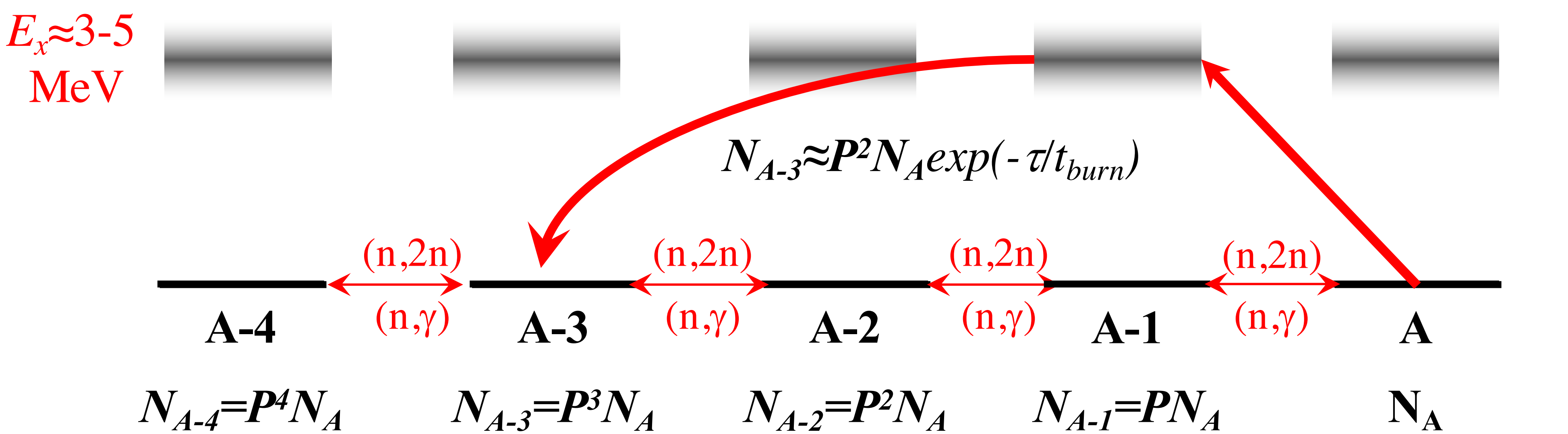
Nuclei absorb a neutron and interact with an HEDP before particle emission

The lifetimes of highly-excited nuclear states in heavy nuclei is comparable to the NIF burn time



What would happen if an excited nucleus were hit be a second neutron prior to decaying to the ground state?

The large flux of 14 MeV neutrons in the NIF would drive multiple (n,2n) reactions, rather than (n,γ)



- The probability that a nucleus *A* will be converted via (n,2n) to a nucleus *A-1* is given by:

$$P_{reaction} = \int_0^{\tau_{burn}} \int_0^{14} \phi_n(E_n)\times\sigma_n(E_n)\times e^{-t/\tau_{state}}\, dE_n\, dt$$

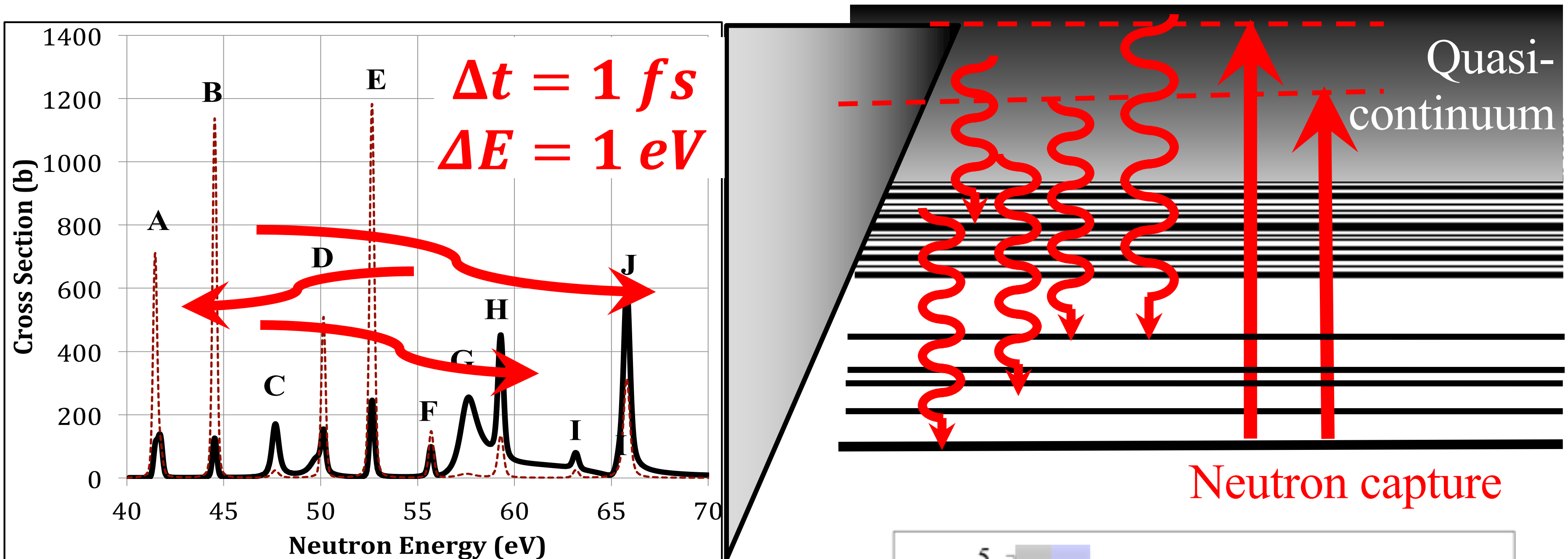
$\Delta t \approx 1\%\ t_{burn}$

$$P_{reaction} \approx \frac{10^{17}\ neutrons/MeV}{4\pi(30\ \mu m)^2\times10^{-11}\ s}\times10^{-24}\ cm^2\times10^{-13}\ s \bullet MeV$$

$$P_{reaction} \approx \frac{10^{17}\ neutrons/MeV}{10^{-4}\ cm^2\times10^{-11}\ s}\times10^{-24}\ cm^2\times10^{-13}$$

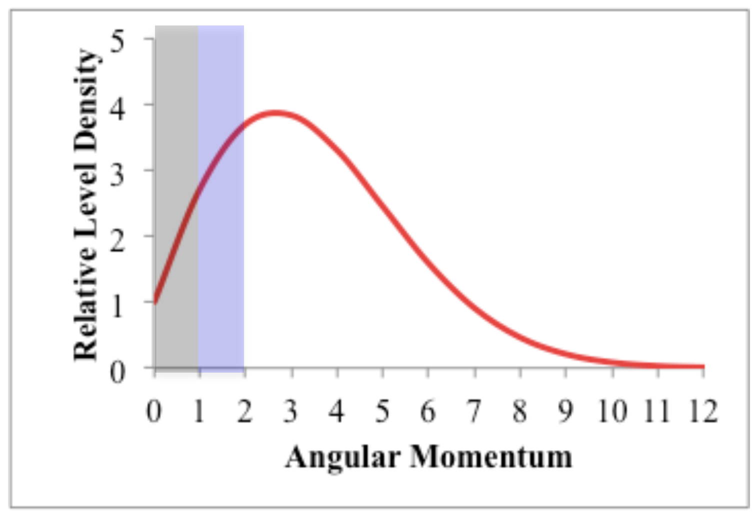
The $\frac{N_{A-3}}{N_{A-1}}$ ratio would produce a solid radchem observable

At multi-MeV energies the high nuclear level density makes the nucleus a much better absorber of energy from the HEDP

