Lifetime of the key $^{30}P(p,\gamma)^{31}S$ resonance in novae

Barry Davids, Lijie Sun, Chris Wrede

Spokespersons for S2373

TRIUMF NP-EEC Meeting, Jan 30, 2024

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Bottleneck for Nova Nucleosynthesis

Presolar grains of nova origin

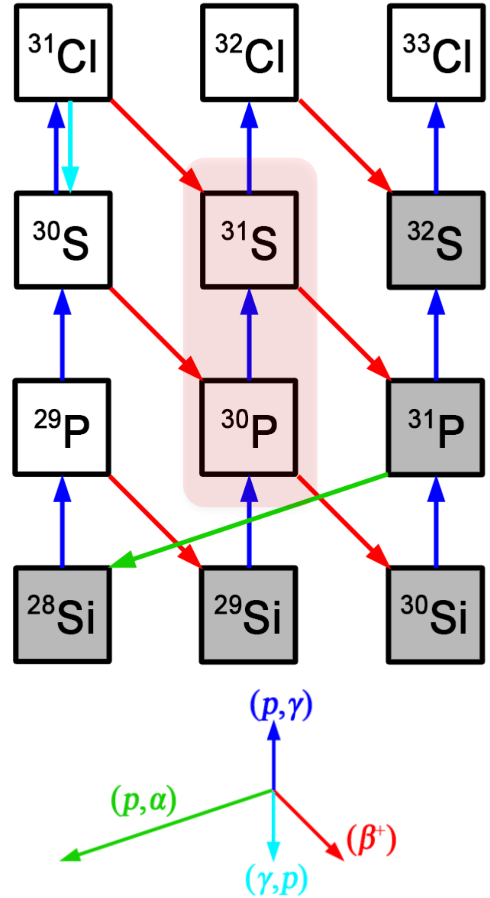
J. José *et al*., Astrophys. J. 612, 414 (2004).

Nuclear thermometers for novae

L. N. Downen *et al*., Astrophys. J. 762, 105 (2013).

Nuclear mixing meters for novae

K. J. Kelly *et al*., Astrophys. J. 777, 130 (2013).



J. José *et al*., Nucl. Phys. A 777, 550 (2006).

C. Wrede, AIP Advances 4, 041004 (2014).

Thermonuclear ^{30}P(p,γ)^{31}S Reaction Rate

Resonant reaction rate

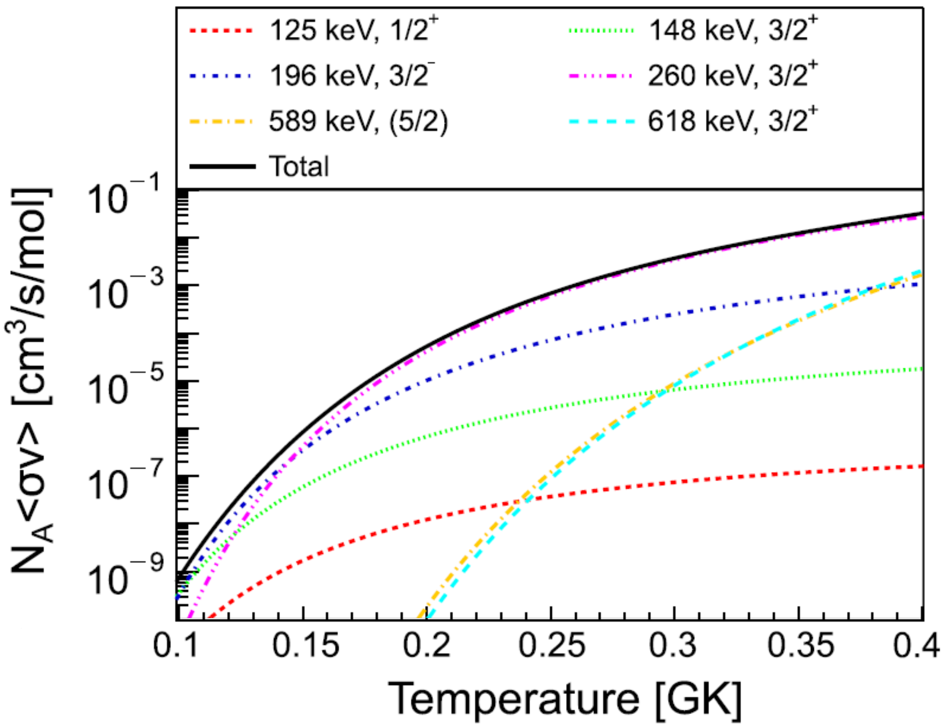
$$N_A\langle\sigma v\rangle_{\mathrm{res}} = N_A\left(\frac{2\pi}{\mu kT}\right)^{3/2}\hbar^2\boldsymbol{\omega\gamma}\exp\left(-\frac{E_r}{kT}\right)$$

Resonance strength

$$\boldsymbol{\omega\gamma} = \frac{2J_r+1}{(2J_p+1)(2J_T+1)}\frac{\Gamma_p\Gamma_\gamma}{\Gamma} \qquad \Gamma = \frac{\hbar}{\tau}$$

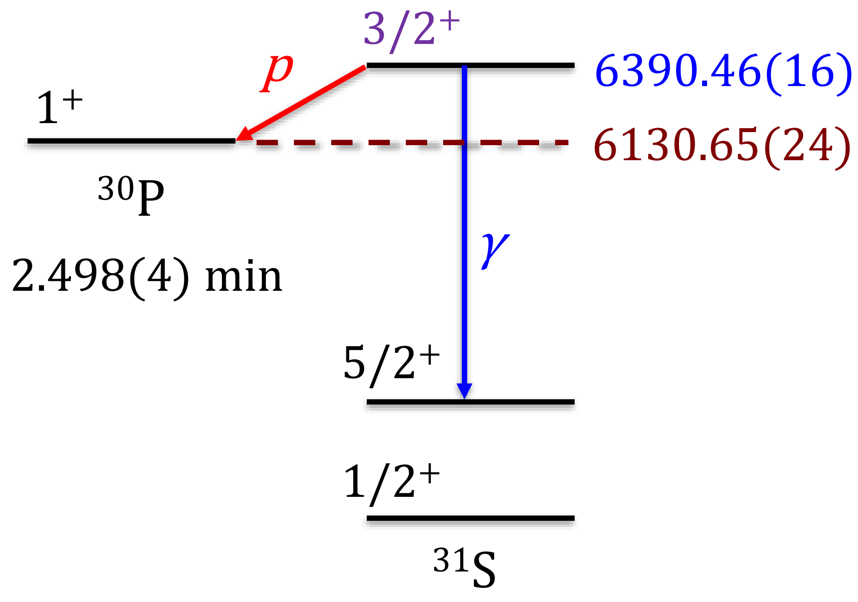
$$= \frac{2J_r+1}{(2J_p+1)(2J_T+1)}B_p(1-B_p)\frac{\hbar}{\tau}$$

C. Iliadis, Nuclear Physics of Stars, Wiley-VCH, 2015.



T. Budner *et al*., Phys. Rev. Lett. 128, 182701 (2022).

Key $^{30}P(p,\gamma)^{31}S$ Resonance



$J^{\pi} = 3/2^{+}$, $E_x = 6390.2(7)$ keV

M. B. Bennett *et al*., Phys. Rev. Lett. 116, 102502 (2016).

$B_p = 2.5^{+0.4}_{-0.3} \times 10^{-4}$

T. Budner *et al*., Phys. Rev. Lett. 128, 182701 (2022).

τ = 4.4 fs (USDA)
τ = 26 fs (USDB)
τ = 3.4 fs (USDC), 1.3 fs (USDC-shifted)
τ = 1.9 fs (USDE)
τ = 3.5 fs (USDI)

B. A. Brown. Shell Model Calculations.

τ < 10 fs (^{31}P $3/2^{+}$ 6381 keV)

E.O. de Neijs *et al*., Nucl. Phys. A 254, 45 (1975).

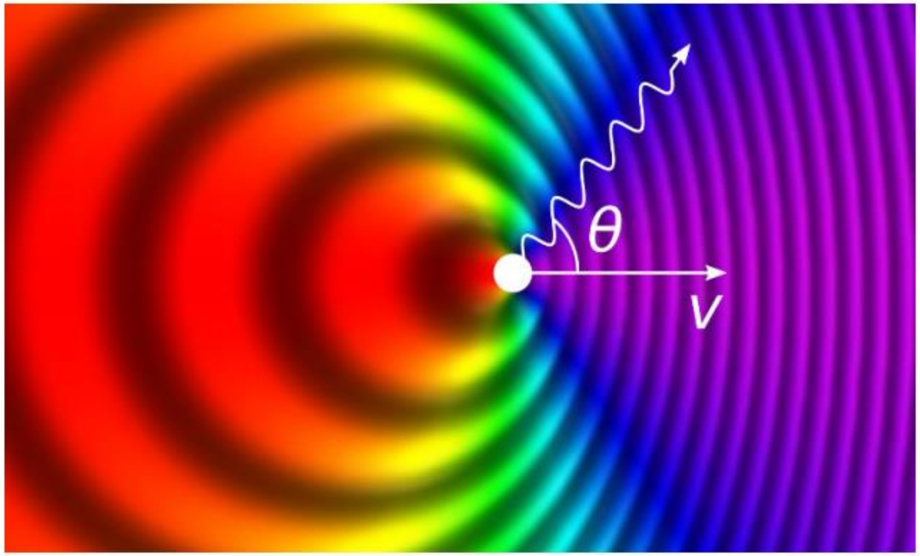
τ < 20 fs (TRIUMF S1582)

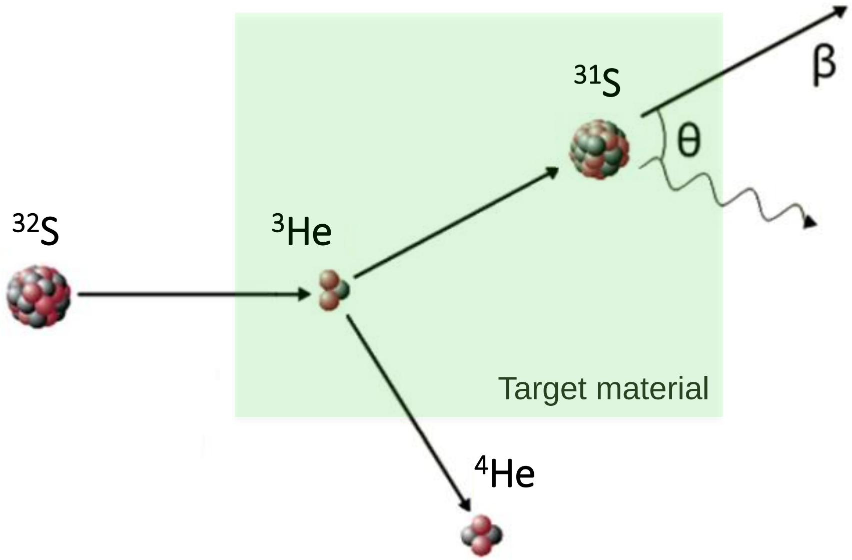
L. J. Sun *et al*., Phys. Lett. B 839, 137801 (2023).

