Nuclear Isomers and other Reactions Induced by High-intensity Lasers

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Outline

1. Intr: **Laser Nucl. Phys.**

2. **Kr83 Isomer** induced by lasers

3. Nucl. Astrphys. **S-factor of D+Li7**

4. Summary

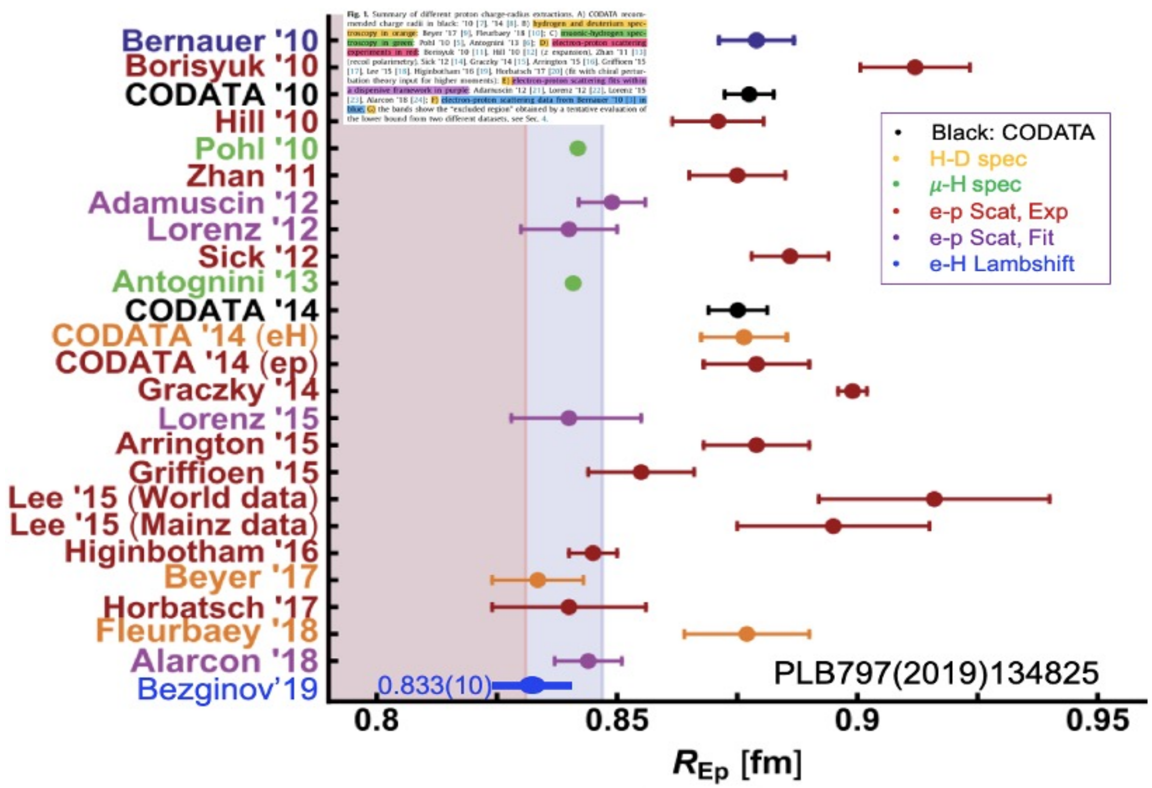
Motivation:
Why isomers?

- fm-ns scale phys.
- Nucl. Astrophys.
- Nucl. Laser
- Medical Isotopes

Why Isomers?

New Phys. in scale of fm-nm

Proton radius?

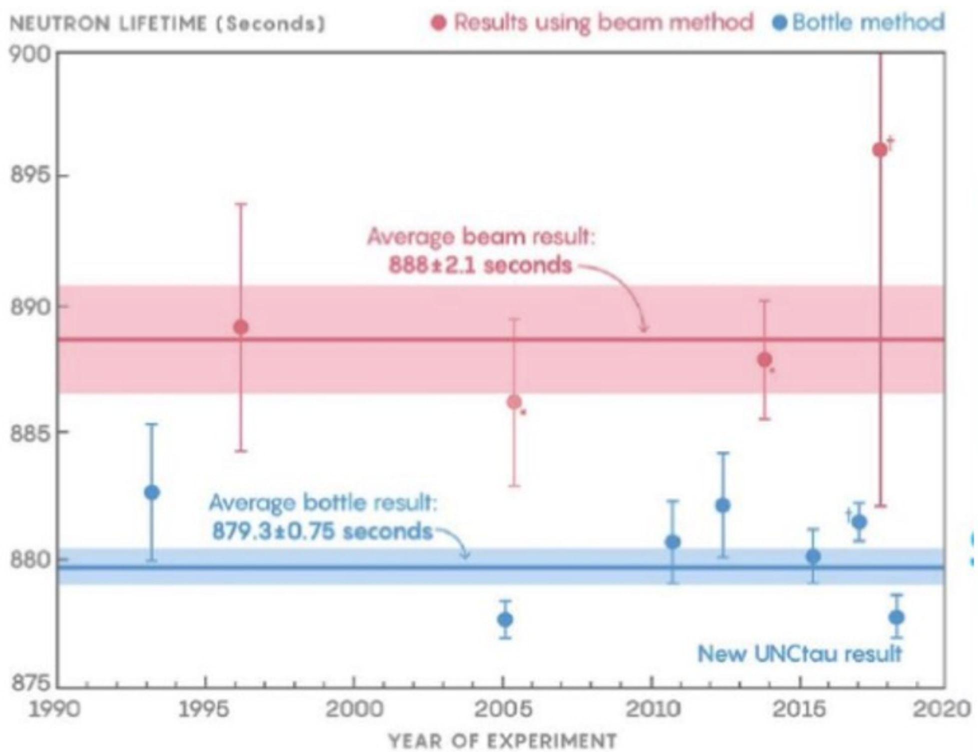


- 1919卢瑟福发现质子
- 101年，半径不确定！
- 测量差异显著
  - **H-D谱**法
  - **μH谱**法
  - **e-p散射**法
  - **eH兰姆位移**法
- 猜测：新结构？

High Intensity Laser can create an enviorment at extreme

New Phys. in scale of fm-nm

- Neutron lifetime?

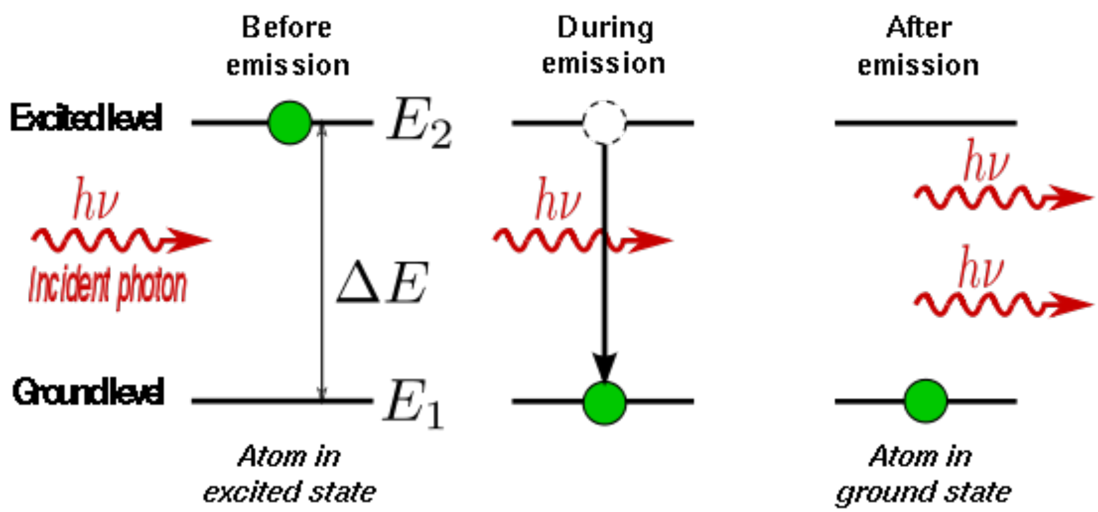


- 1932查德威克发现中子
- 80年后，寿命不确定？
- 测量差异显著
  - **束流**方法
  - **中子瓶**方法
- 猜测：新结构？

High Intensity Laser can create an enviorment at extreme

Why Isomers?

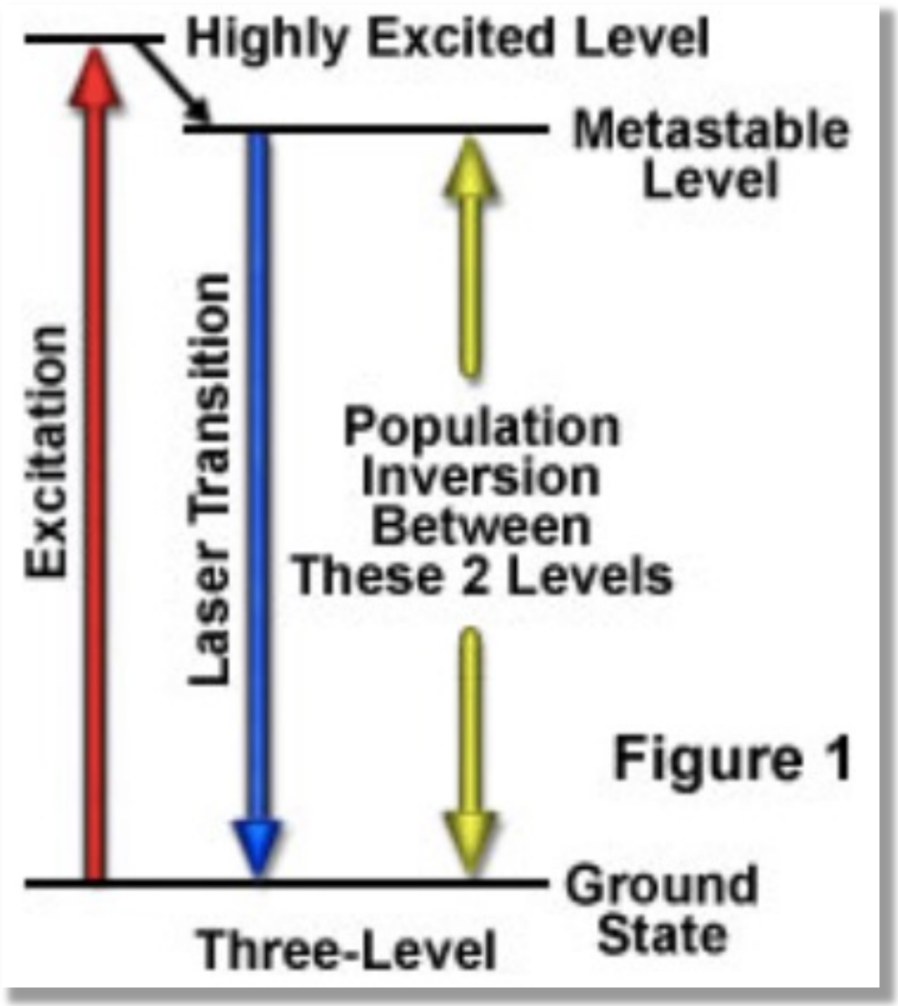
From Atomic laser to Nucl. one

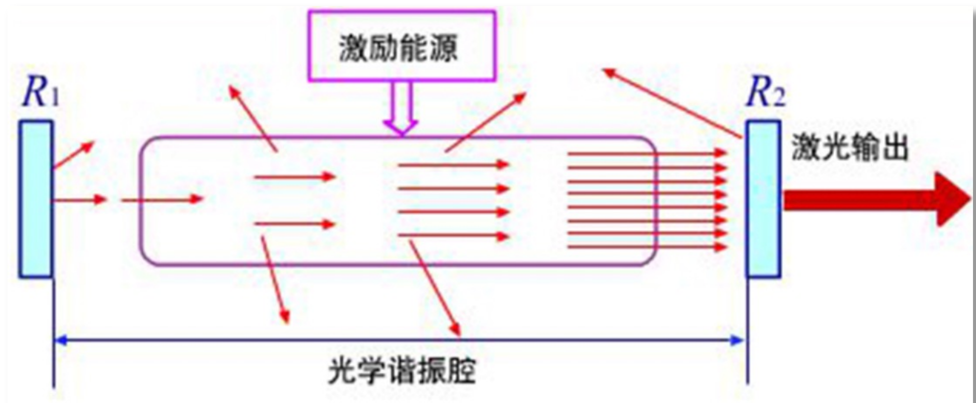


$$E_2 - E_1 = \Delta E = h\nu$$

- Exciting efficiency
- Stimulated decay rate $W_{21} = \left[\frac{dN_{21}}{dt}\right]_{st} * \frac{1}{N_2} = B_{21}\rho\nu$