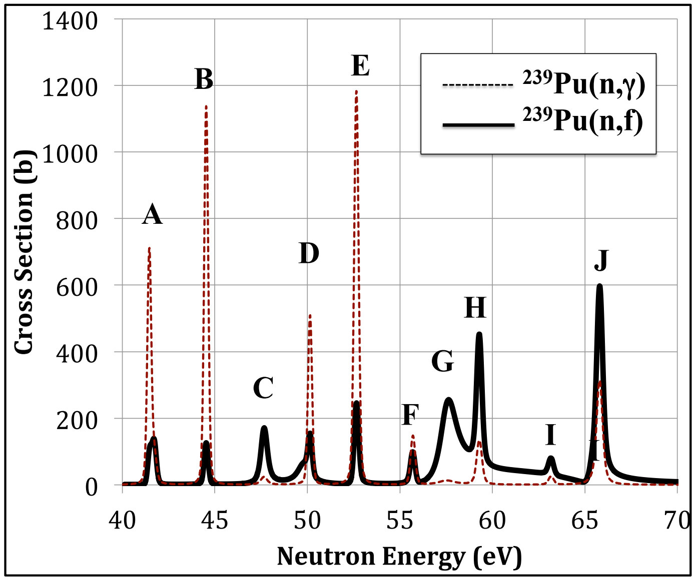


The large density of states would make these nuclear-plasma rate ≈ 10^{14} Hz!

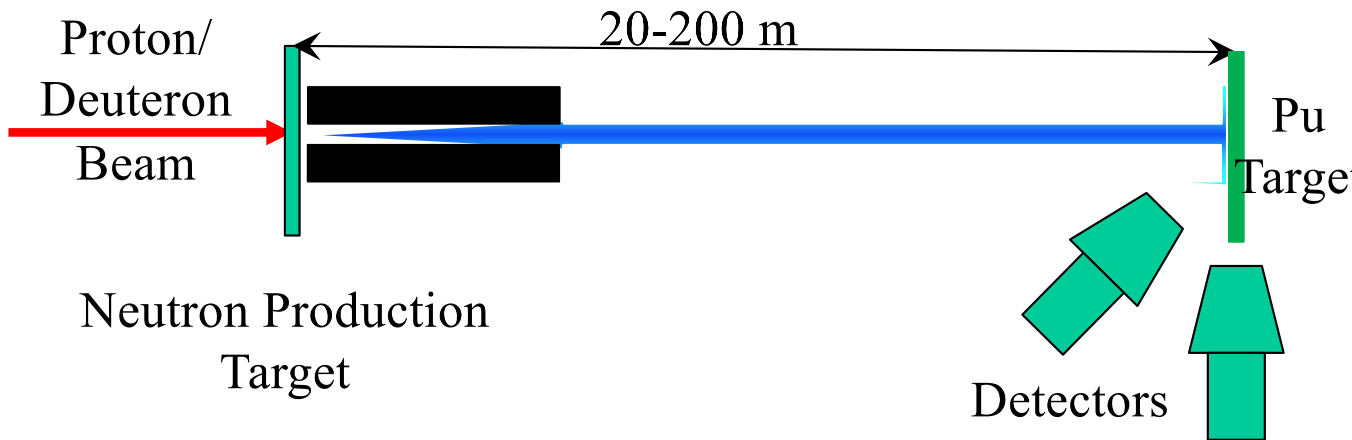
Each photon (real or virtual) will shift J^{π} toward the most likely value



Changing excited states could have a big influence on fission as well - The (in)famous “wheel” experiments

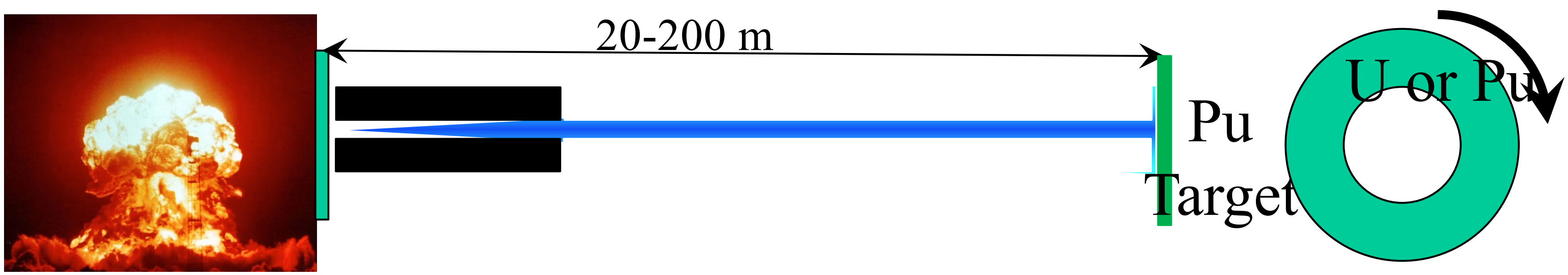


“Time-of-Flight” (TOF) technique – Multi-Day Experiment



Longer Path → Better Energy Resolution

Best TOF – Experiment – LOTS of neutrons in one pulse viewed from REALLY far away

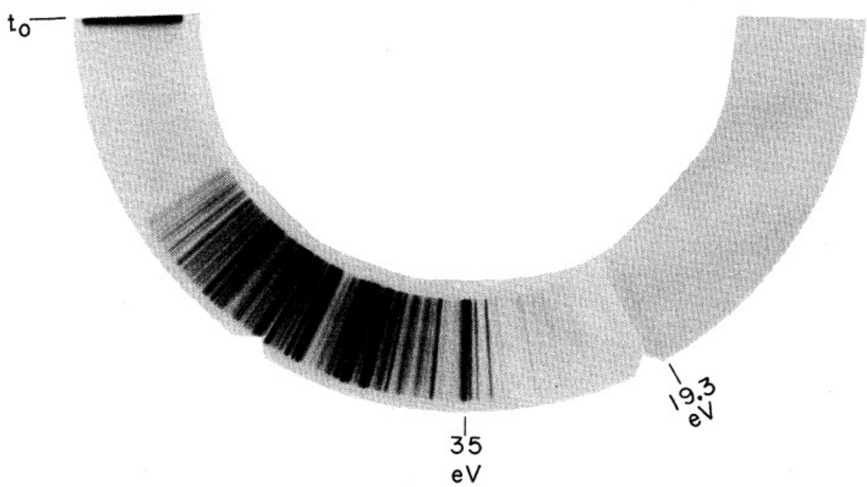


Yes. We did that (not me personally)

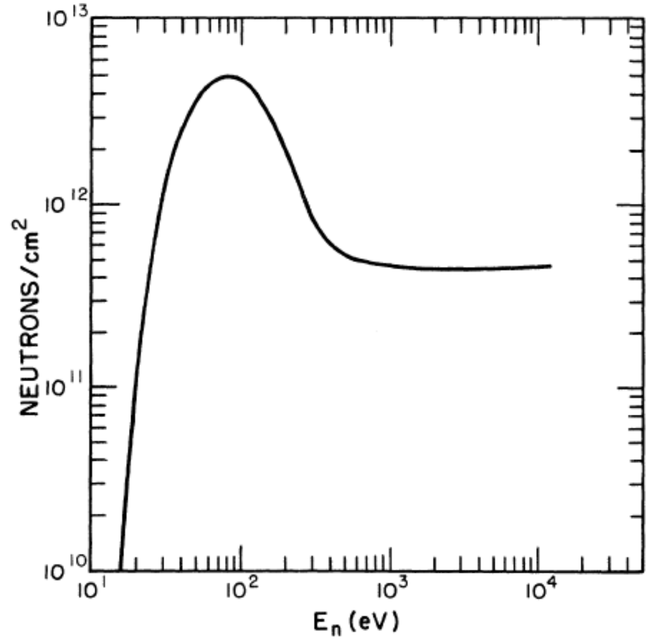
PHYSICAL REVIEW C　　VOLUME 2, NUMBER 2　　AUGUST 1970