S_p:

A. Kankainen *et al*., Phys. Rev. C 82, 052501(R) (2010).
L. Canete *et al*., Eur. Phys. J. A 52, 124 (2016).

Doppler Shift Attenuation Method



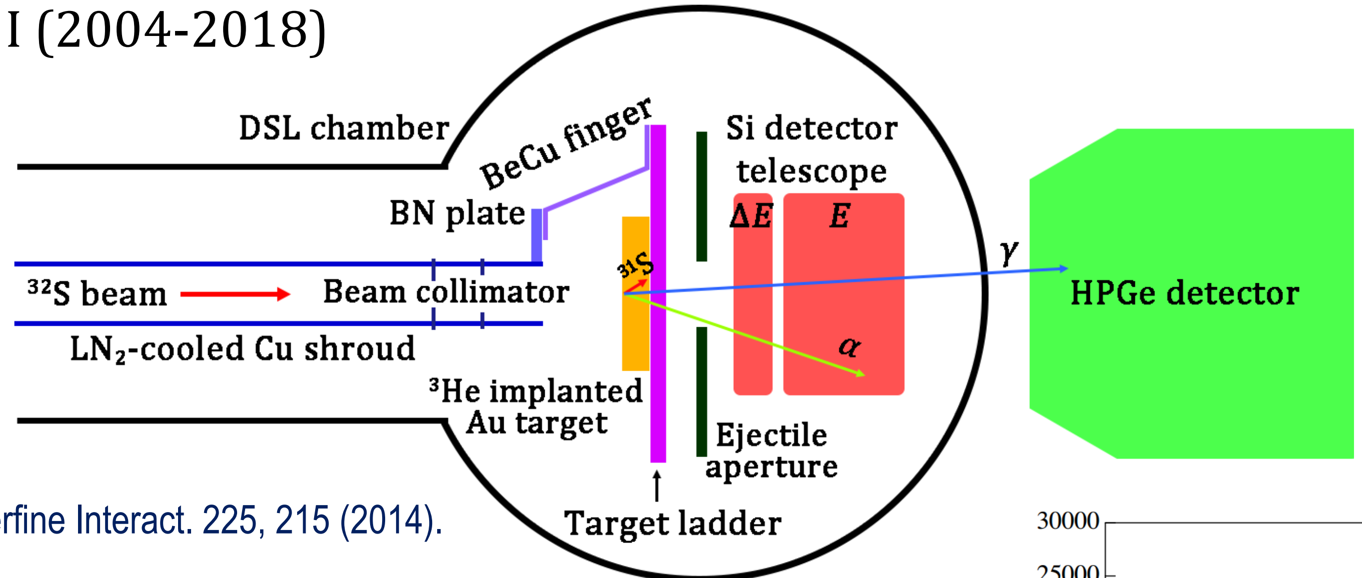


$$E_\gamma = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}, \qquad \beta = \frac{v}{c}$$

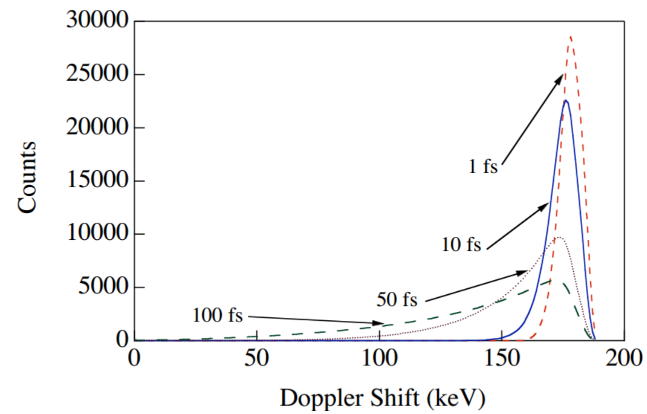
D. Branford *et al*., Nucl. Instrum. Methods 106, 437 (1973).
T. K. Alexander *et al*., Adv. Nucl. Phys. 10, 197 (1978).
P. J. Nolan *et al*., Rep. Prog. Phys. 42, 1 (1979).

Doppler Shift Lifetimes (DSL) @ ISAC-II

DSL Phase I (2004-2018)

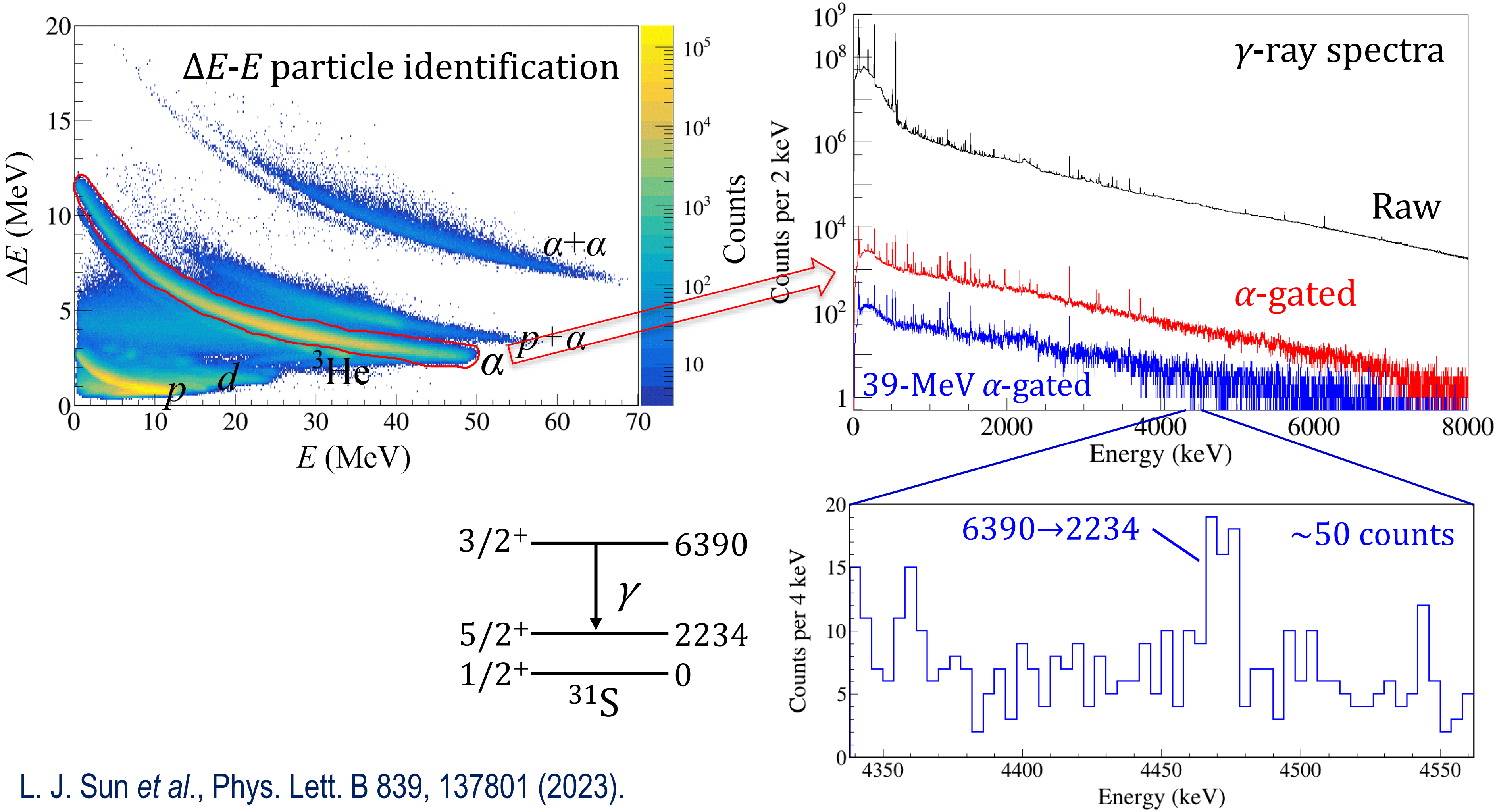


B. Davids, Hyperfine Interact. 225, 215 (2014).



S992	^{19}Ne	R. Kanungo *et al.*, Phys. Rev. C 74, 045803 (2006).
S992	^{19}Ne	S. Mythili *et al.*, Phys. Rev. C 77, 035803 (2008).
S1151	^{15}O	N. Galinski *et al.*, Phys. Rev. C 90, 035803 (2014).
S1378	^{23}Mg	O. S. Kirsebom *et al.*, Phys. Rev. C 93, 025802 (2016).
S1582	^{31}S	L. J. Sun *et al.*, Phys. Lett. B 839, 137801 (2023).