From Atomic laser to Nucl. one



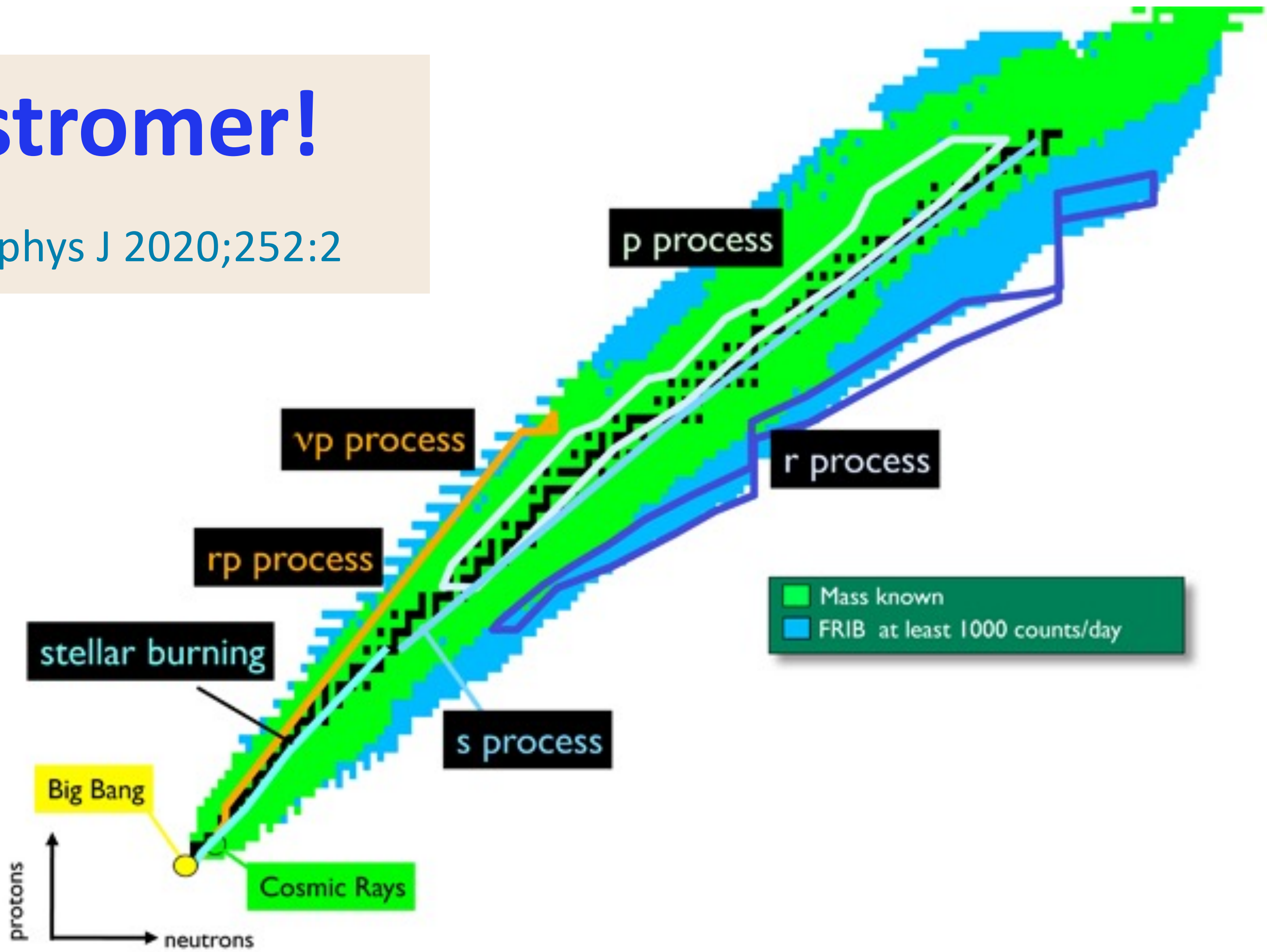


- **Exciting Eff.**
- Stimulated decay
- Resonance cavity

Isomer and nucleosynthesis

Astromer!

Astrophys J 2020;252:2

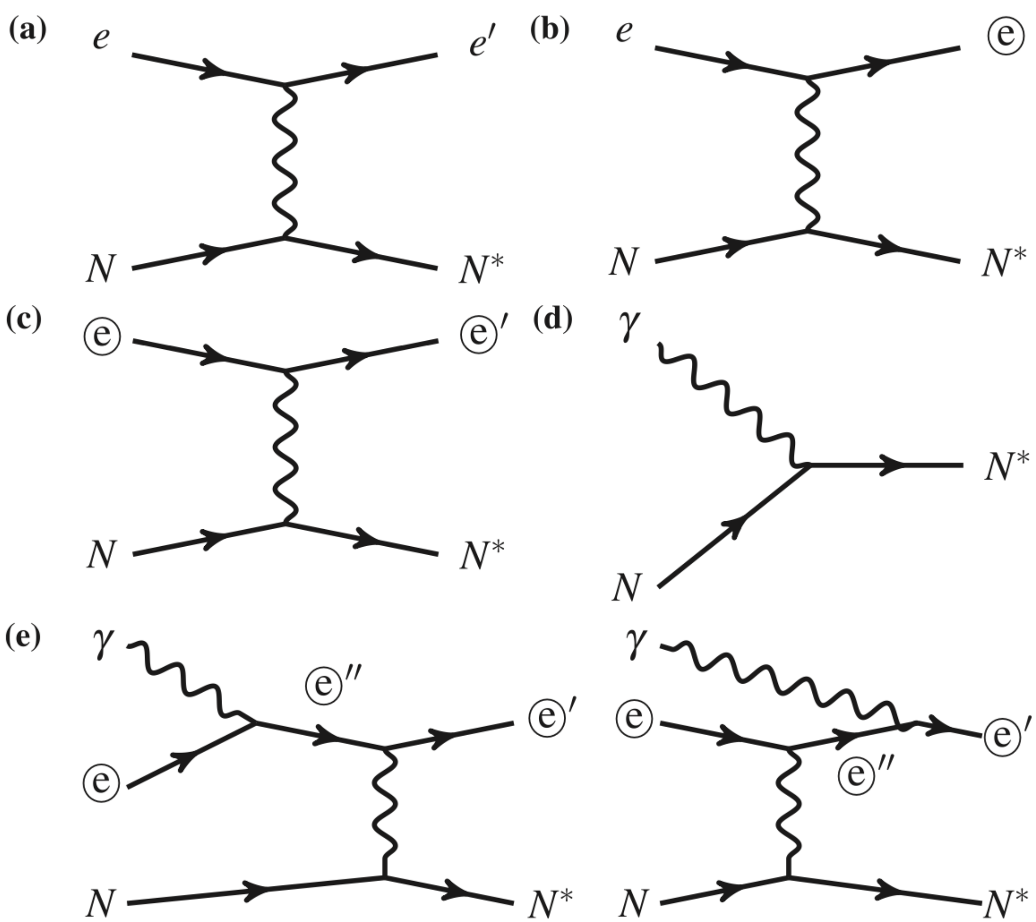


How to excite isomer with high efficiency

High Intensity Laser (HIL) + Nuclear Phys

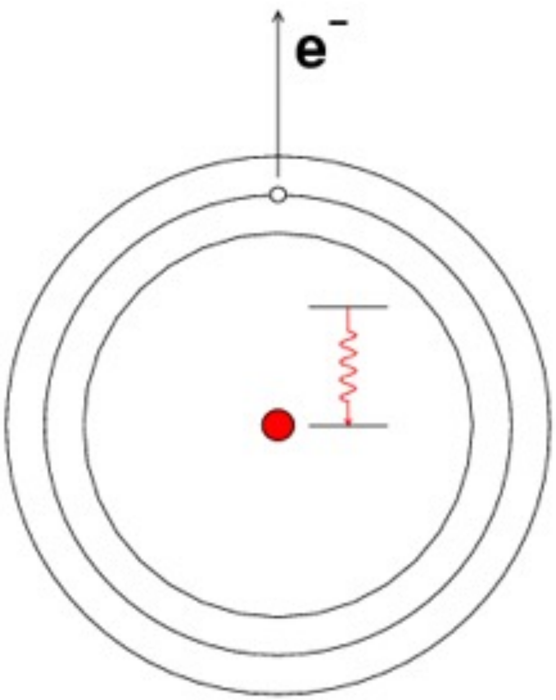
- New Environment, New Phys.?
- **Fundamental Phys.**
  - **Big Bang Nucleosynthesis**
  - Nucleosynthesis in supernova (Nucl. Astrophys. in lab.)
  - Vacuum excitation by HIL (QED)
  - Unruh-Hawking Rad.
  - Nuclear(gamma) Laser
- Application Phys.
  - Nucl. Energy ; Nuclear Waster
  - Neutron\gamma radiography
  - Medical isotope production
  - 2^{nd} beam (p, D, alpha, e, e+、n…) induce by HIL

Phys. with scale of fm- nm



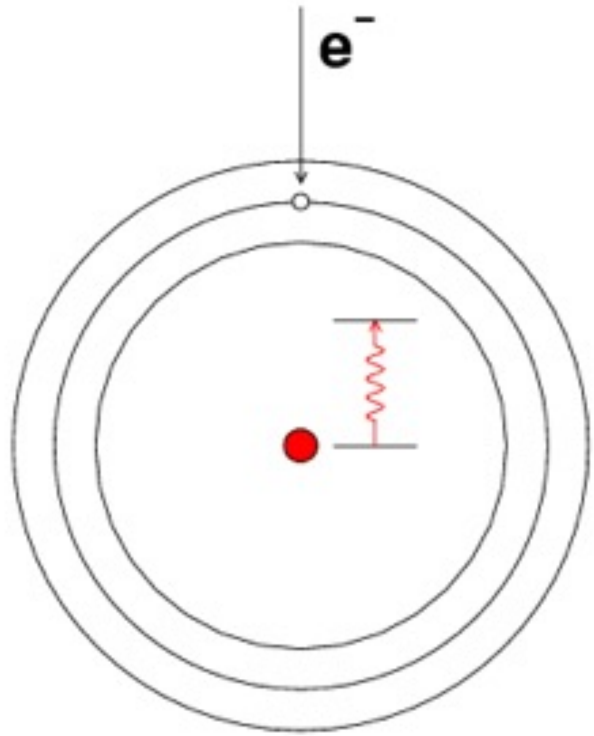
- **Possible processes**
  - CE, Coulomb Excitation
  - EC, Electron Capture
  - IC (Internal Conversion)
  - *NEET(nucl. exc. e trans.)*
  - NEEC(nucl.exc. e capture)
  - EB(Electronic Bridge)
  - DDL(Deep Dirac Level) ?