Symmetry of Neutron-Induced ^{235}U Fission at Individual Resonances. III*

G. A. Cowan, B. P. Bayhurst, R. J. Prestwood, J. S. Gilmore, and G. W. Knobeloch
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico 87544
(Received 13 February 1970)



The symmetry of neutron-induced fission in ^{235}U has been measured at a large number of epithermal levels with a time-of-flight energy-resolved beam from an underground nuclear explosion. The energy resolution was improved over previous similar "wheel" experiments. The symmetry of fission, as measured radiochemically by the ratio of ^{115}Cd to ^{99}Mo, shows a bimodal distribution. If the results are averaged separately for the two apparent groups, the first group (I) has an average ^{115}Cd/^{99}Mo ratio which is 0.593 times the thermal value; the second-group (II) average is 1.11 times the thermal value. The average fission width in I is one-half the average fission width in II. The numbers of levels assigned to I and II are 24 and 14, respectively. The energies of levels assigned to I are 19.30, 21.07, 22.94, 23.63, 26.44, 27.81, 30.91, 32.10, 33.55, 34.85, 40.51, 41.91, 43.41, 44.04, 45.79, 46.93, 48.06, 48.82, 51.37, 56.58, 57.83, 58.15, 60.25, and 61.10 eV; assignments to II are at 24.23, 25.65, 28.35, 34.39, 35.21, 35.75, 36.64, 38.42, 39.44, 44.75, 49.51, 52.27, 53.56, and 58.68 eV. From analogy with conclusions based on a similar set of observations in the fission of ^{239}Pu and on arguments derived from fission-channel theory, it is hypothesized that $J=4$ in I and 3 in II.



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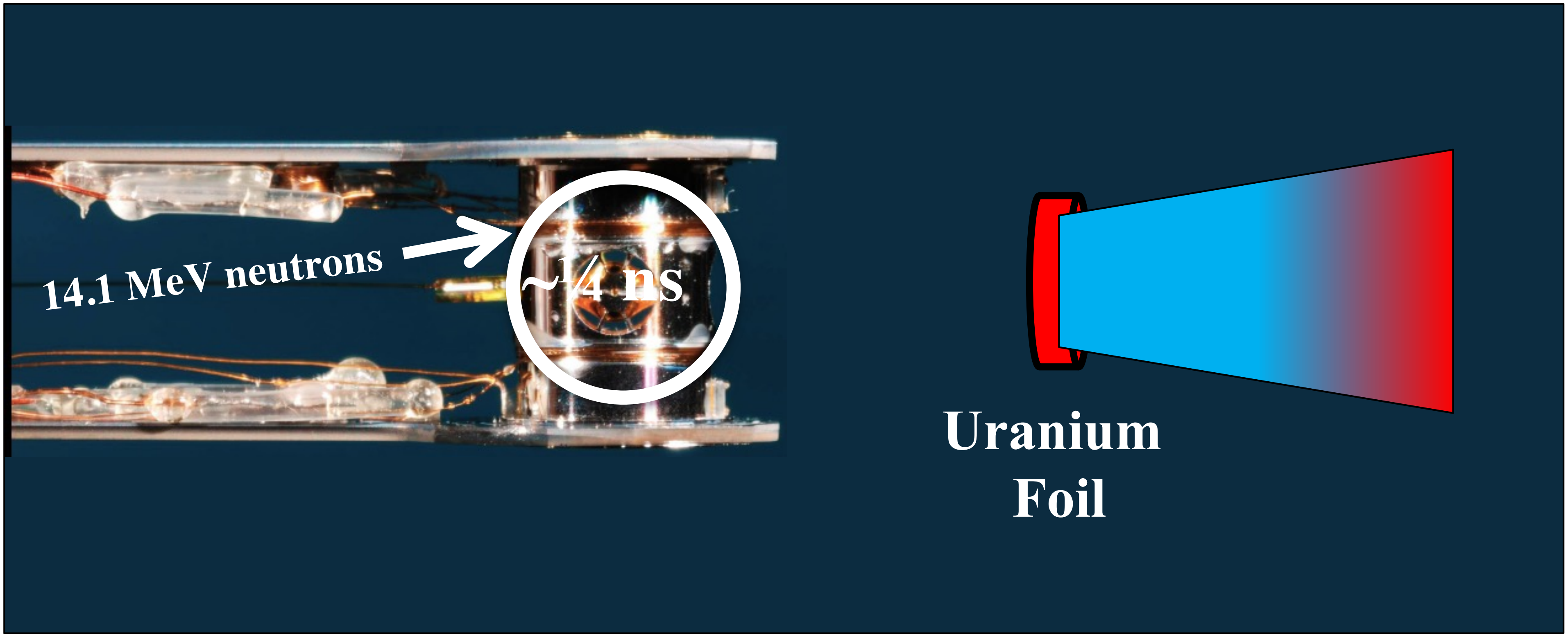
NIF+ARC could be used to study the effects of an HEDP on fission yields in a controlled manner

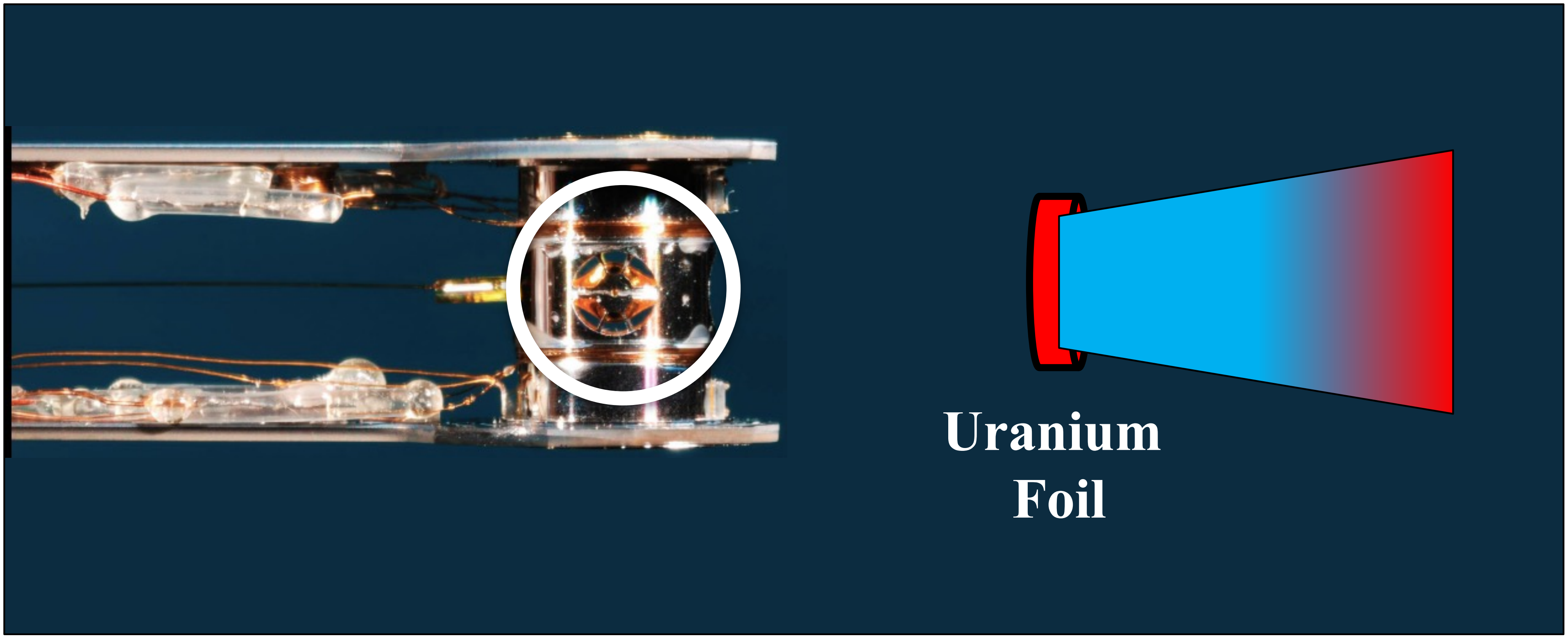
Use ARC to put a small uranium sample into an HEDP state just as the 14 MeV neutron pulse arrives