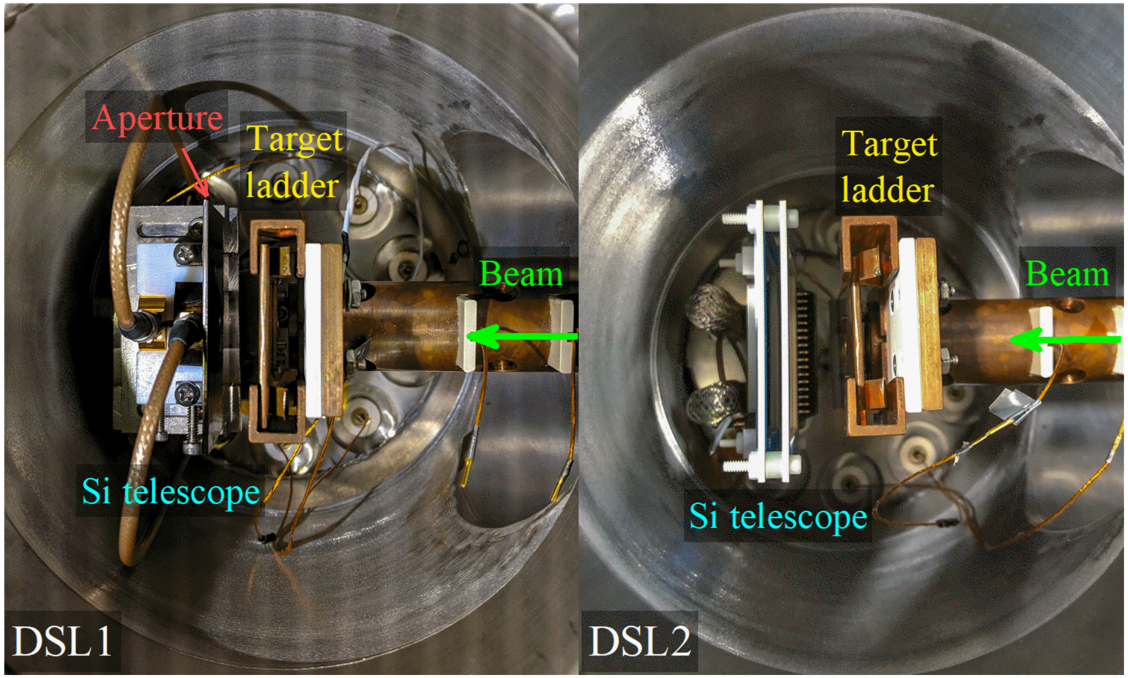
$^{3}He(^{32}S,\alpha\gamma)^{31}S$ Reaction with DSL1

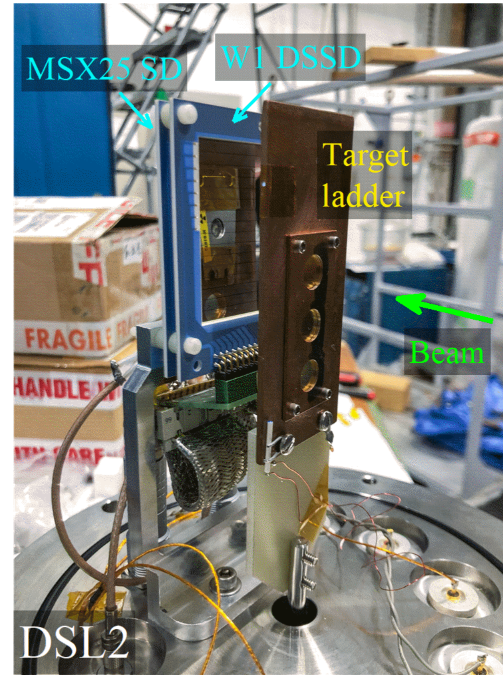


L. J. Sun *et al.*, Phys. Lett. B 839, 137801 (2023).

DSL2 Upgrade

DSL Phase II (2020–)





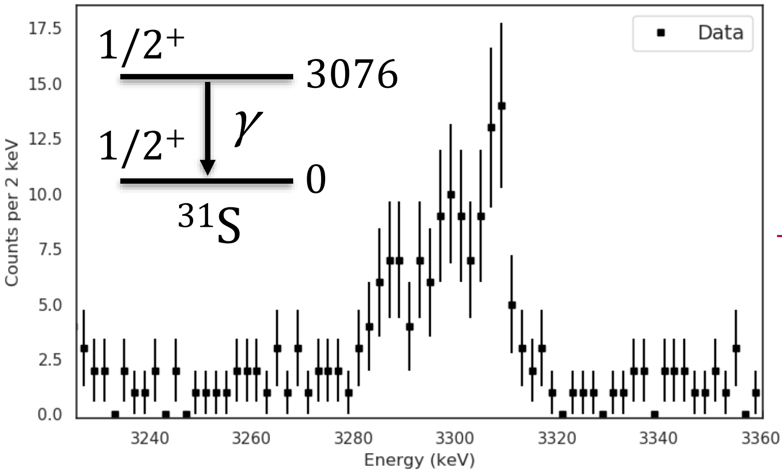
α detection efficiency ×11

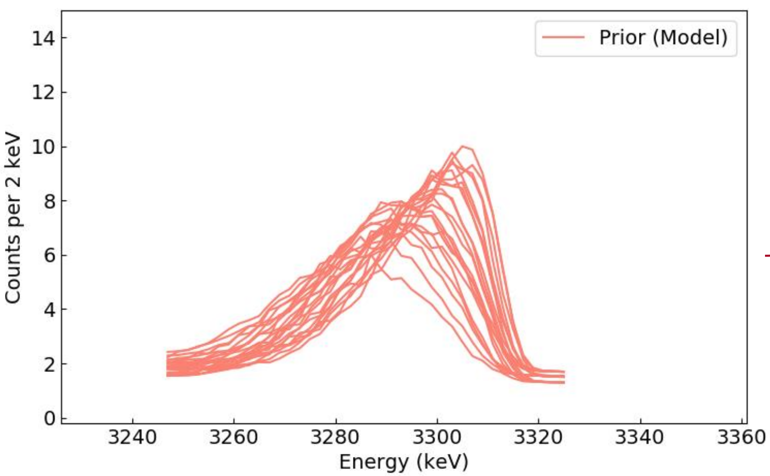
γ detection efficiency ×1.3

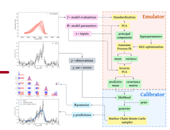
~1000 counts with 19 shifts

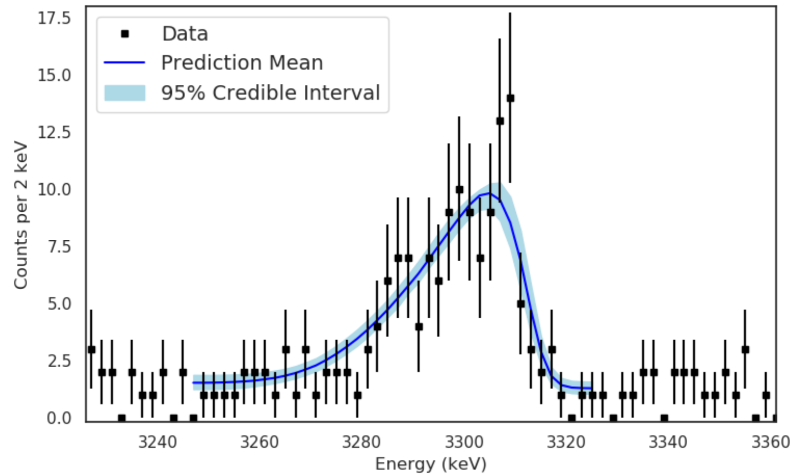
S2193	^{23}Mg	L. E. Weghorn, PhD Thesis Project.
S2373	^{31}S	Proposed to NP-EEC 202401