Nucl. Ex. e Capture



Internal Conversion

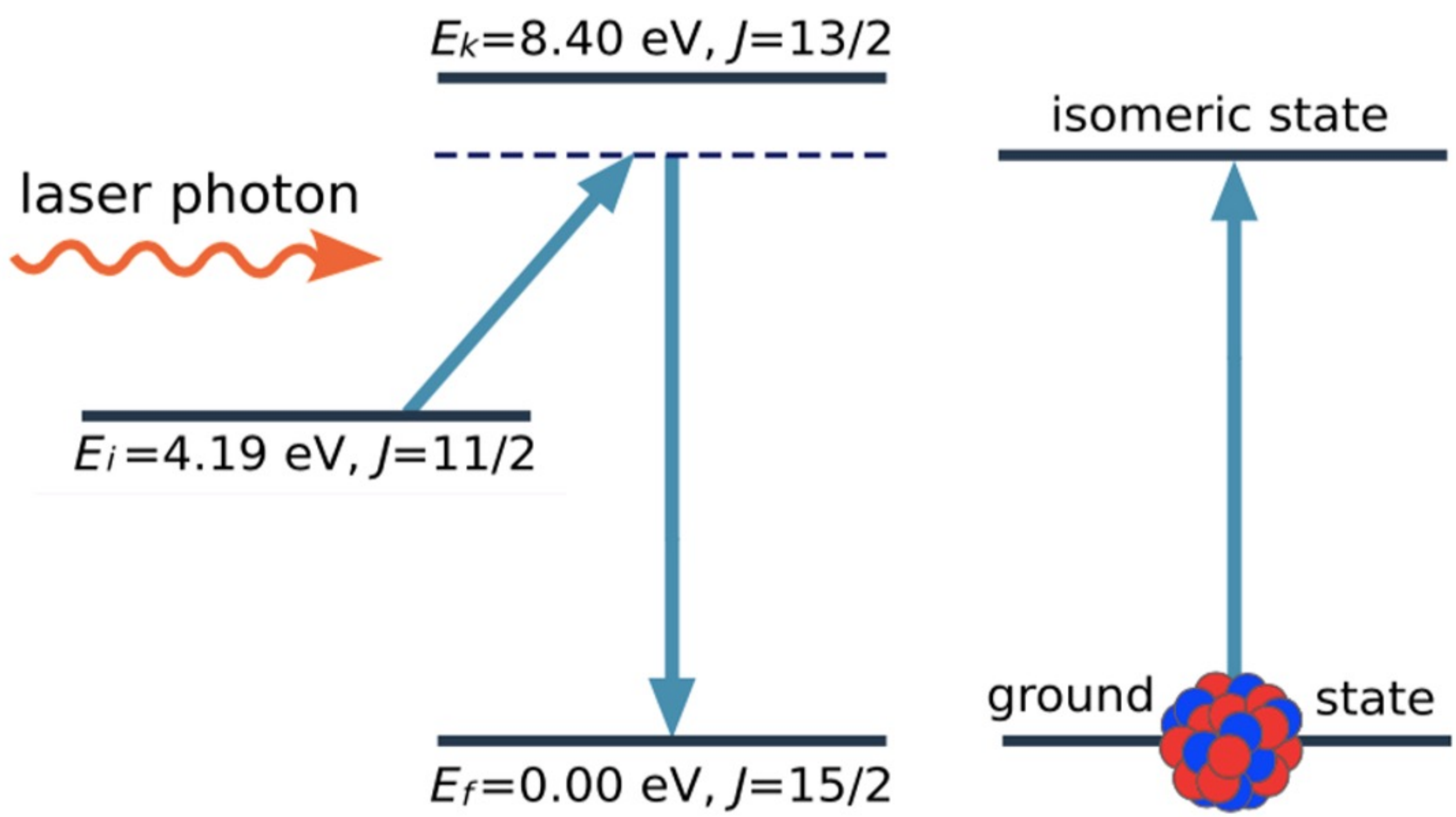
$$\alpha = p_{IC}/p_{\gamma}$$



NEEC

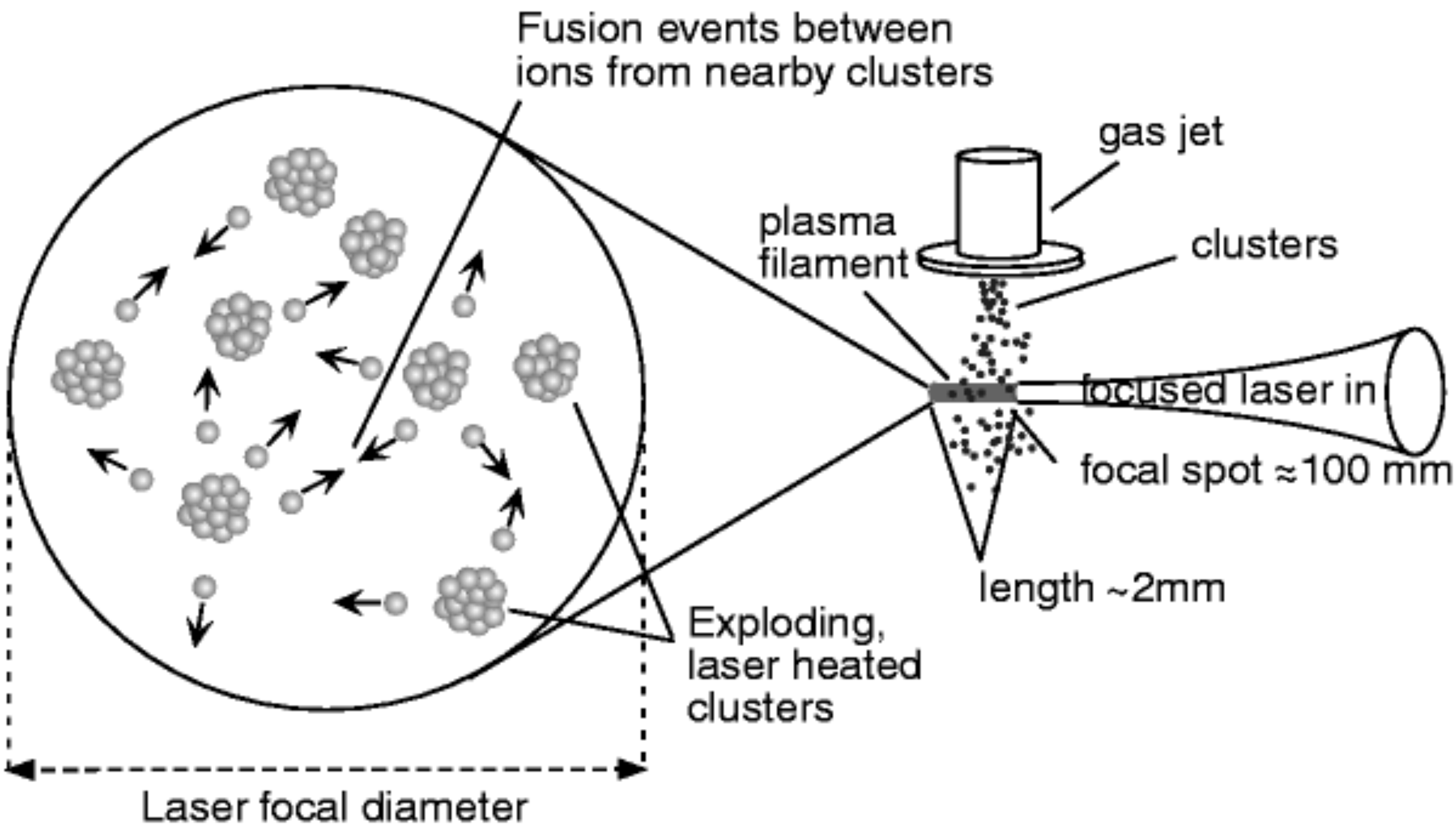
Nucl. Ex. by e Capt.

Electron Bridge



Th299 isomer

Coulomb Explosion

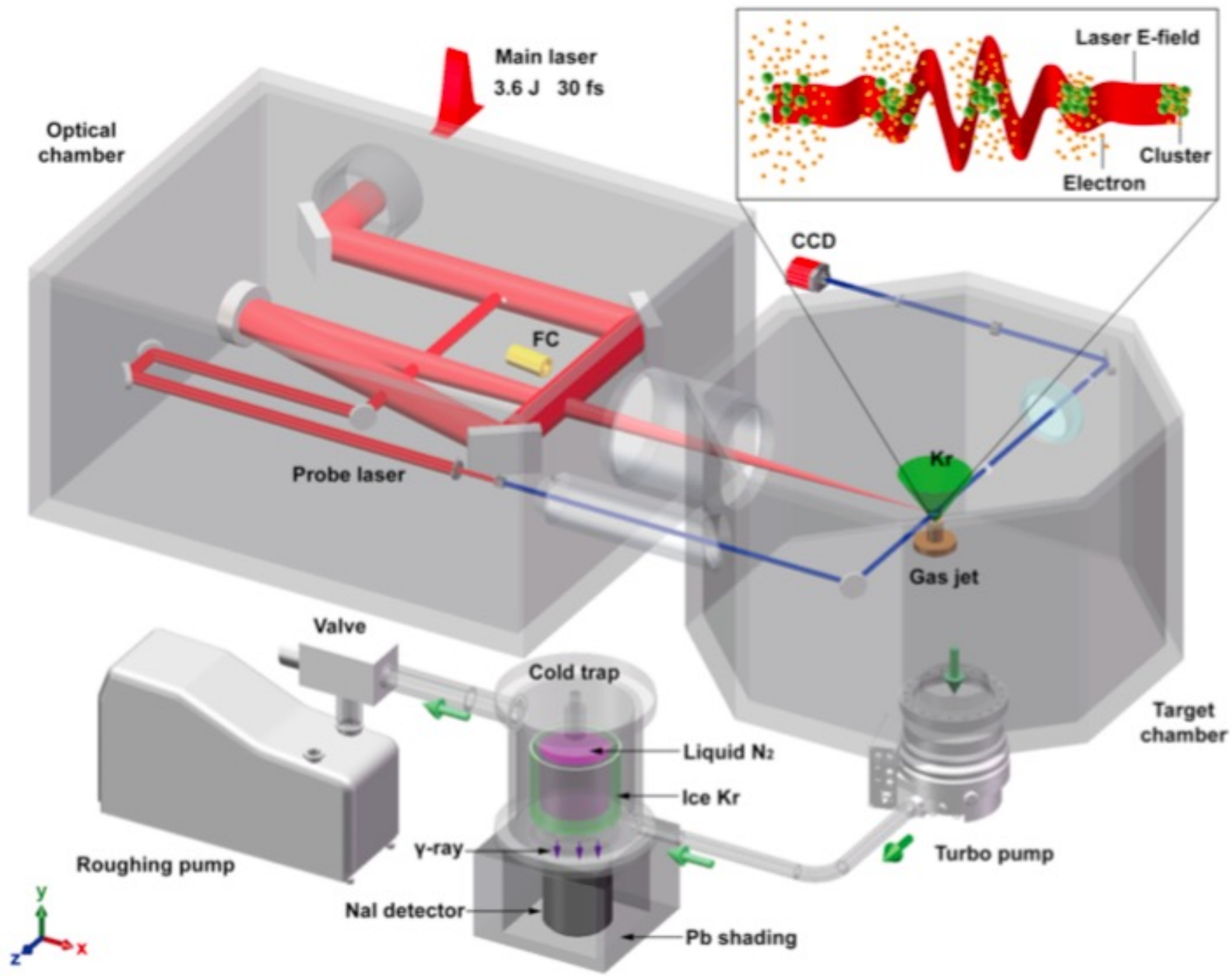


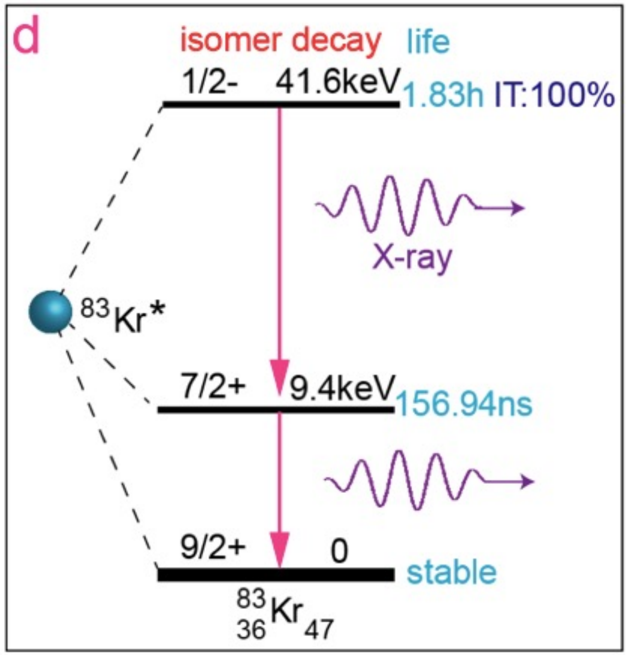
Nature **398**, pages489–492 (1999)