Timing is everything ☺

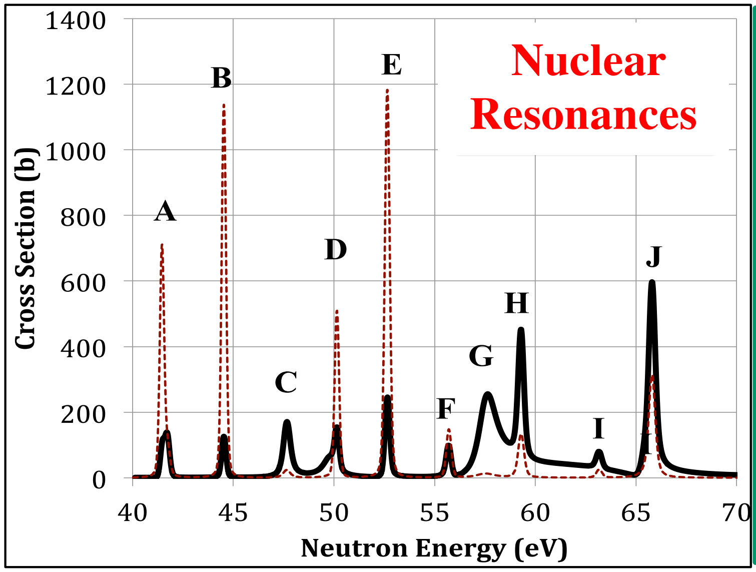
NIF+ARC could be used to study the effects of an HEDP on fission yields in a controlled manner

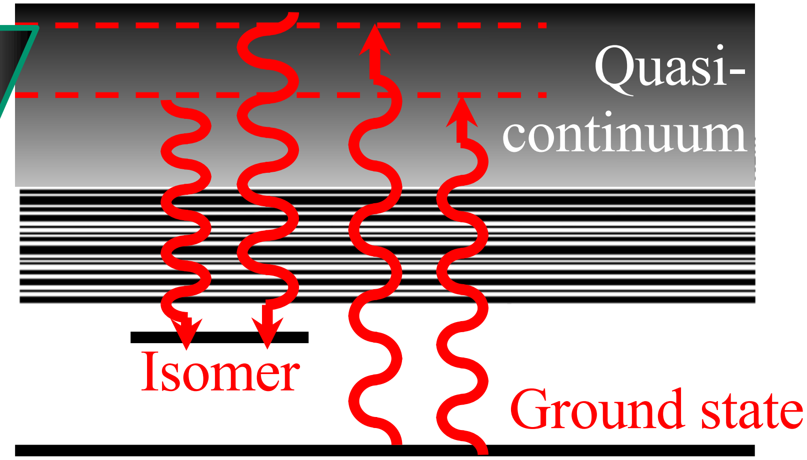
Repeat, but delay the ARC pulse to arrive well-after the 14 MeV neutrons

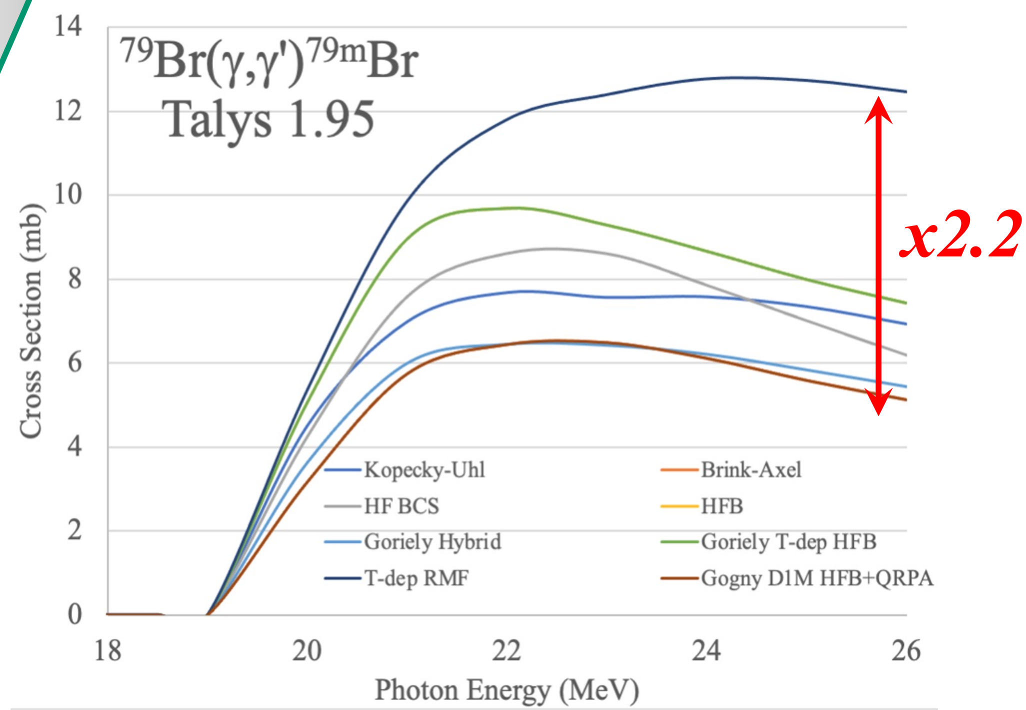


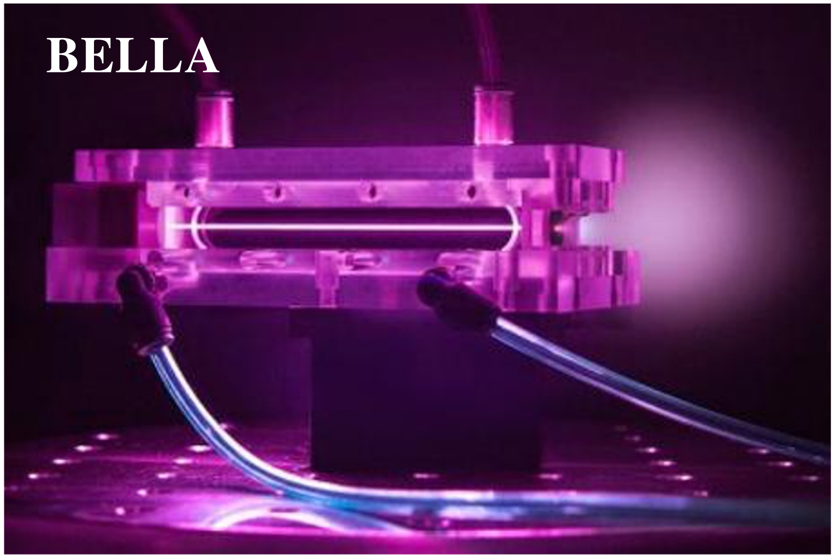
Controlled experiments are always best

Moving to Berkeley: The BELLA facility has provided a capability to study Nuclear Plasma Interactions in HEDPs