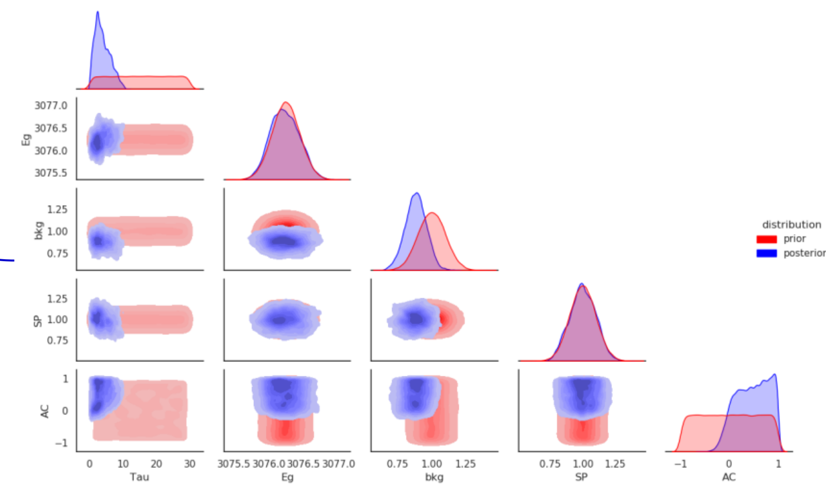
Bayesian Uncertainty Quantification







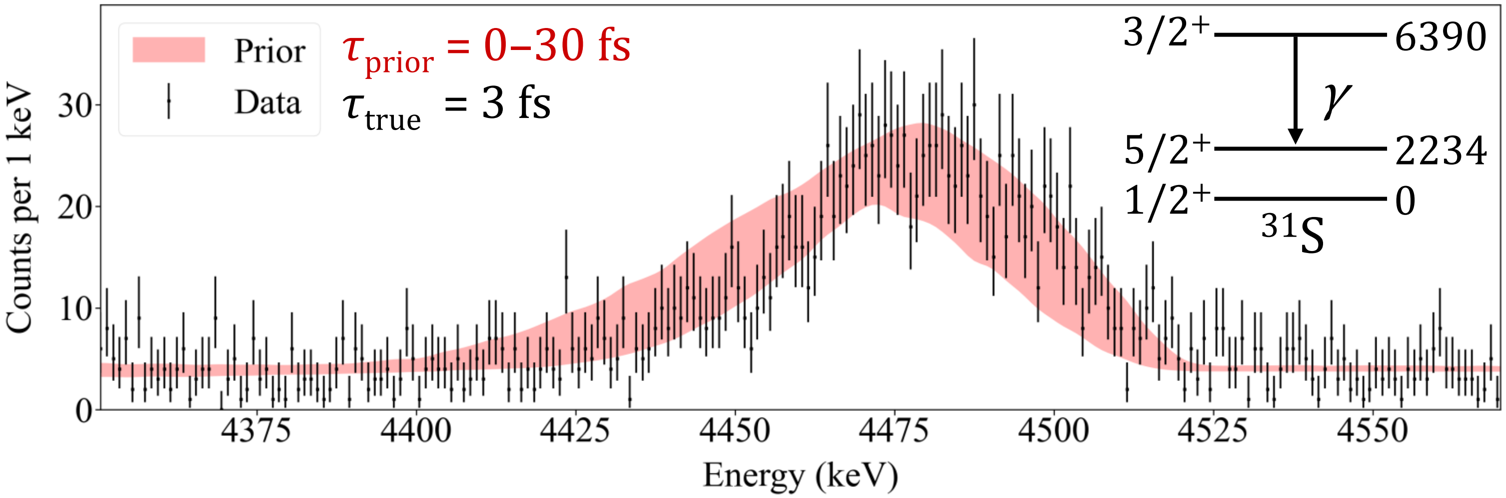


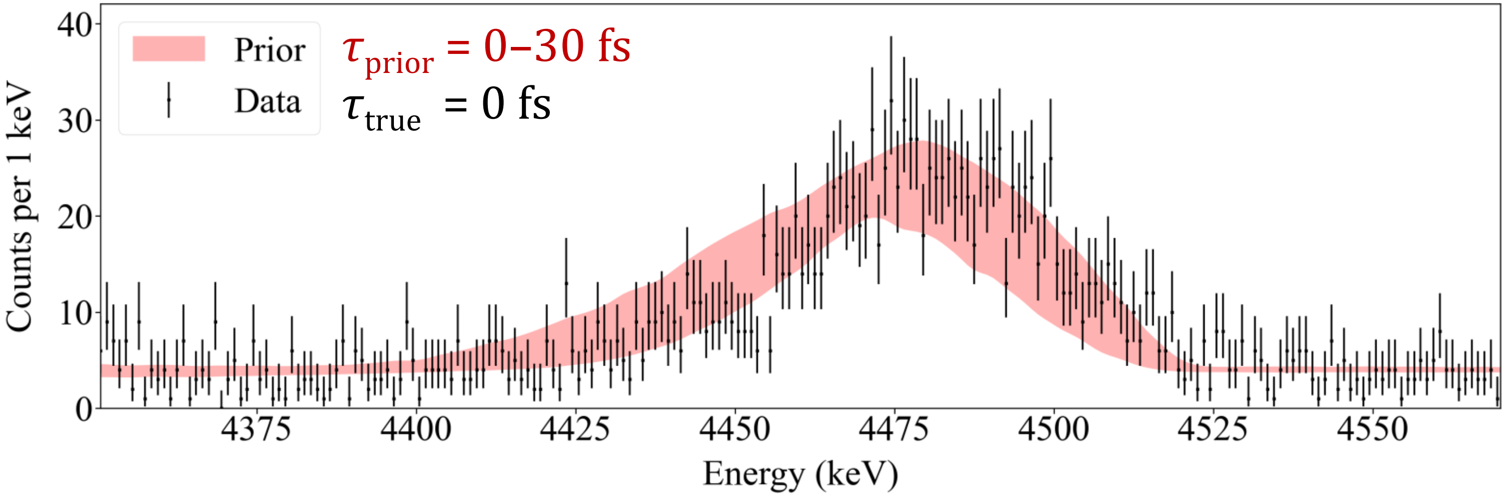


S1582 L. J. Sun *et al.*, Phys. Lett. B 839, 137801 (2023).

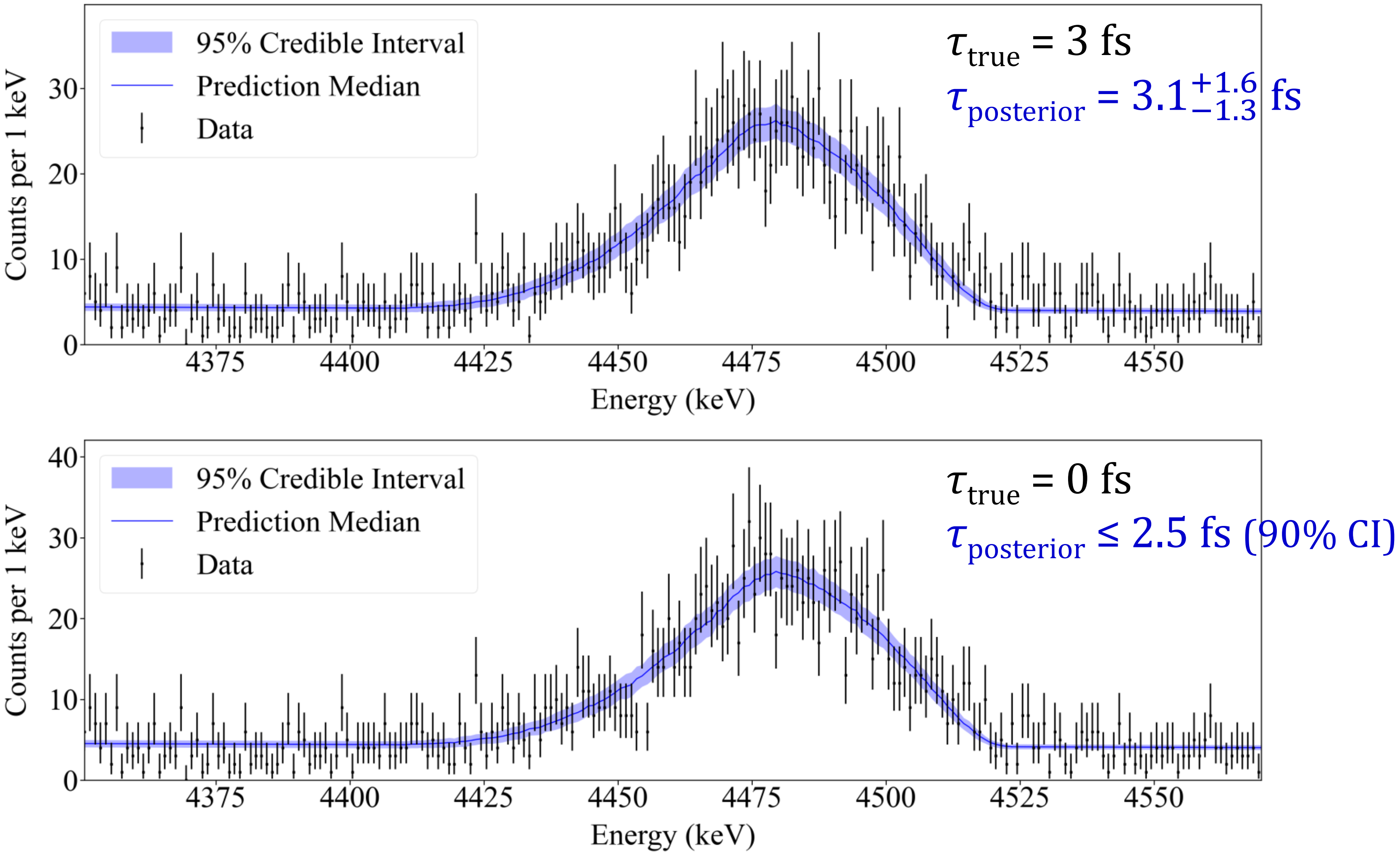
Ö. Sürer *et al.*, Phys. Rev. C 106, 024607 (2022).