Nucl. Isomer Induced by HIL

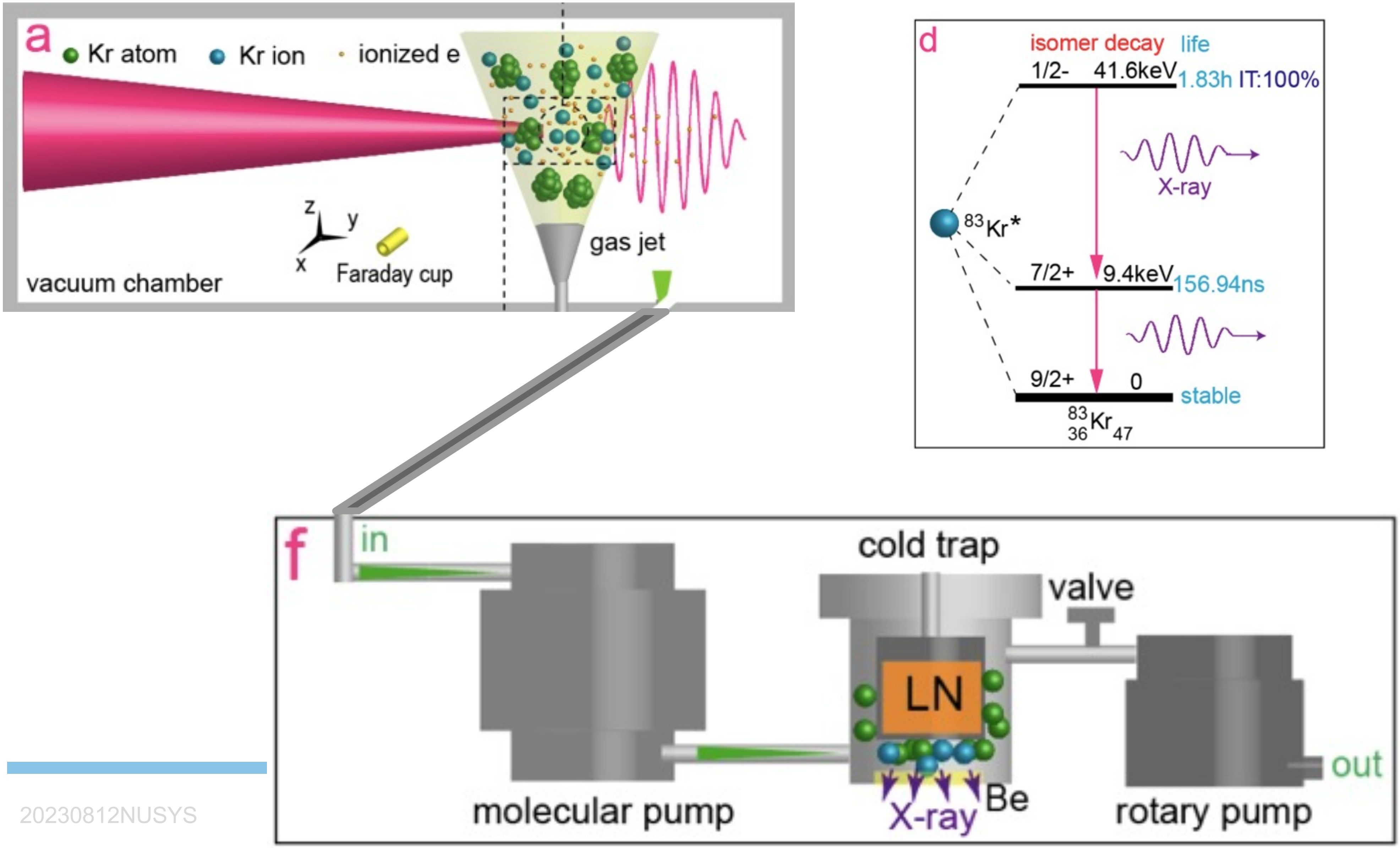
An experimental example ---Kr83

Experimental Setup

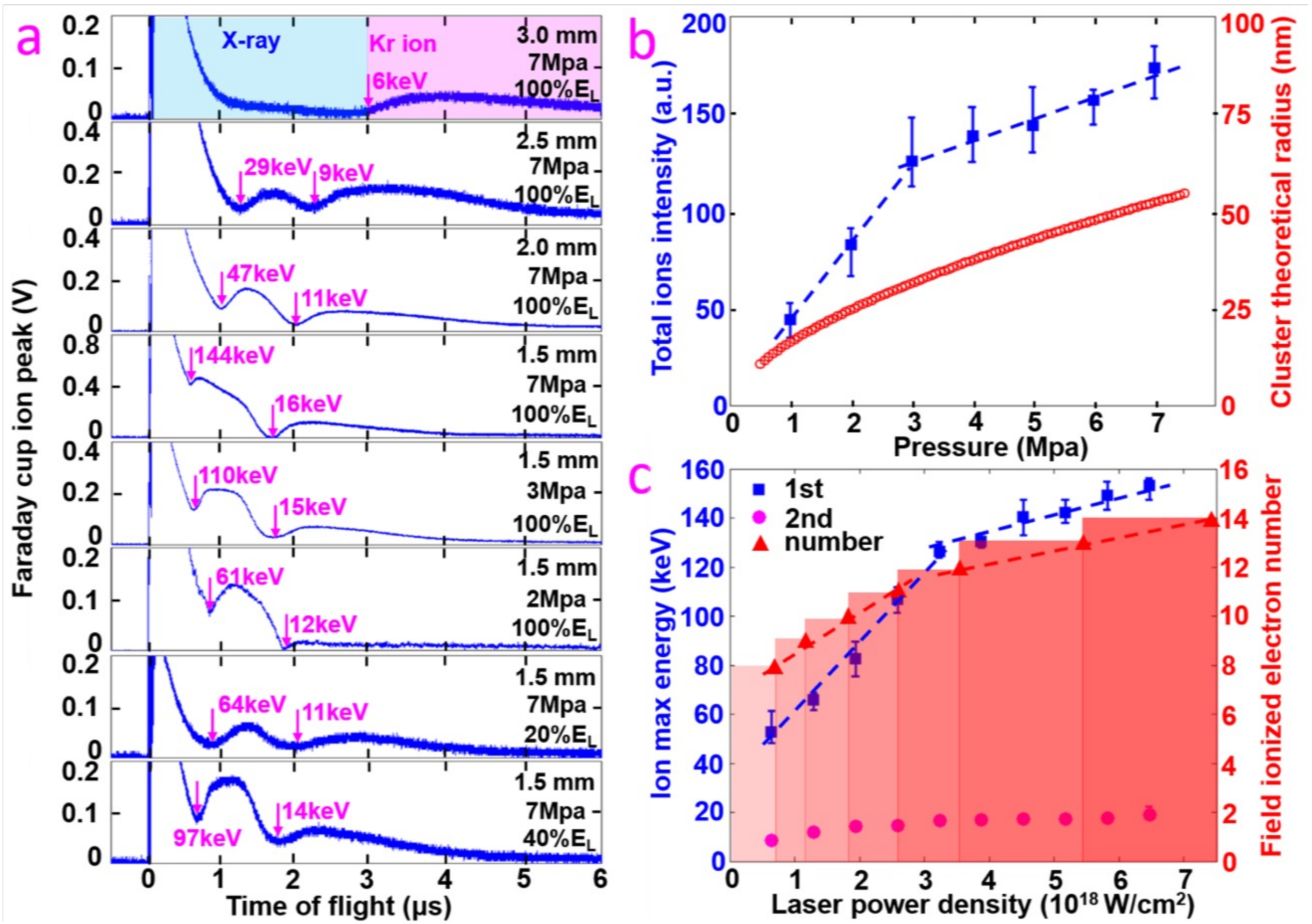




Experimental setup

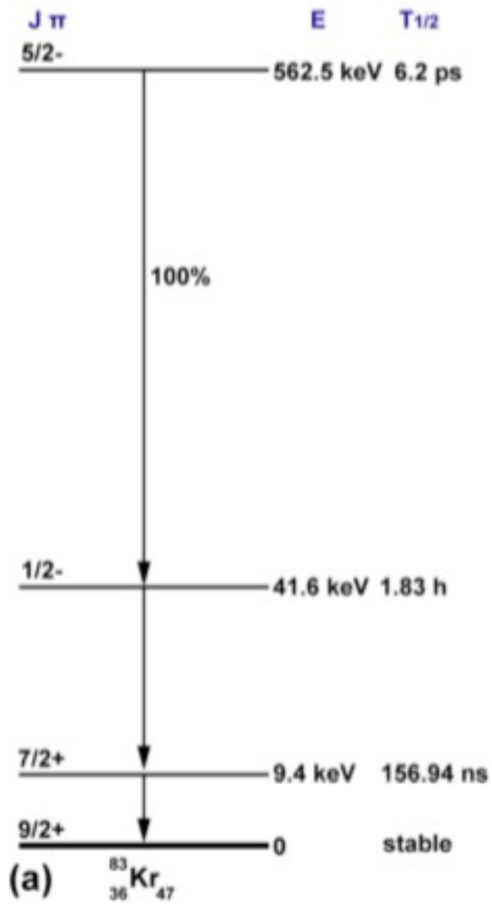


电子能谱

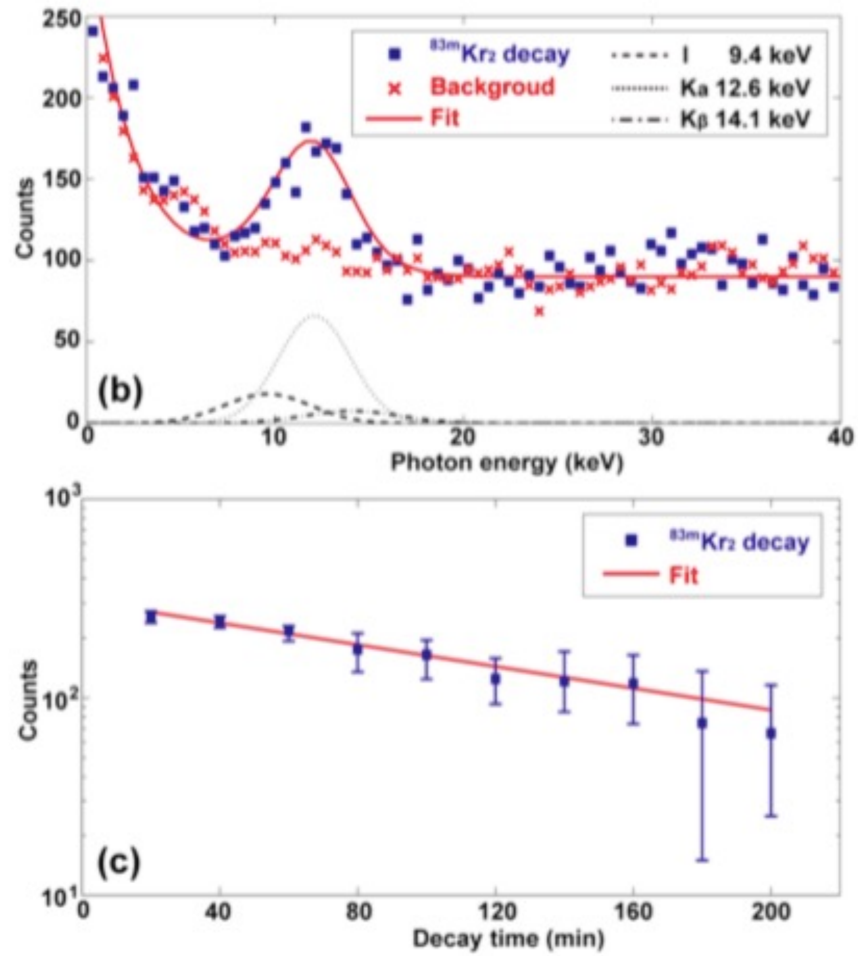


a
X-ray
Kr ion
6keV
3.0 mm
7Mpa
100%E$_L$
29keV
9keV
2.5 mm
7Mpa
100%E$_L$
47keV
11keV
2.0 mm
7Mpa
100%E$_L$
144keV
16keV
1.5 mm
7Mpa
100%E$_L$
110keV
15keV
1.5 mm
3Mpa
100%E$_L$
61keV
12keV
1.5 mm
2Mpa
100%E$_L$
64keV
11keV
1.5 mm
7Mpa
20%E$_L$
97keV
14keV
1.5 mm
7Mpa
40%E$_L$
Faraday cup ion peak (V)
Time of flight (μs)
b
Total ions intensity (a.u.)
Cluster theoretical radius (nm)
Pressure (Mpa)
c
1st
2nd
number
Ion max energy (keV)
Field ionized electron number
Laser power density (10^{18} W/cm^2)

^{83m}Kr (2nd ex.)