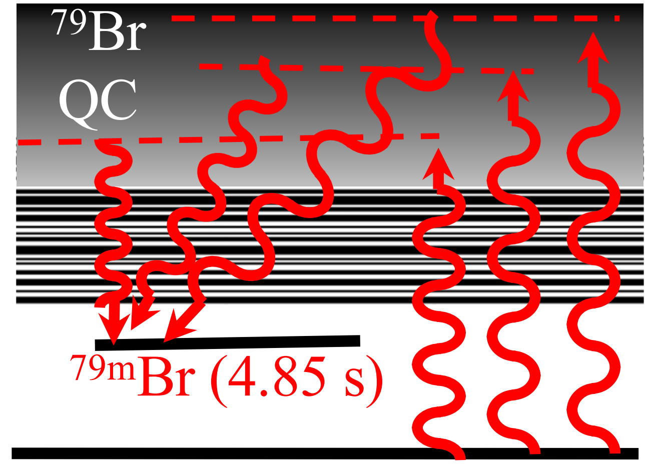


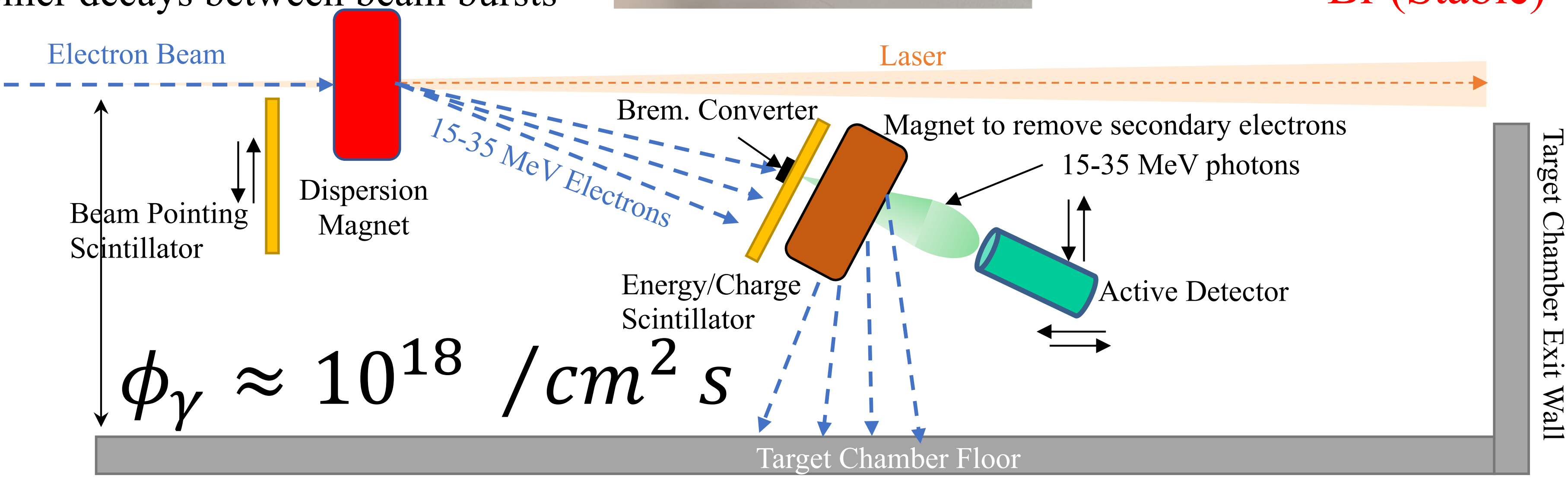




Part I: $^{79}Br(\gamma,x\gamma')^{79m}Br$ via Brehmsstrahlung

1. Install LaBr detector for use as a ^{79}Br active targets
2. Install adjustable *Bremsstrahlung* converter (energy selection via geometry, few pC/MeV expected)
3. Use photons to populate ^{79m}Br
4. Repeat at up to 1 Hz & count isomer decays between beam bursts



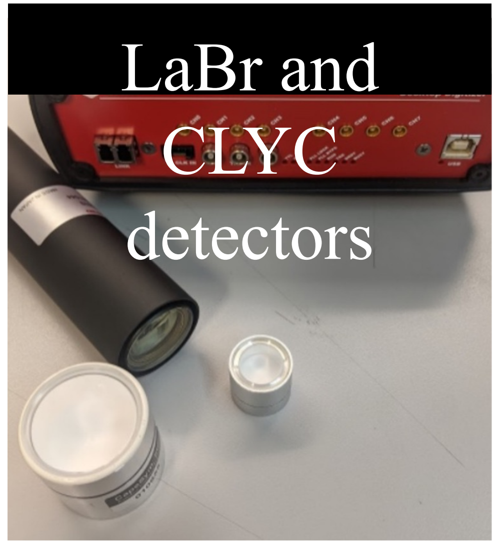


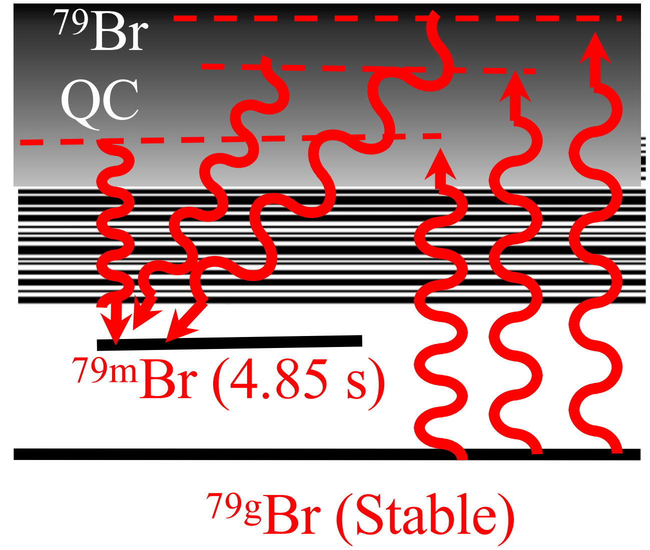
$$\phi_\gamma \approx 10^{18} \ /cm^2\, s$$

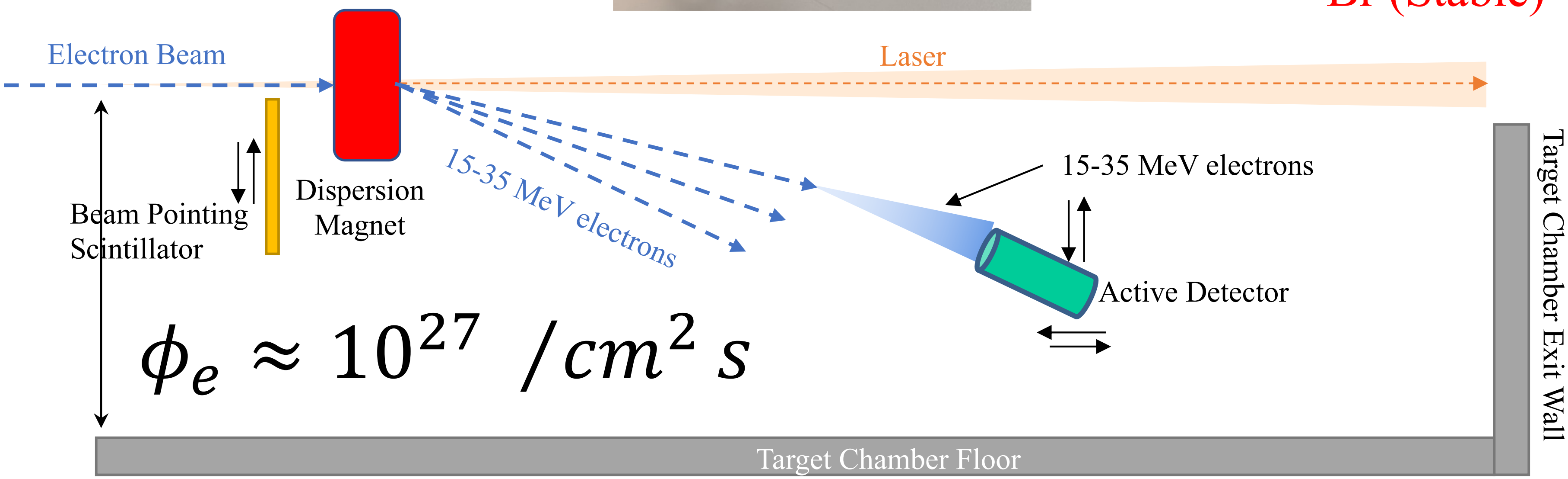
This will determine photoexcitation to the QC

Part II: $^{79}Br(e,e')^{79m}Br$ using the direct electron beam

1. Remove the *bremsstrahlung* radiator and the bending magnet to allow the electrons hit the target
2. Perform the experiment again.
3. Measure the additional isomer population signal to determine the electron-driven NPI contributions.