Prior Lineshape



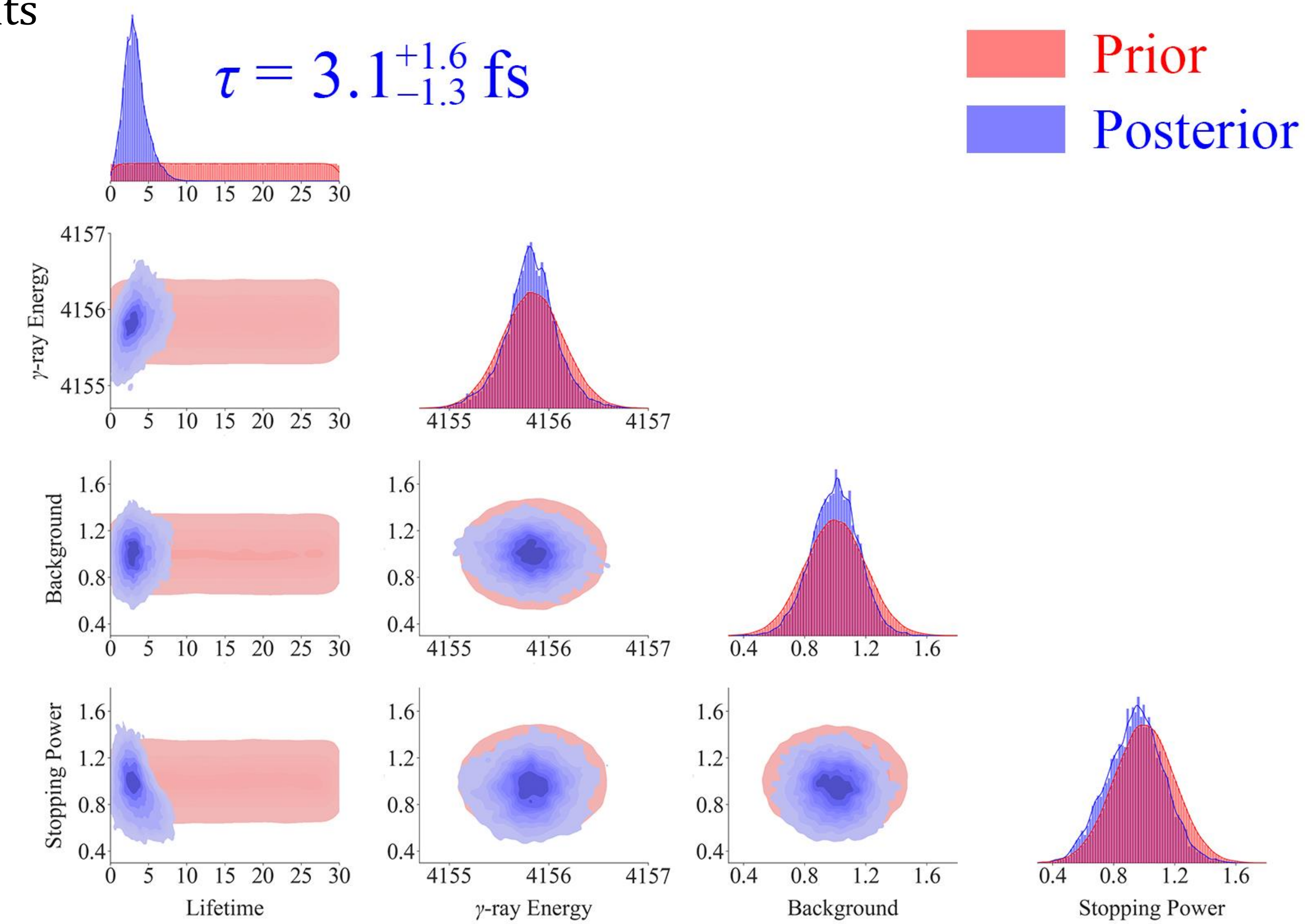


Posterior Predictive Lineshape



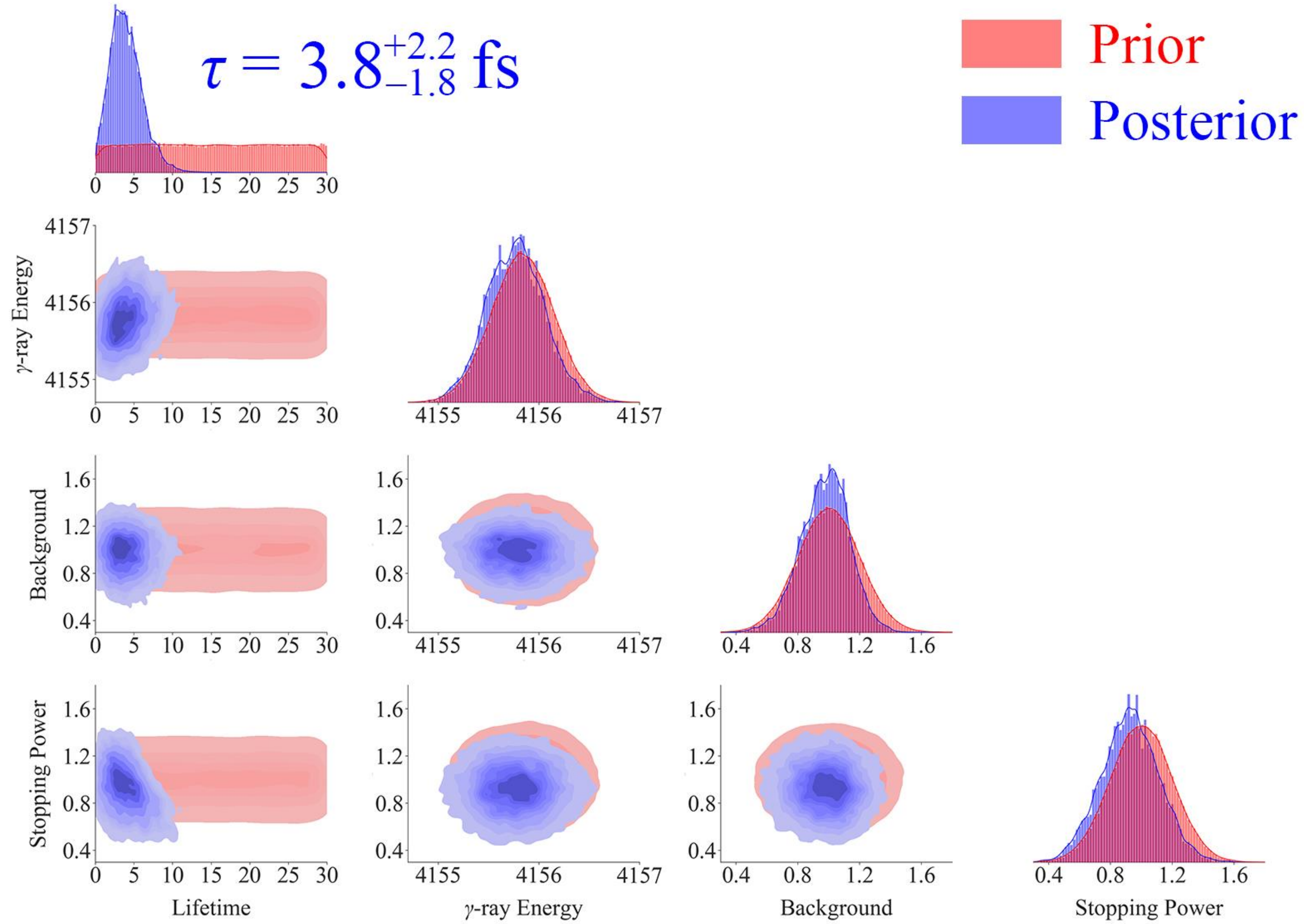
Posterior Distribution of Model Parameters

1000 counts



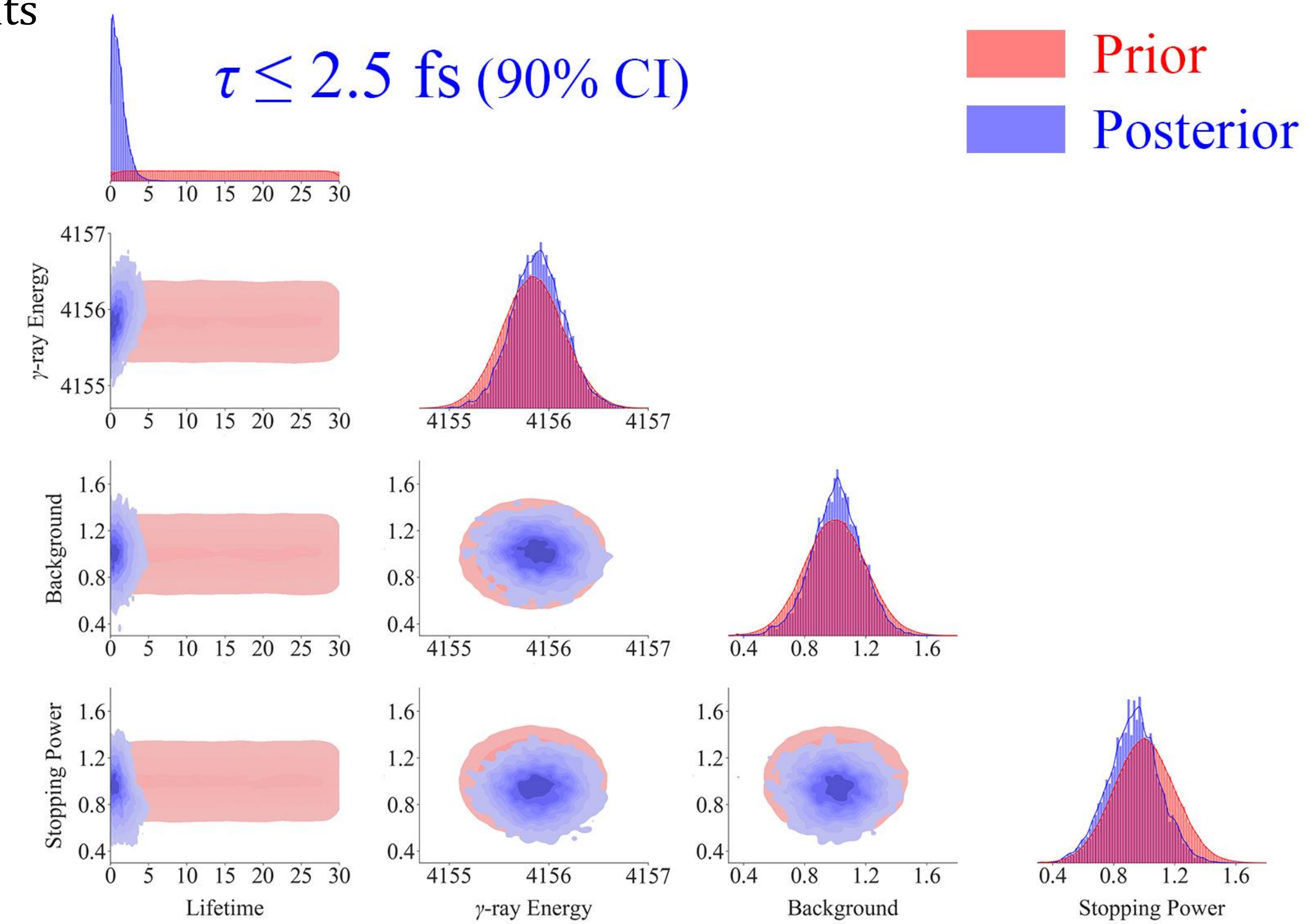
Posterior Distribution of Model Parameters