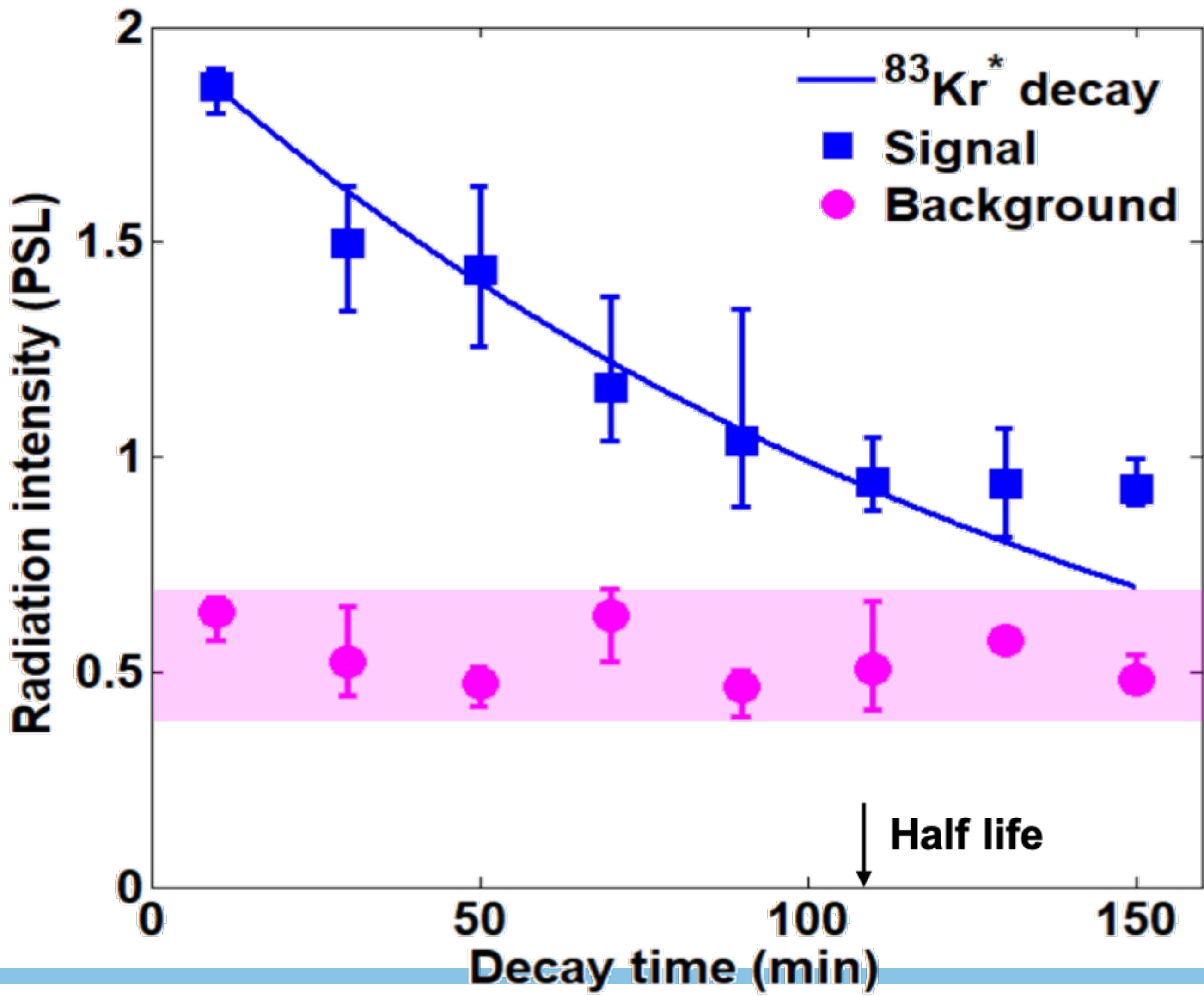


J π
E
T1/2
5/2-
562.5 keV 6.2 ps
100%
1/2-
41.6 keV 1.83 h
7/2+
9.4 keV 156.94 ns
9/2+
0
stable
(a)
$^{83}_{36}Kr_{47}$



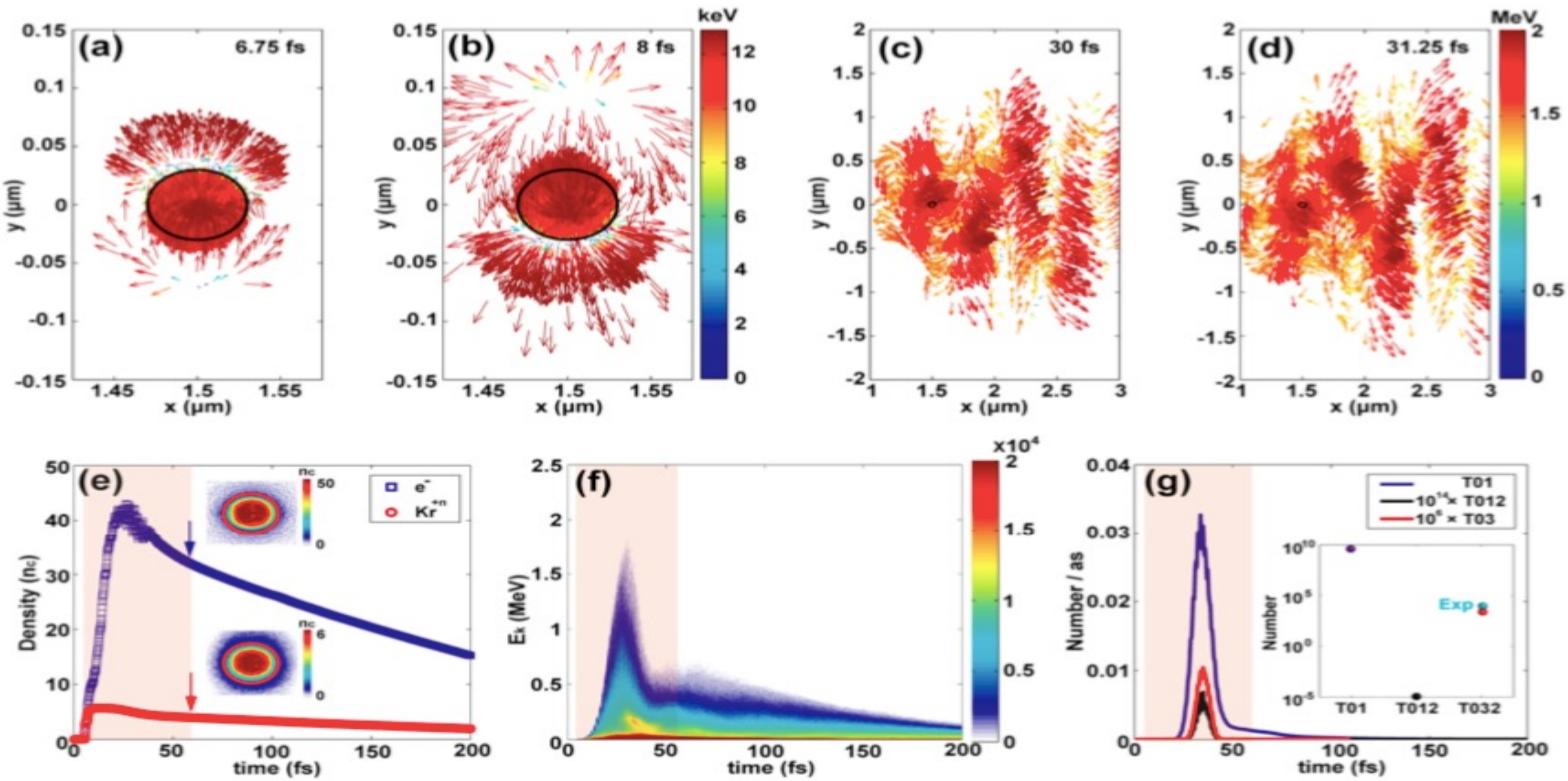
83mKr2 decay
Backgroud
Fit
I 9.4 keV
Kα 12.6 keV
Kβ 14.1 keV
Counts
Photon energy (keV)
(b)
83mKr2 decay
Fit
Counts
Decay time (min)
(c)

Results



^{83}Kr* decay
Signal
Background
Half life
Radiation intensity (PSL)
Decay time (min)
2
1.5
1
0.5
0
0
50
100
150

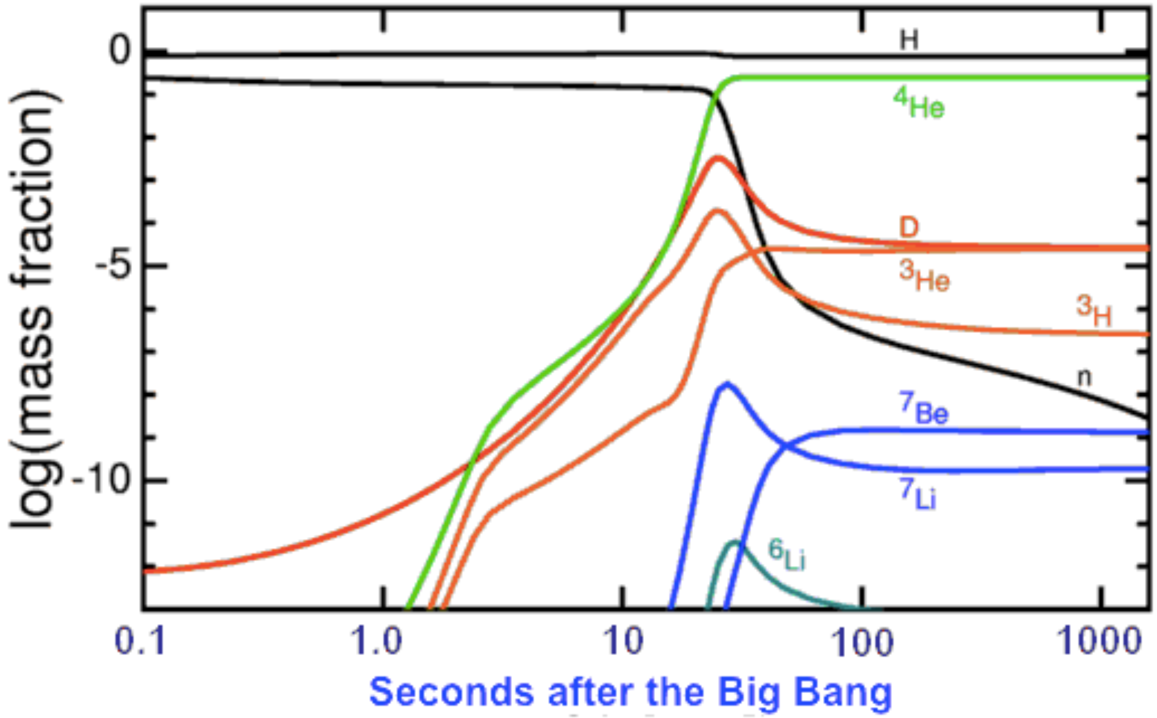
Simulation together with results

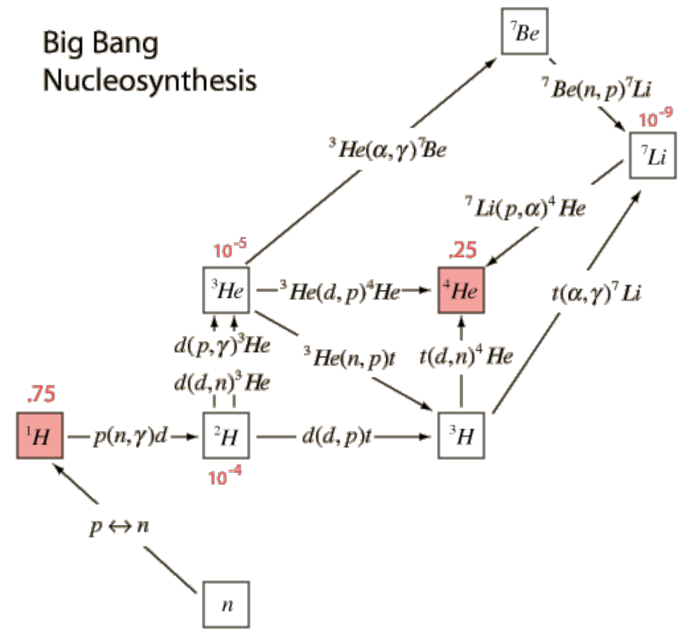


Phys. Rev. Lett. **128(2022)** 052501

D+Li7 and BigBang Nucleosynthesis

Lithium Abundance Puzzle

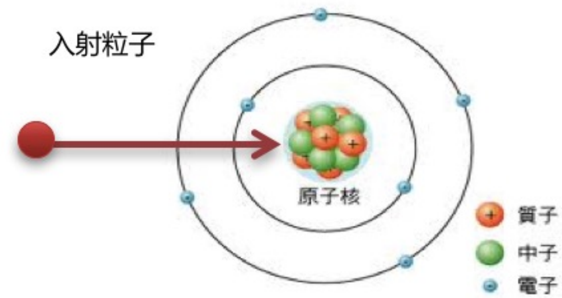


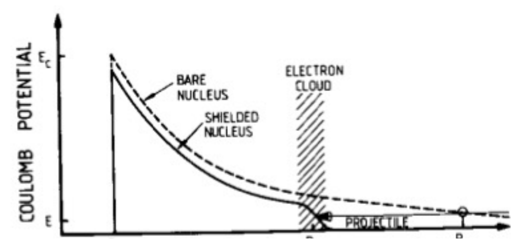


	计算值	观测值
4He	0.248	0.249 ± 0.009
D/p	2.64E-5	$2.78^{+0.44}_{-0.38} \times 10^{-5}$
3He/p	1.06E-5	(0.9—1.3)E-5
7Li/p	4.22E-10	$1.23^{+0.68}_{-0.32} \times 10^{-10}$
6Li/p	1E-14	1E-11