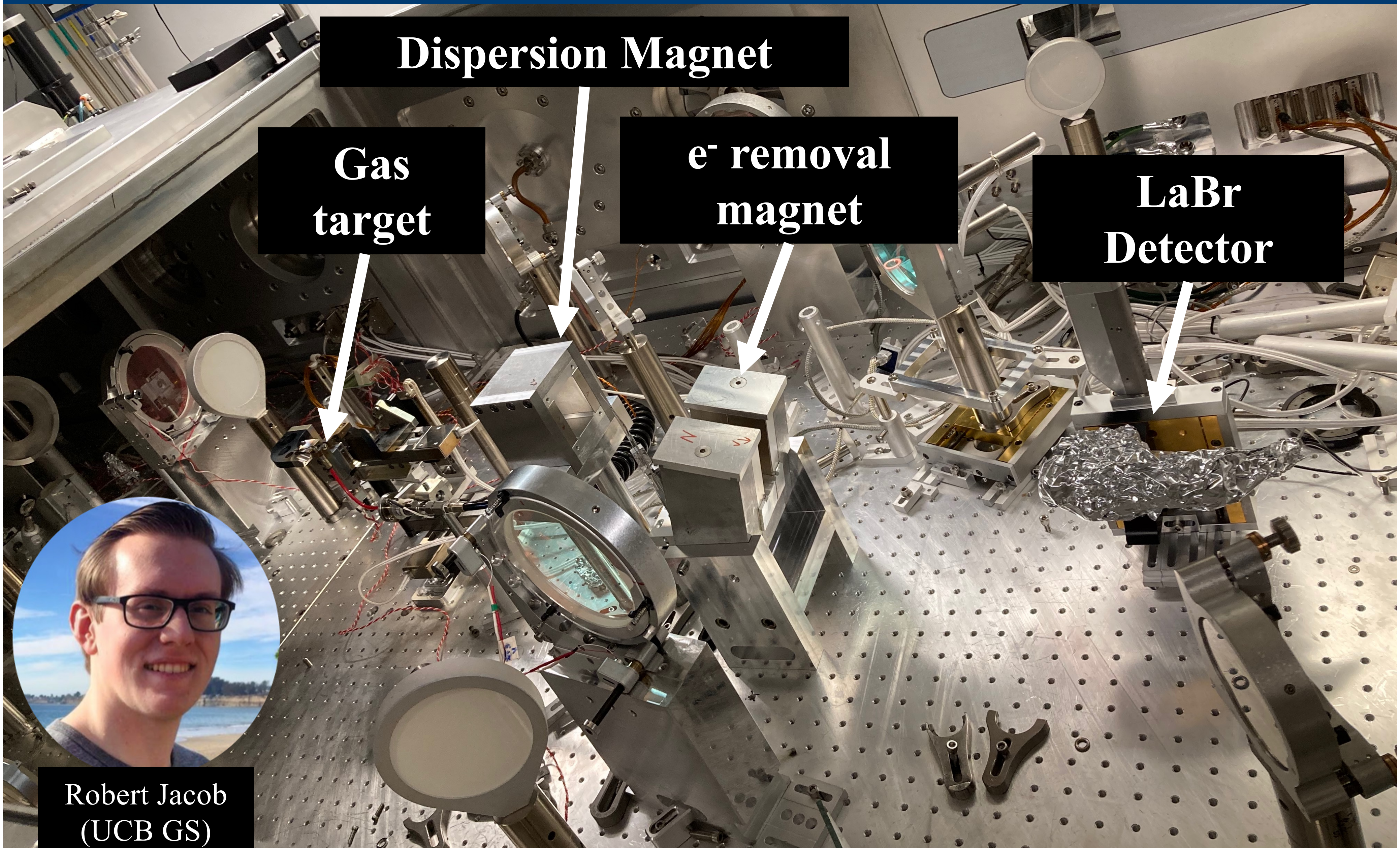




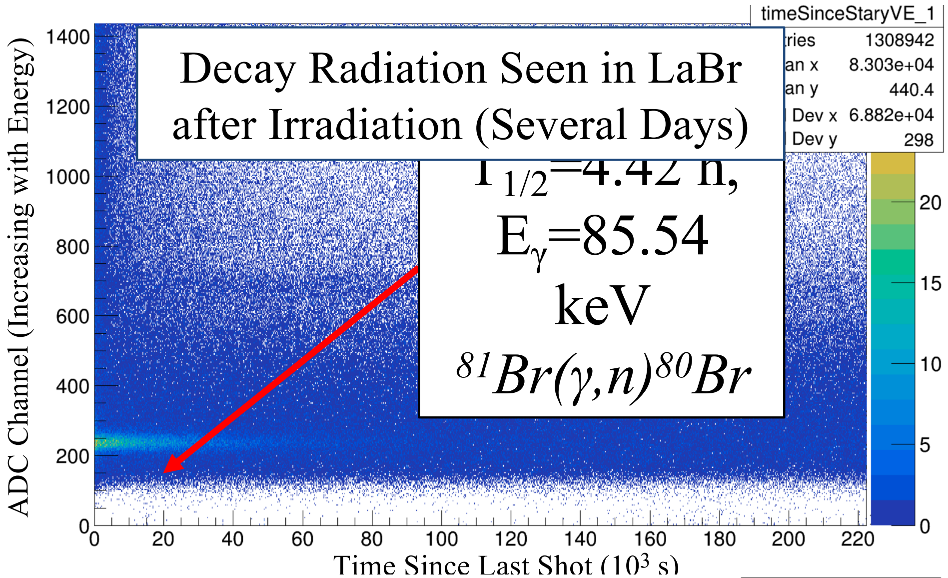
$$\phi_e \approx 10^{27}\ /cm^2\, s$$

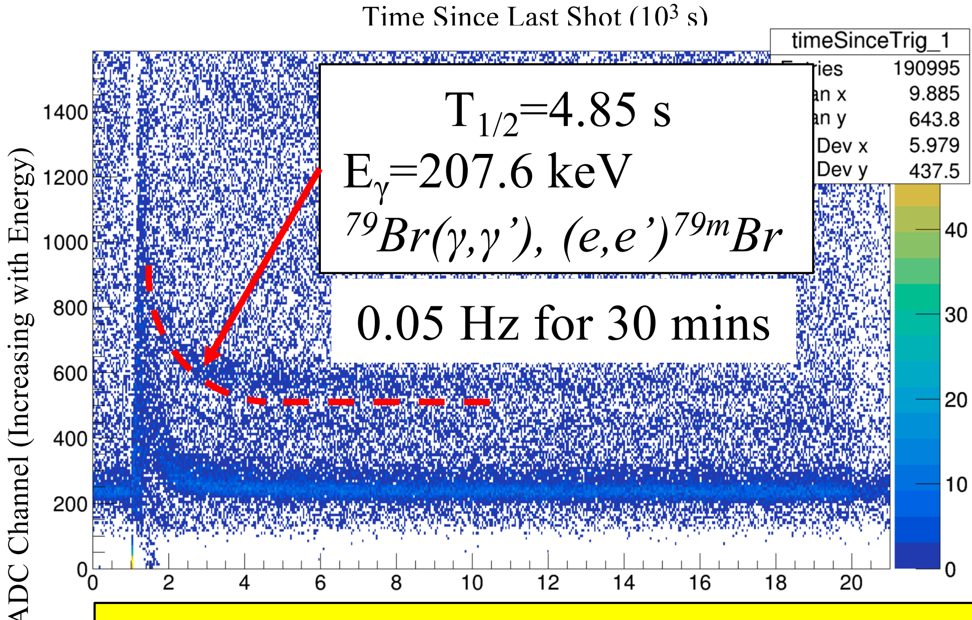
The higher flux could allow for reactions on QC states