500 counts



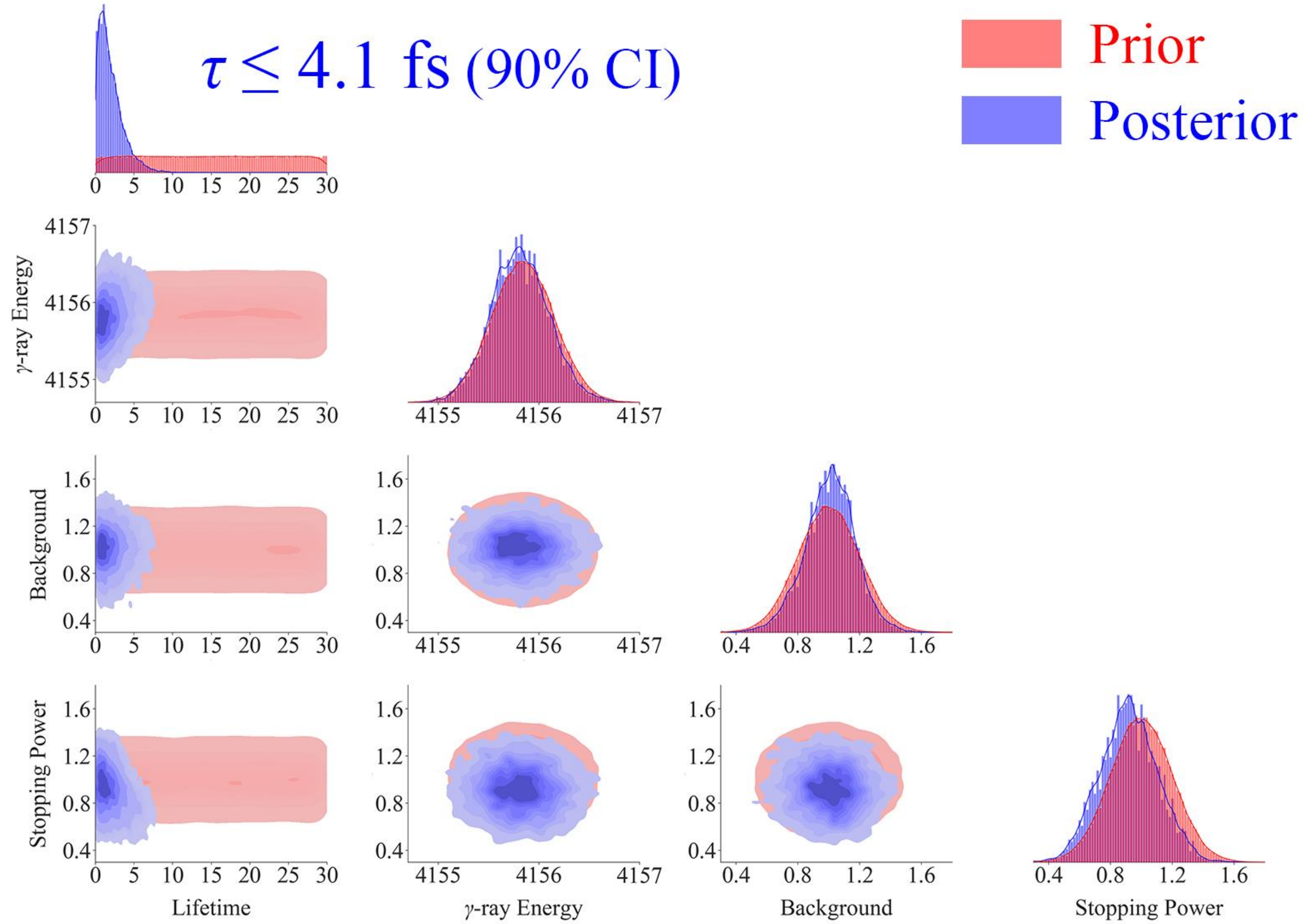
Posterior Distribution of Model Parameters

1000 counts



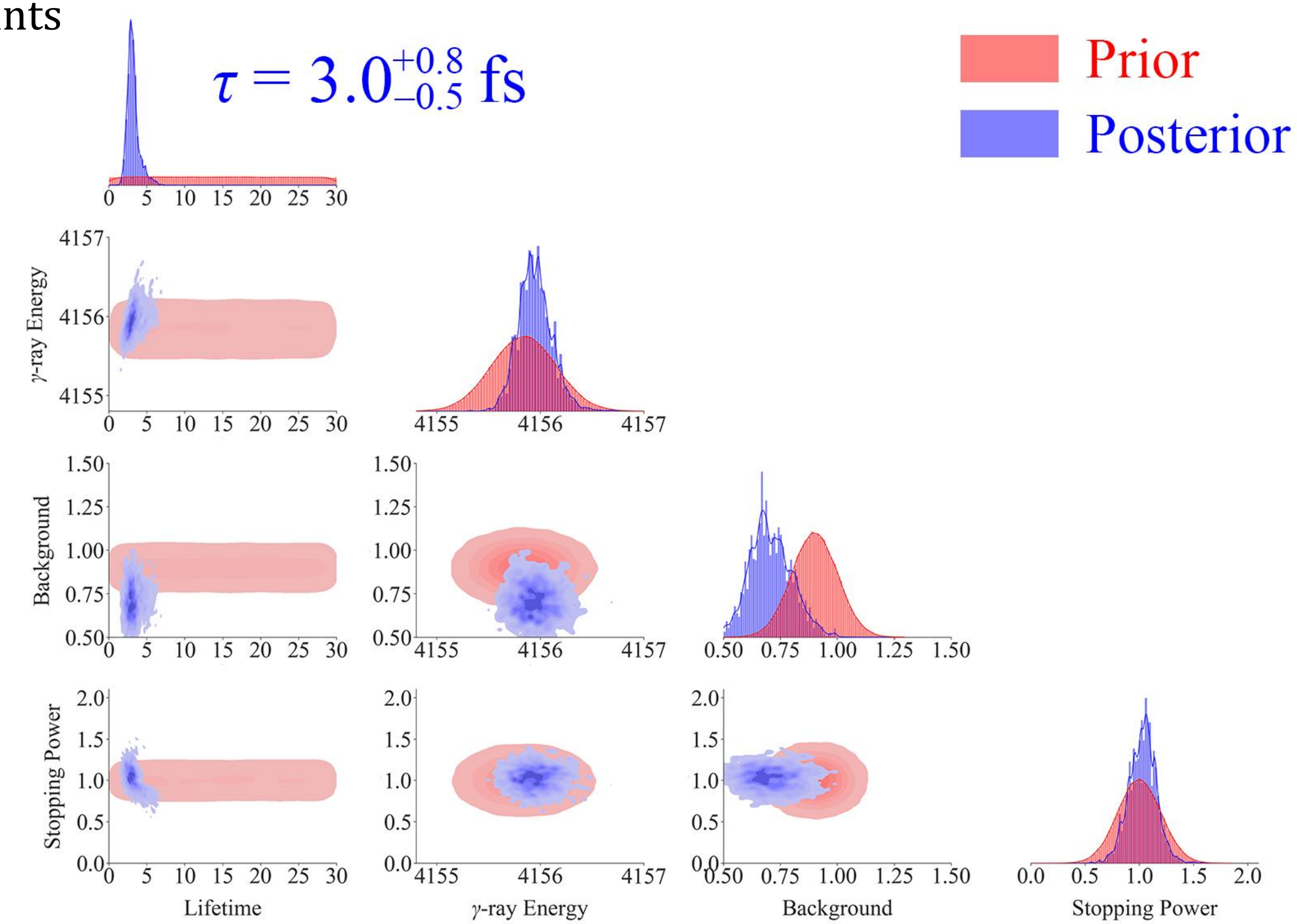
Posterior Distribution of Model Parameters