Nucl. Reaction in Astr. Plasma

- Decay Lifetime may diff.
  - $^{7}Be^{neutral}$ $t_{1/2}$ =52d ; $^{7}Be^{4+}$: Stable !
- Potential may diff.
- Collisionless Shock Acc.
- Revolution
  - In the sun, Li on surface is 140 times lower than the primordial sun (Nature464(2009)189
  - With or without planets





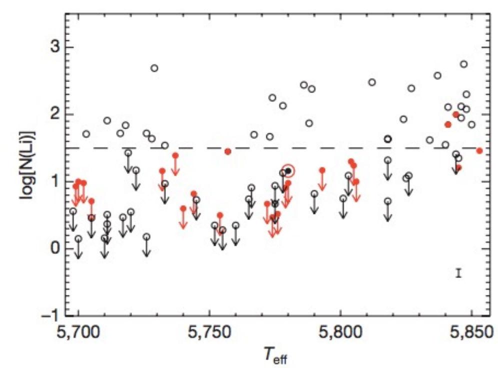


Figure 1 | Lithium abundance plotted against effective temperature in solar-analogue stars with and without detected planets. The planet-hosting and single stars are shown by filled red and empty black circles,

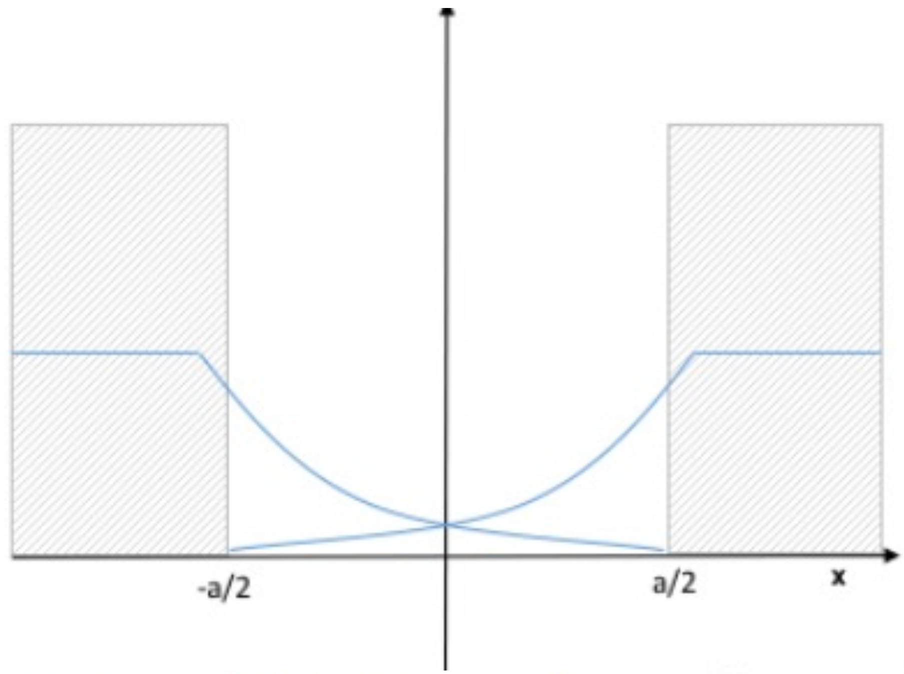
Self-calibration: D+D vs. D+Li

$$Y = A \iint n_1(x,t)\, n_2(x,t)\sigma(E_{cm}) v\, dx dt,$$

$$\sigma(E_{\mathrm{cm}}) = \sigma(\frac{1}{2}mv^2) = S(E_{\mathrm{cm}})\exp(-2\pi\eta)/E_{\mathrm{cm}}$$

$$Y = 2n_{10}n_{20}A \iint \frac{S\, e^{-(2+a/v_c t) - \frac{b/v_c}{(2+a/v_c t)}}}{\mu\left[v_c(2+a/v_c t)\right]^2} dx dt,$$

$$Y \simeq \frac{4n_{10}n_{20}Aa^2\sqrt{\pi}S(v)}{\mu v_c^{7/4} b^{1/4}\left(\sqrt{b/v_c}-2\right)^2}\exp\left[-2\sqrt{b/v_c}\right],$$

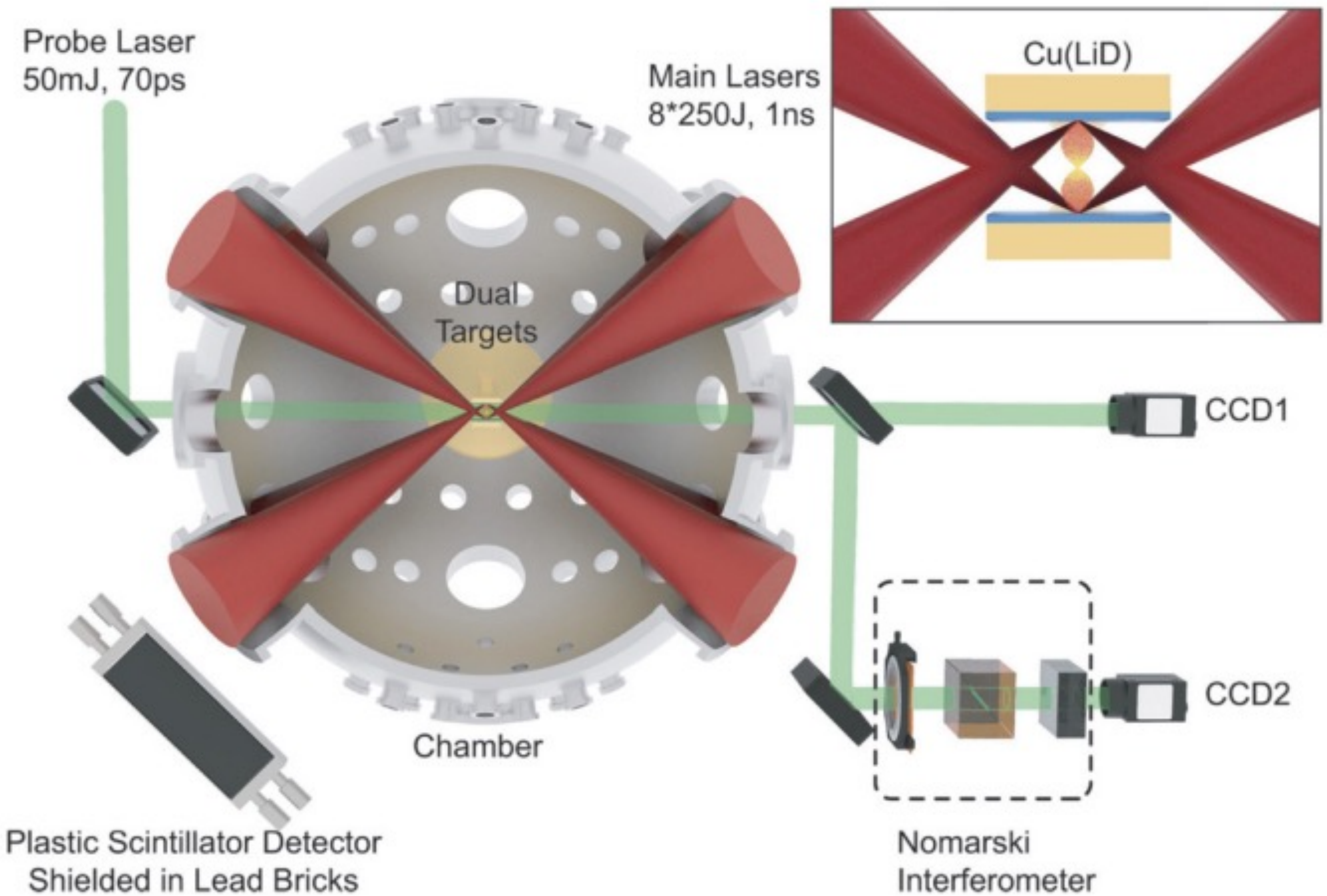


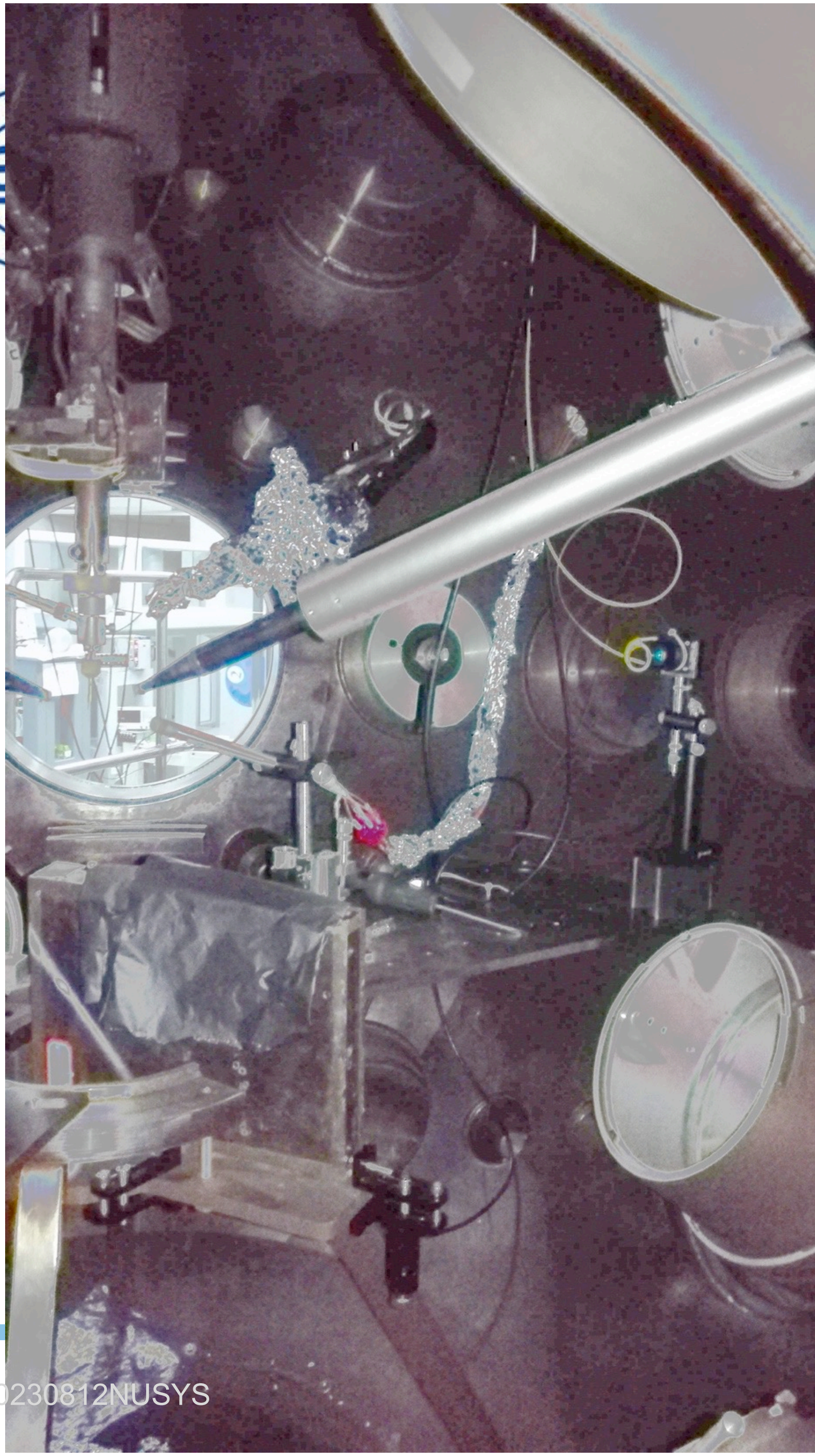
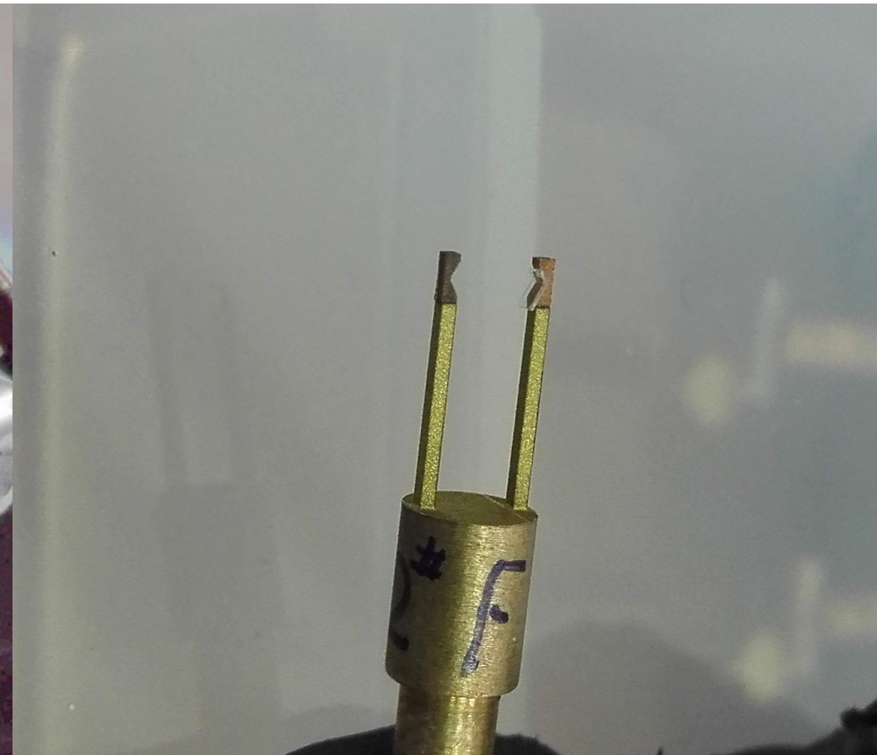
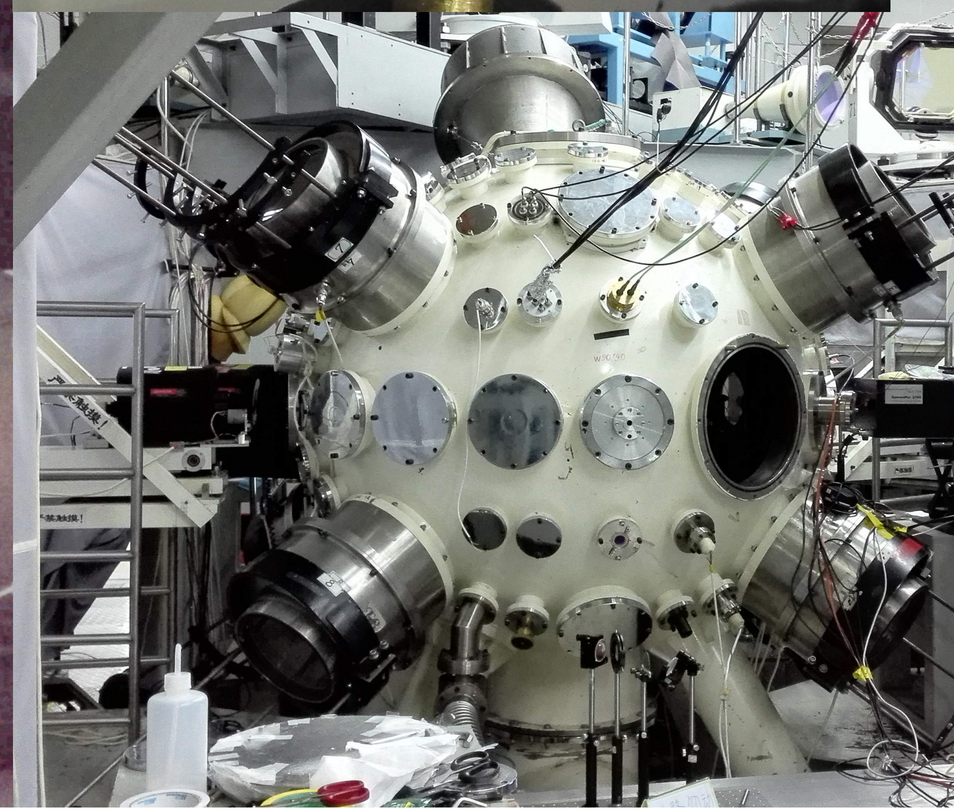
$$\begin{aligned} n_1(x,t) &= n_{10}e^{-[1+(a/2+x)/v_c t)]}, & (1)\\ n_2(x,t) &= n_{20}e^{-[1+(a/2-x)/v_c t)]}, & (2)\\ v_1(x,t) &= v_c + (a/2+x)/t, & (3)\\ v_2(x,t) &= v_c + (a/2-x)/t, & (4) \end{aligned}$$