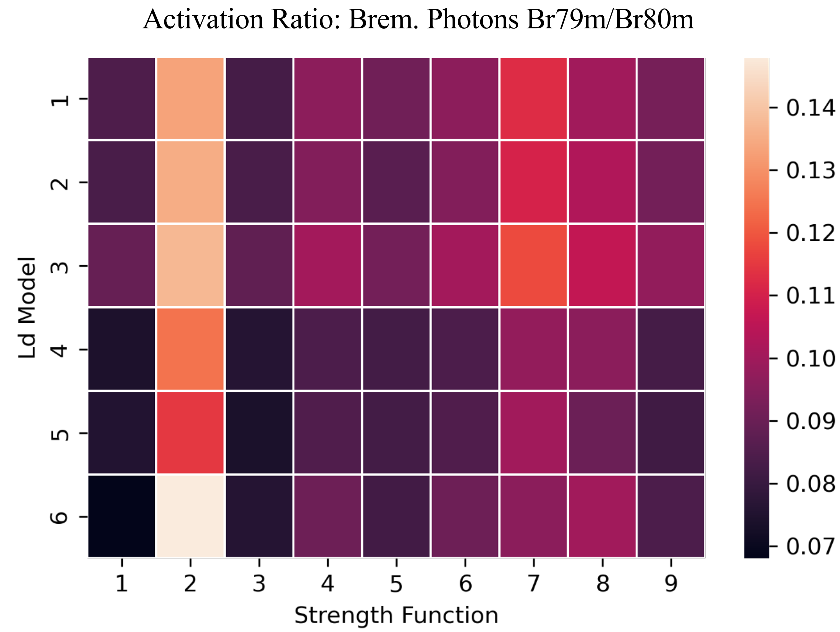
Experimental Set-up @ BELLA



Data analysis



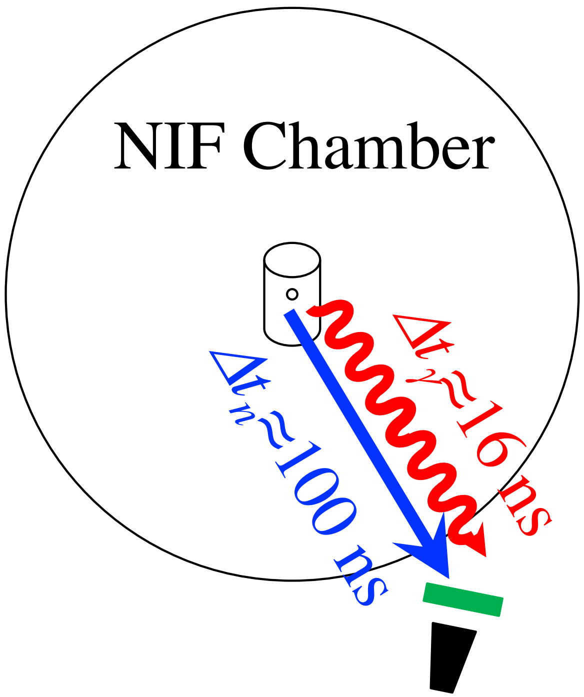


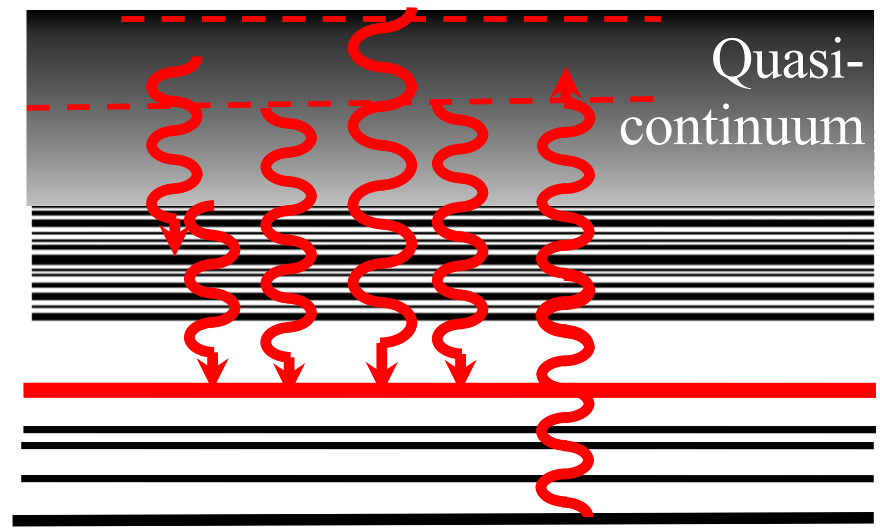


Irradiation Cases	Ratios (#/Shot)
Brem. Photons 79/80	0.023±0.0024
Electrons 79/80	0.033±0.0015
Brem. 79/Electrons 79	0.503±0.0515
Brem. 80/Electrons 80	0.719±0.0326

Results point towards a radically different QC J value

The population of isomers is a potential new NIF γ-diagnostic with a lower threshold than GRH