500 counts

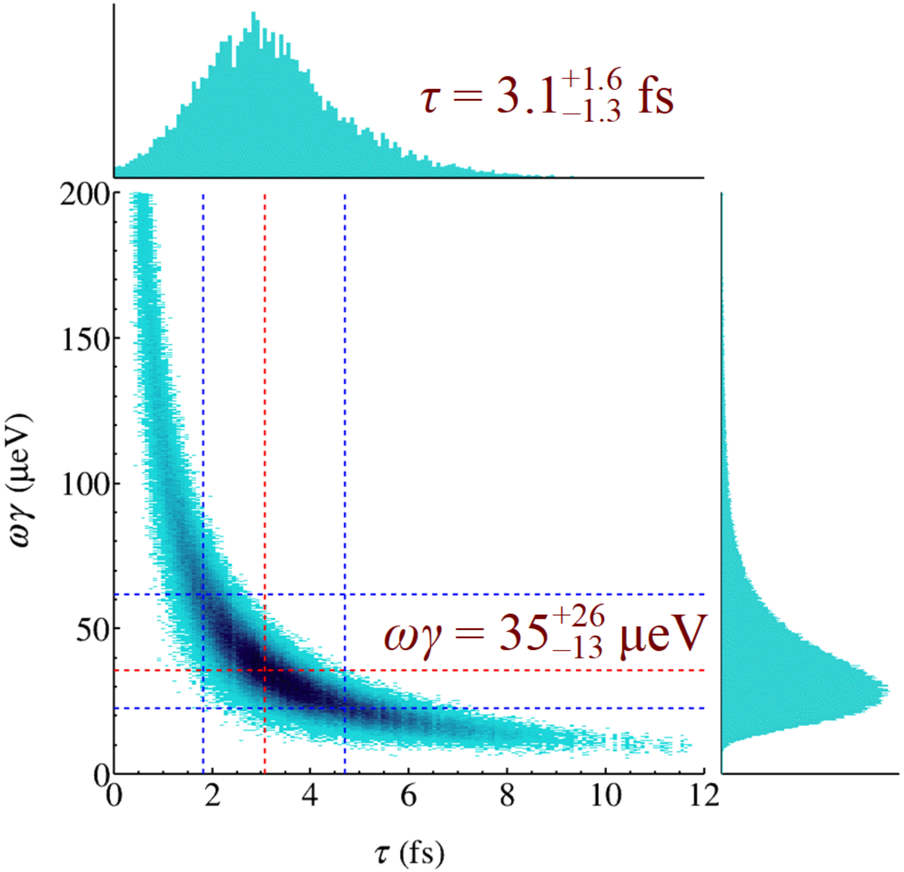


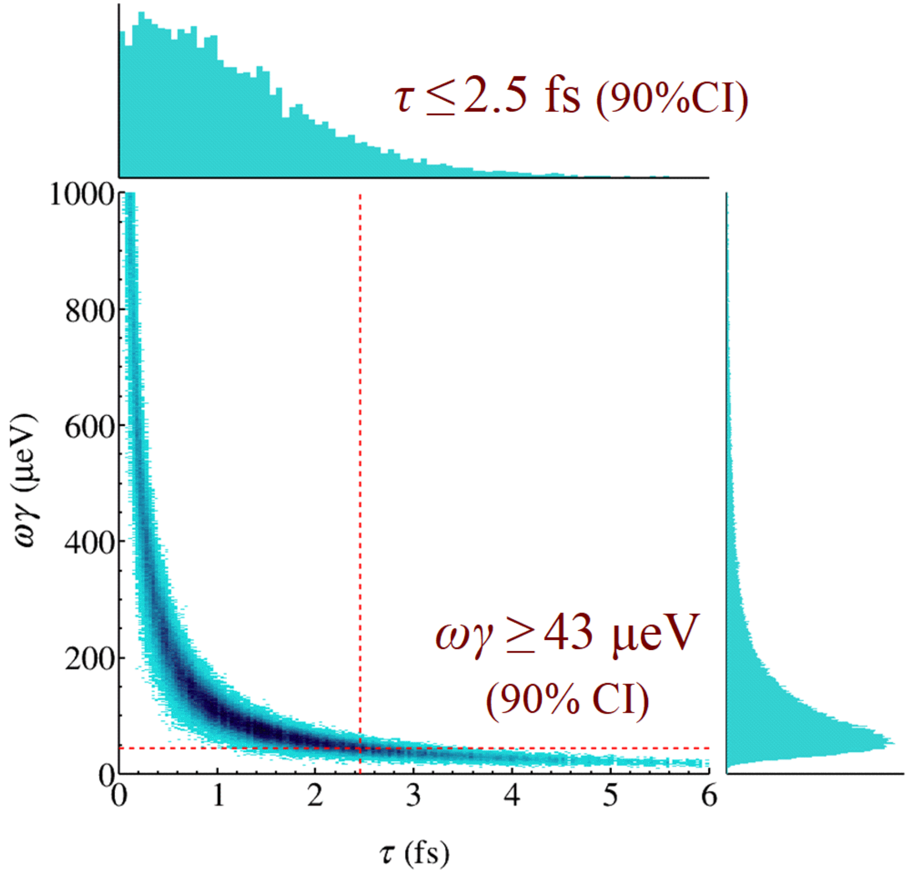
Posterior Distribution of Model Parameters

25000 counts

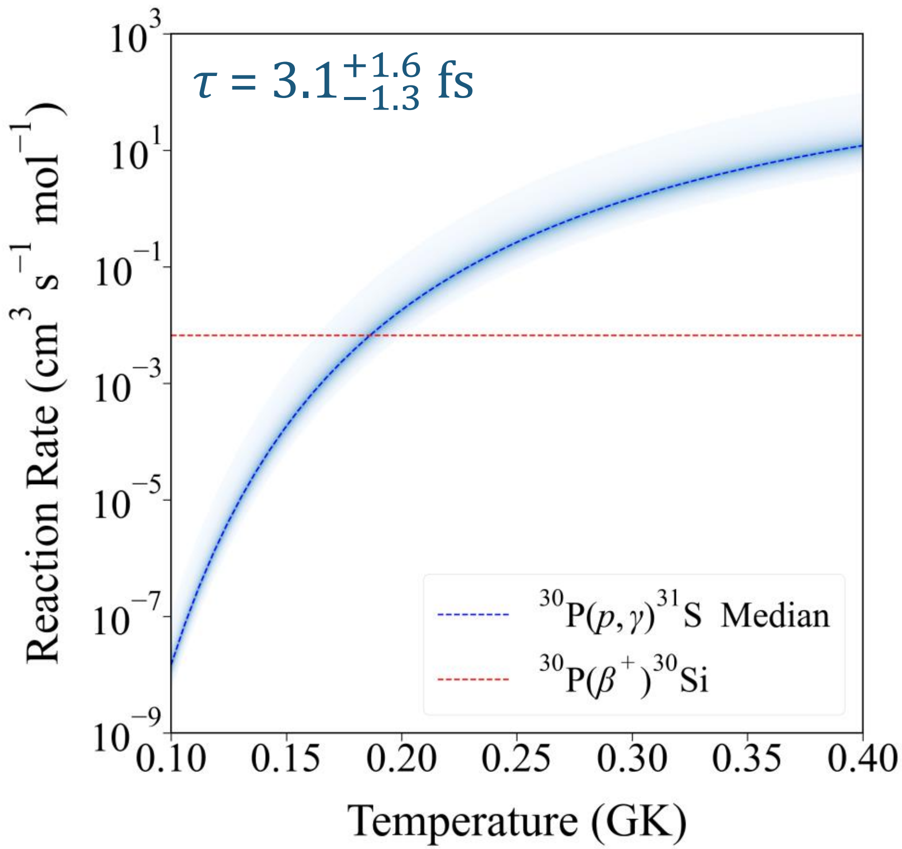


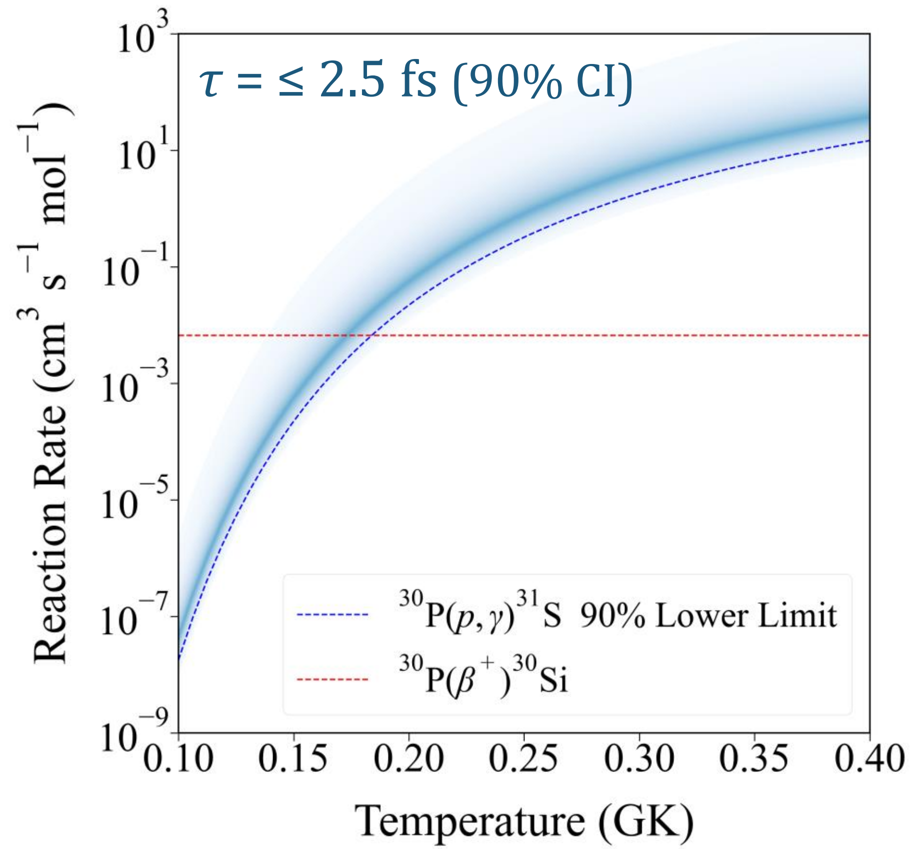
Resonance Strength





^{30}P(p,γ)^{31}S Reaction Rate





Monte Carlo reaction rate calculation https://github.com/rlongland/RatesMC

Nova nucleosynthesis model calculation by Jordi José.

Summary

- Our simulation has demonstrated that with 19 shifts, we can either obtain a finite value as low as 3 fs or set a strong upper limit of 2.5 fs on the lifetime of the astrophysically important $3/2^+$, 260-keV ^{30}P(p,γ)^{31}S resonance.
- This level of precision will put the ^{30}P(p,γ)^{31}S reaction rate on a fully experimental footing for the first time, and will potentially eliminate the largest nuclear uncertainty associated with a series of isotopic and elemental abundance ratios in nova ejecta.
  - The new rate will provide valuable insights into identifying the origin of several presolar grains using the **^{29}Si:^{28}Si and ^{30}Si:^{28}Si** ratios.
  - The new rate will calibrate nova thermometers based on the elemental abundance ratios of **O:S, O:P, S:Al, and P:Al**.
  - The new rate will make the **Si/H** abundance ratio a more accurate constraint on the degree of mixing between the white dwarf's outer layers and the accreted envelope.