$$\frac{Y_{LiD}}{Y_{DD}} = 2\frac{S_{LiD}}{S_{DD}}\frac{\mu_{DD}}{\mu_{LiD}}\frac{(\sqrt{\frac{b_{DD}}{v_c}}-2)^2}{(\sqrt{\frac{b_{LiD}}{v_c}}-2)^2}\frac{Z_D^{1/4}}{Z_{Li}^{1/4}}e^{-2(\sqrt{b_{DLi}}-\sqrt{b_{DD}})/\sqrt{v_c}}$$

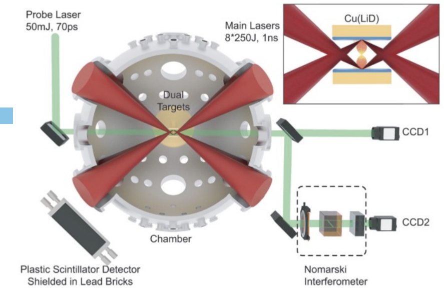
$$S_{LiD}(174keV) = 5377\frac{Q_{LiD}}{Q_{DD}}\frac{q_{DD}}{q_{DLi}}S_{DD}$$

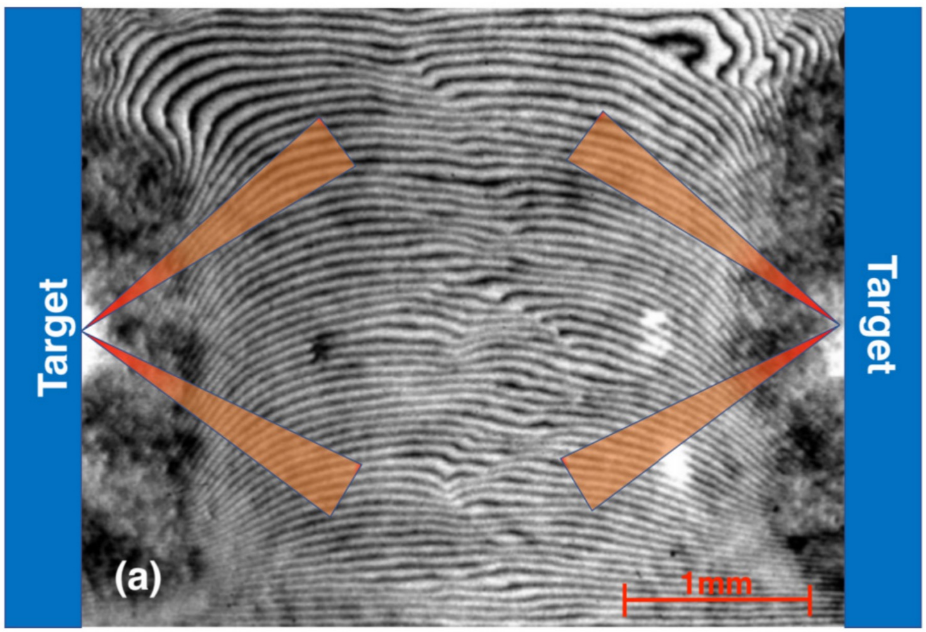
Experimental Setup

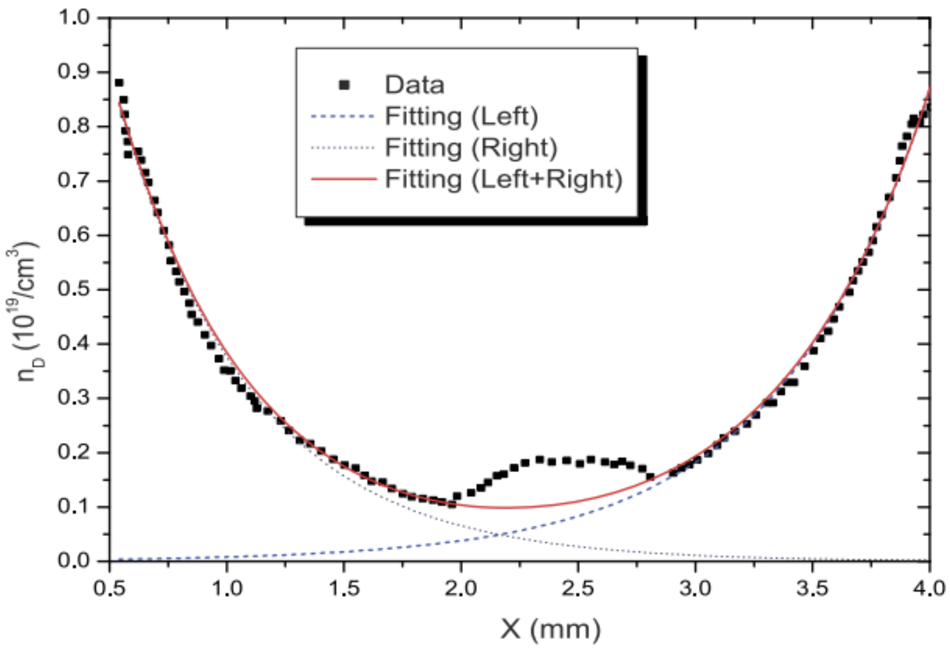


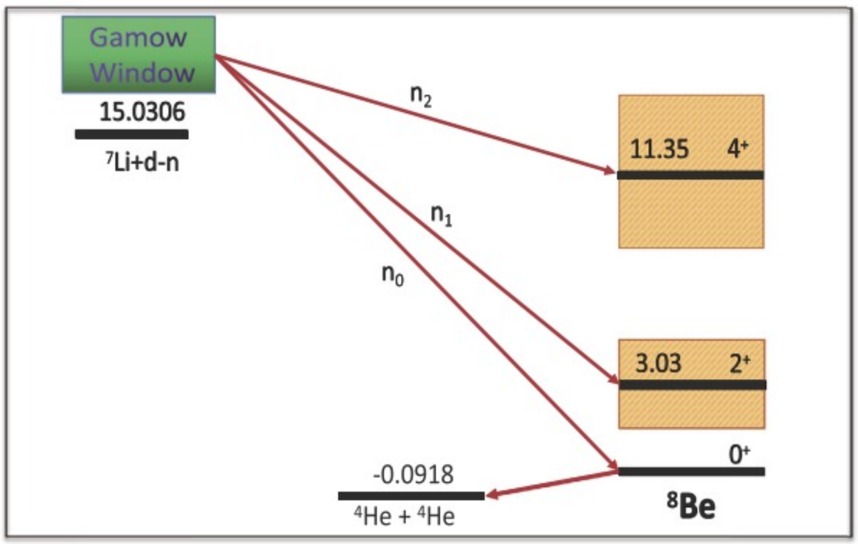
D、Li Density Dist.