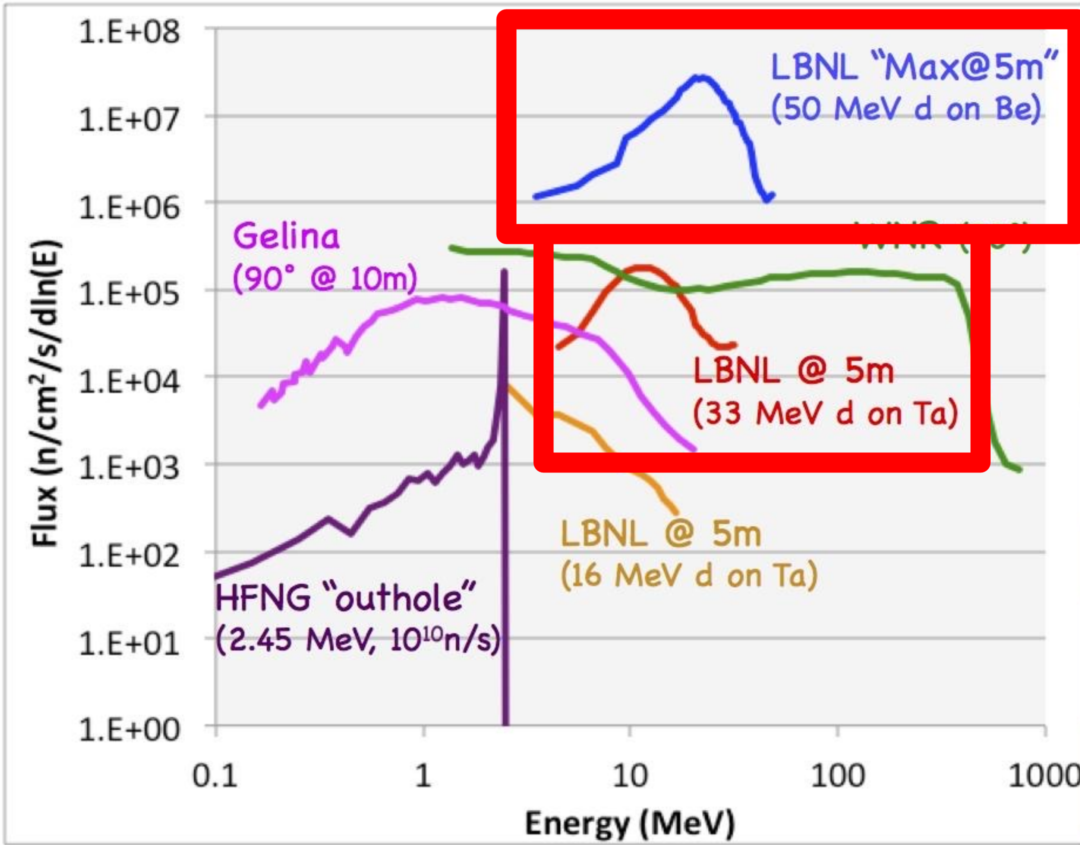




Element	E_x (keV)	J^π	$t_{1/2}$ (ns)
^{181}Ta	482	5/2+	10.8
^{93m1}Nb	1335	17/2+	14
^{93m2}Nb	1491	15/2+	14
^{98}Mo	735	0+	21.8
^{91}Zr	2288	(15/2)-	29
^{96}Zr	1582	0+	38
^{90}Zr	1761	0+	61.3
^{94}Mo	2956	8+	98

- Photons reach the chamber wall 84 ns before the 14 MeV neutrons.
- A nuclear excited state with $\tau \leq 50+$ *ns* will give a clear temporal signal.
- Candidates include, Nb, Ta, Y and Zr.
- A greater distance would provide a longer list of candidates

LBNL hosts one of the most intense 14 MeV-like neutron sources in the country based on thick target deuteron breakup



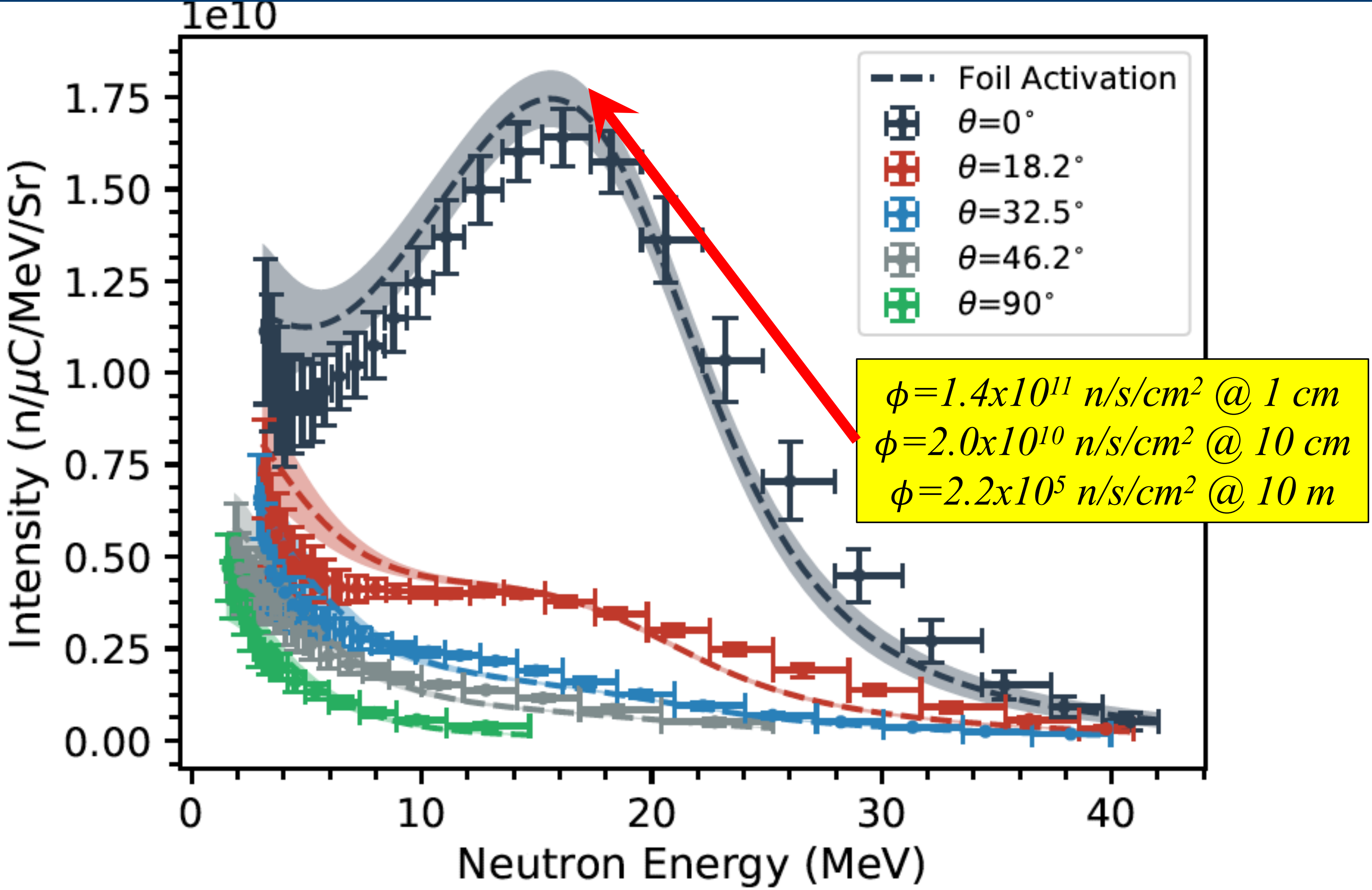
Source	Tot. Flux (n/cm2/s)
50 MeV d on Be (10μA, 5m)	$2x10^7$
WNR (30°)	10^6
Gelina (90° @ 10m)	$2x10^5$
33 MeV d on Ta (2μA @ 5m)	$2x10^5$
HFNG (2.27m)	10^4
16 MeV d on Ta (2μA @ 5m)	$5x10^3$
Kentucky T(p,n) (@ 2m)	$2x10^3$

This neutron source could be used to test and benchmark new neutron diagnostics and to assess neutron damage on optics etc.

https://bang.berkeley.edu/events/ndnca/whitepaper/

Thanks to Darren Bleuel (LLNL)!

The TTDB neutron spectrum is adjustable depending on E_d and the breakup target material (Example: 1 cm beam, I_D=20 μA)*



Some of my students interested in working @ LLNL

Joey Gordon

- 4^{th} year UCB Ph.D. Student.
- 12/23 Graduation
  Ph.D. project: ^{56}Fe(n,n'γ)
- Expertise in GEANT, neutron/γ-ray spectroscopy

Tyler Nagel

- 5^{th} year UCB Ph.D. Student
- 12/23 Graduation
- Ph.D. project: ^{35}Cl(n,x) using CLYC, activation and prompt neutron/γ-spectroscopy

C. Joe Henderson

- UCB senior in Nuclear Engineering
- 5/23 Graduation
- B.S. projects: (p,xnγ) cross sections, Neutron air-scatter modeling
  Coming to NIF this summer!

Summary

- What NIF can do for Nuclear Physics
  - Nuclear reactions in HEDP environments
  - Using DD shots at NIF to study s-process neutron capture nucleosynthesis in an HEDP
  - The wheel experiments using NIF+ARC to study fission in High Energy Density Plasmas
- What Berkeley can do for NIF & LLNL
  - The 88-Inch cyclotron high-intensity neutron source
  - The BELLA petawatt laser-driven HED facility
    - New gamma diagnostic for $E_\gamma < 3$ MeV
  - Workforce Development

Closing note: The White House is holding a one-day meeting on nuclear data for fusion on 5/4 with LLNL representation. Fusion is on the rise ☺

Backup slides (not shown)