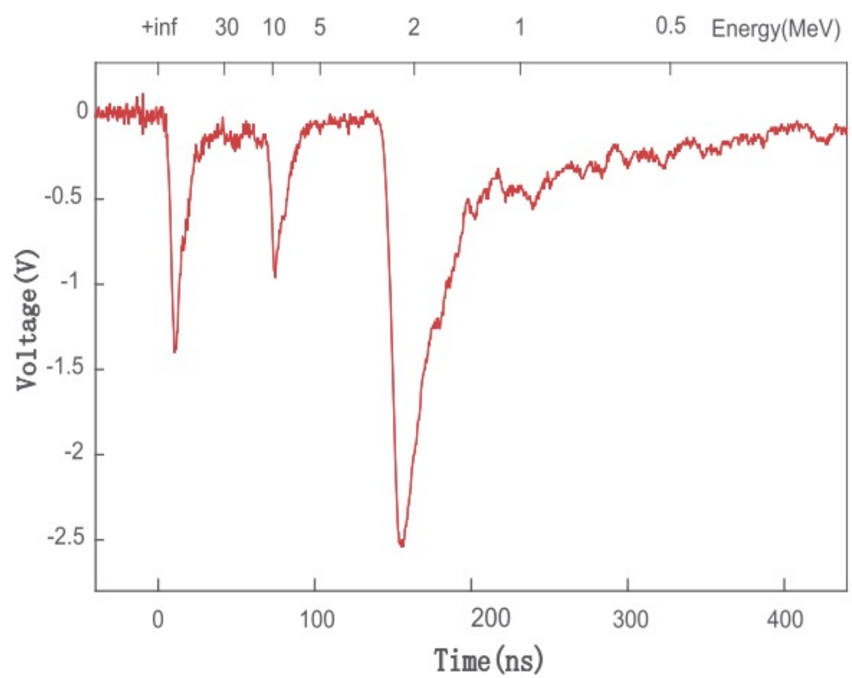




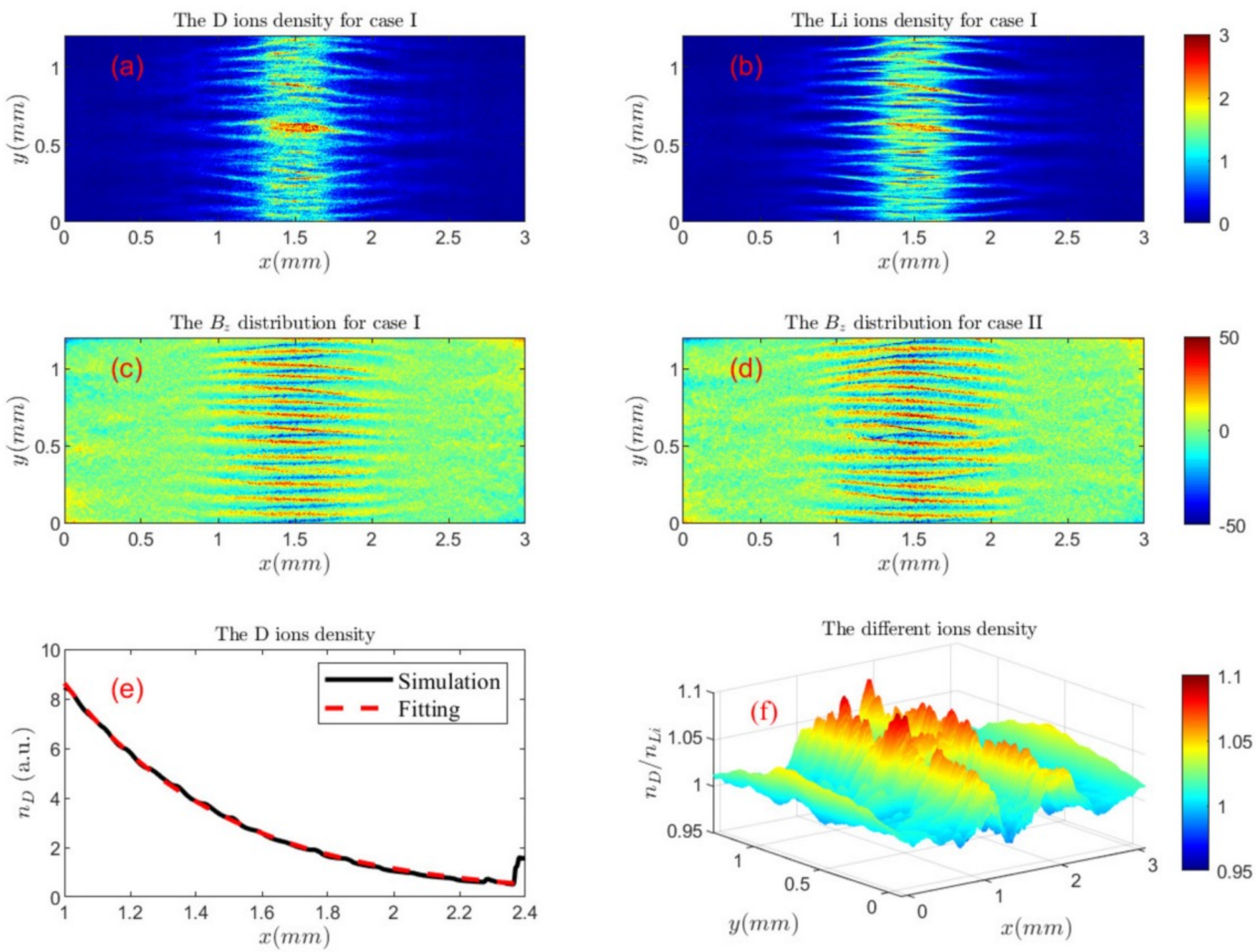


Neutron spectrum

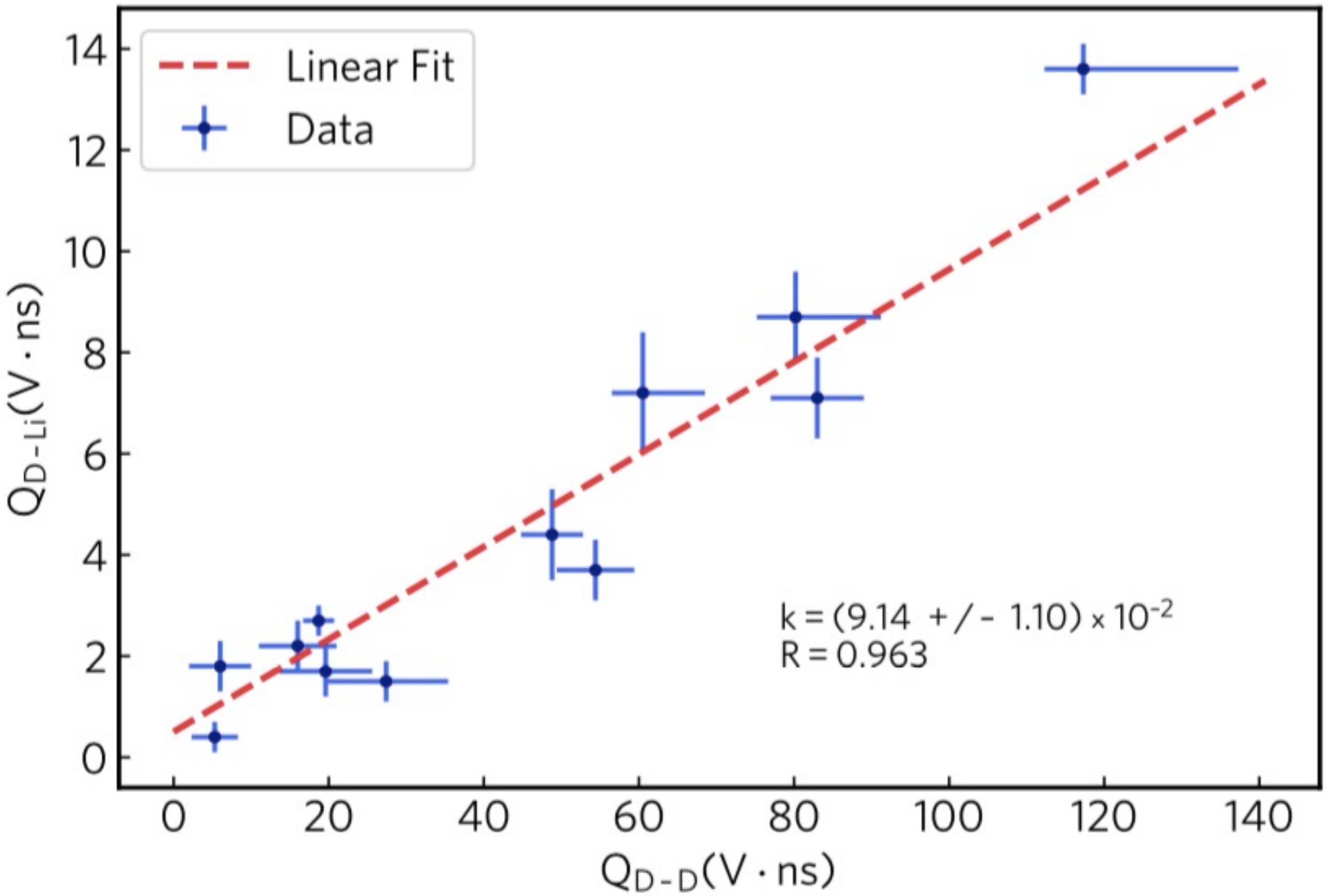




Simulation: How well the Self Cal.



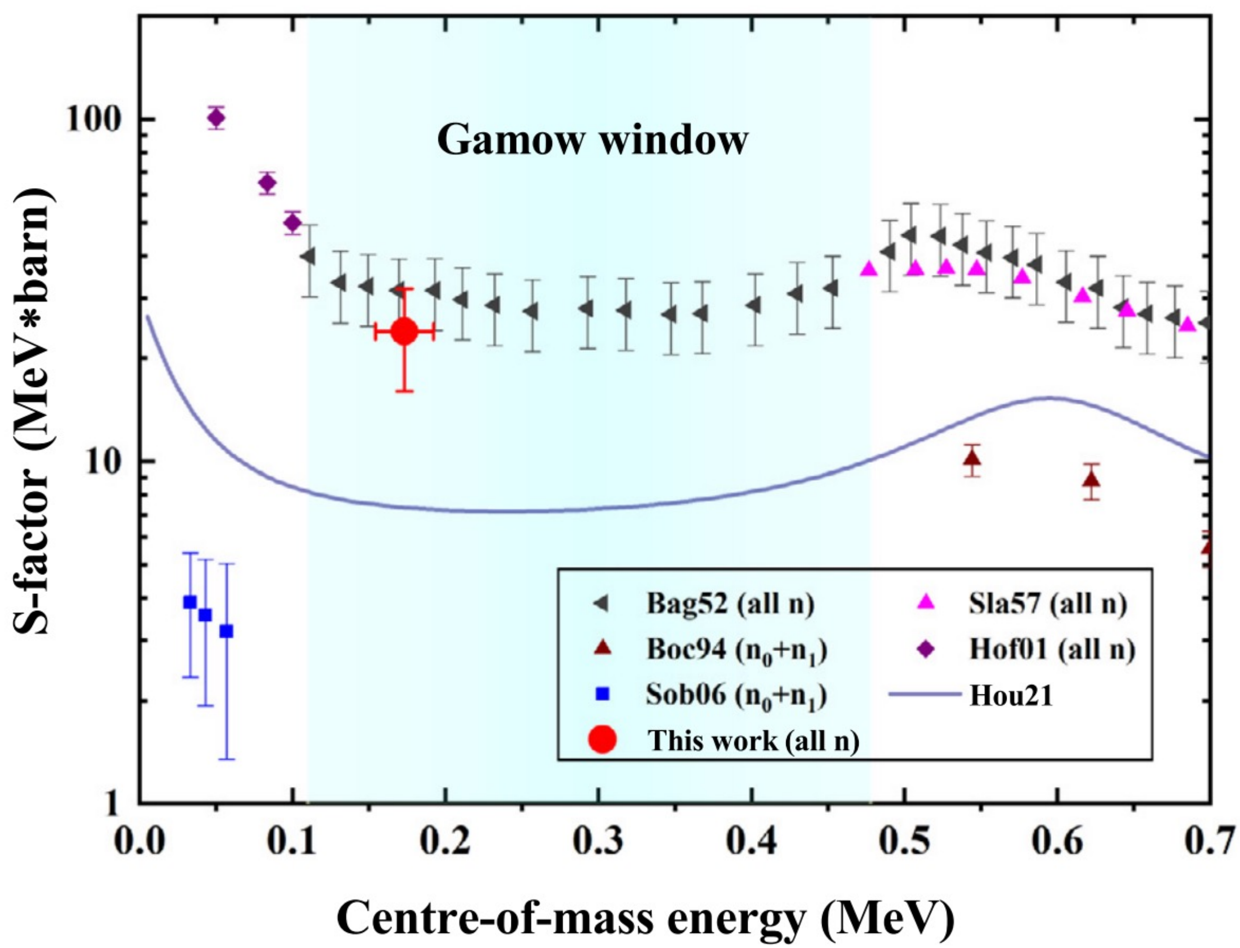
D/Li Ratio



$$S_{LiD}(174keV) = 5377\frac{Q_{LiD}}{Q_{DD}}\frac{q_{DD}}{q_{DLi}}S_{DD} = 6.2\times10^{3}keV\cdot b$$

$$\frac{Y_{LiD}}{Y_{DD}} = 2\frac{S_{LiD}}{S_{DD}}\frac{\mu_{DD}}{\mu_{LiD}}\frac{(\sqrt{\frac{b_{DD}}{v_c}}-2)^2}{(\sqrt{\frac{b_{LiD}}{v_c}}-2)^2}\frac{Z_D^{1/4}}{Z_{Li}^{1/4}}e^{-2(\sqrt{b_{DLi}}-\sqrt{b_{DD}})/\sqrt{v_c}}$$

D+Li S-factor



Physics Letters B

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Summary

- **New optunities**
  - fm-nm scale Phys.
  - Nucl. Laser
  - Nucl. Astrophys.

- First excited **nucl. Isomer** exp. with fs laser.

- First Measurement **S-factor** of D+7Li

- We expect more new phys. with HIL!