Collaboration

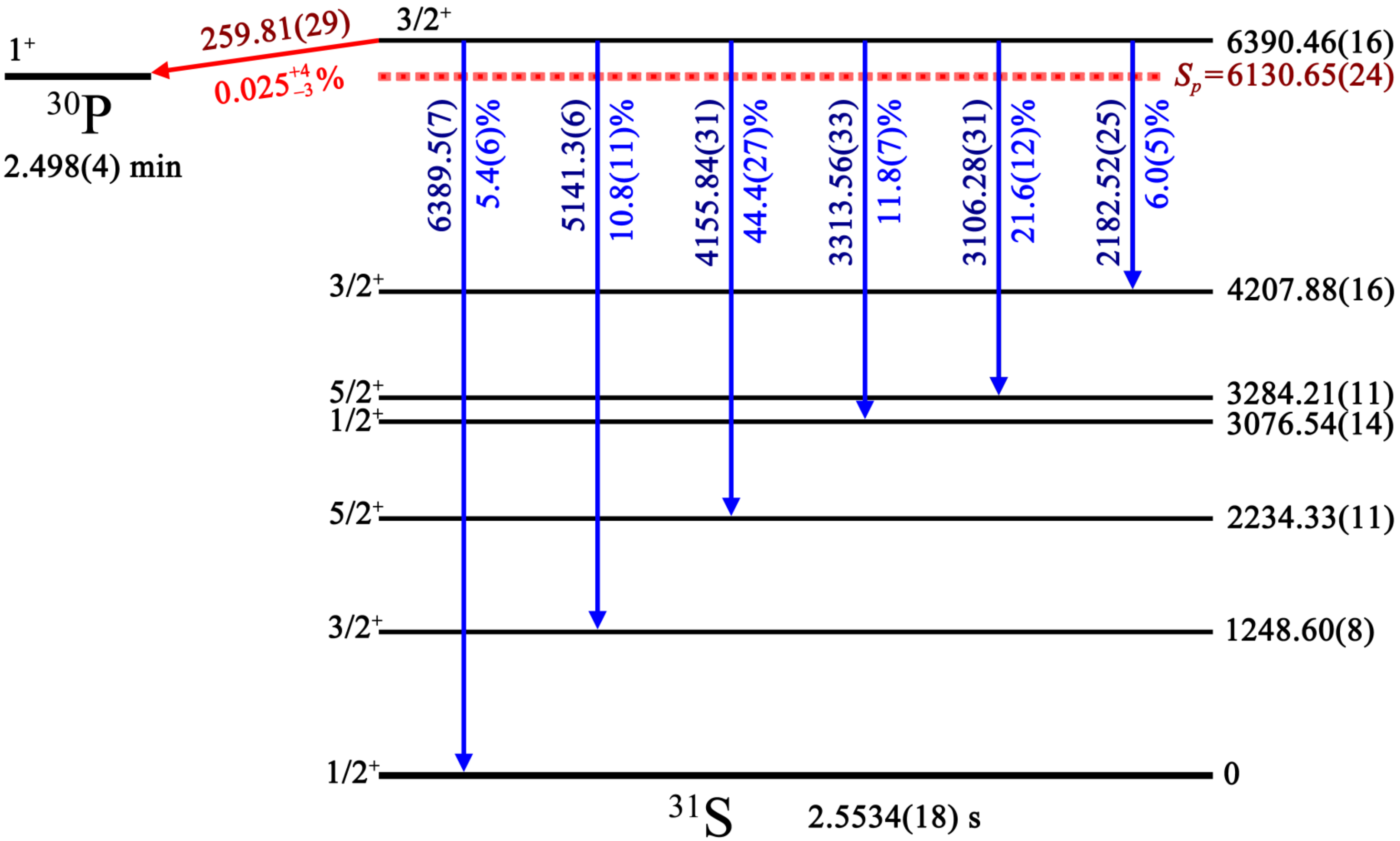
B. Davids	TRIUMF/SFU	V. Karayonchev	TRIUMF
L. J. Sun	MSU/FRIB	O.S. Kirsebom	Dalhousie U.
C. Wrede	MSU/FRIB	L. Le	SJSU
A. Adams	MSU/FRIB	R. Mahajan	LSU/FSU
C. Angus	University of York	M. Oliver	SJSU
A. Banerjee	SINP	C. Ruiz	TRIUMF
T. Budner	ANL	R. Russell	University of Surrey
M.Y.H. Chan	Northwestern U.	J. Surbrook	LANL
J. Chen	MSU/FRIB	Ö. Sürer	Miami U.
J. Dopfer	MSU/FRIB	V. Vedia	TRIUMF
N. Esker	SJSU	L. Wagner	TRIUMF
M. Friedman	HUJI	L. Weghorn	MSU/FRIB
C. Fry	LANL	T. Wheeler	MSU/FRIB
A.B. Garnsworthy	TRIUMF	J. Wilkinson	LLNL
G. Hackman	TRIUMF	E.J. Williams	TRIUMF
K. Hudson	SFU	D. Yates	UBC
J. Jose	UPC		


Google - Noto Color Emoji 15.0 (Animated)

Known Lifetimes of ^{31}S Excited States

^{31}S state		Evaluated τ (fs)	Literature
$3/2^+$	1248	720(90)	Engmann NPA 1971 Doornenbal NIMA 2010 Tonev PLB 2021 Herlitzius Thesis 2013 Sun PLB 2023
$5/2^+$	2234	290(80)	Engmann NPA 1971 Sun PLB 2023
$1/2^+$	3076	<11	Sun PLB 2023
$3/2^+$	3435	<16	Sun PLB 2023
$7/2^-$	4450	790(250)	Pattabiraman PRC 2008 Tonev PLB 2021
$(3/2)^-$	4971	<7	Sun PLB 2023
$1/2^+$	5156	<15	Sun PLB 2023
$9/2^-$	6376	245(45)	Pattabiraman PRC 2008
$11/2^{(-)}$	6833	180(35)	Pattabiraman PRC 2008

Known Decay Scheme of the Key Resonance

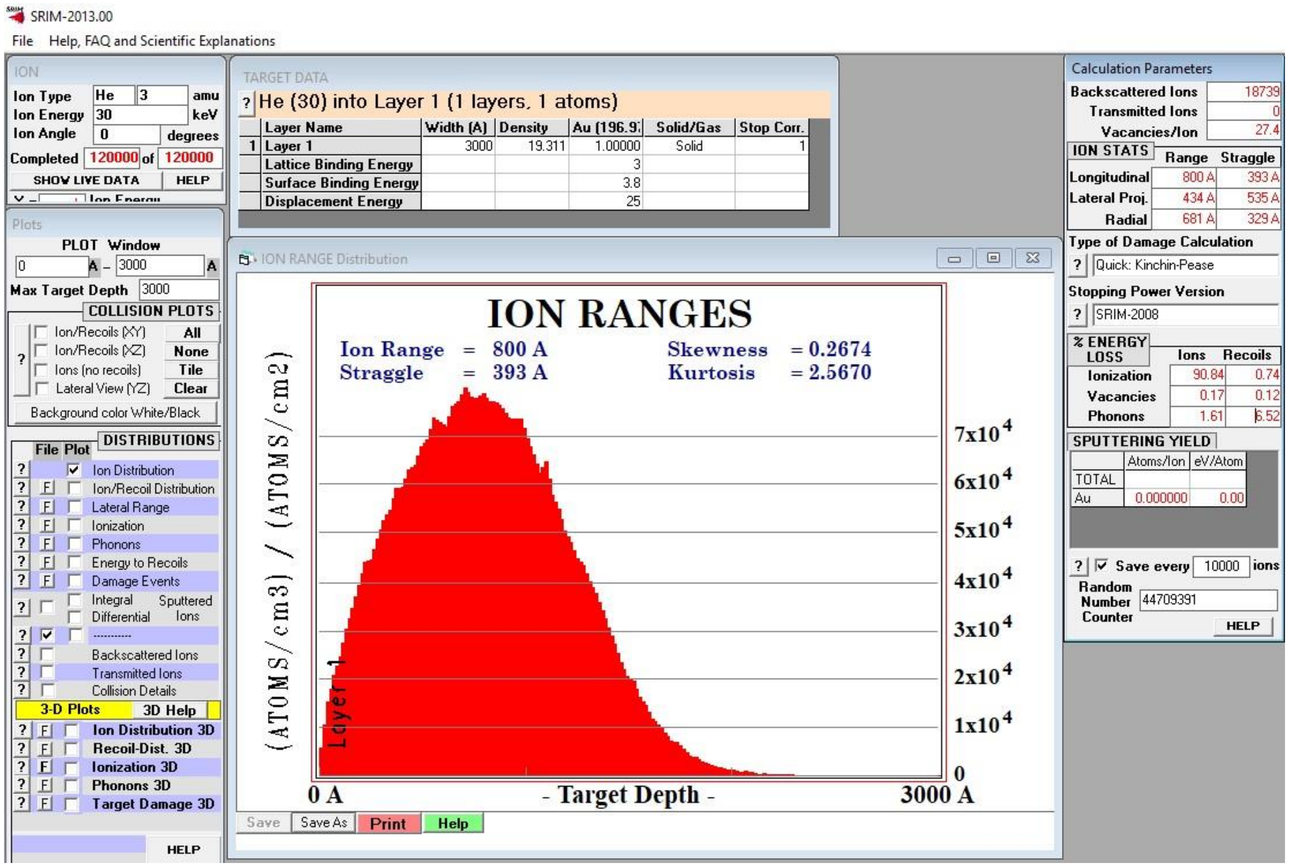


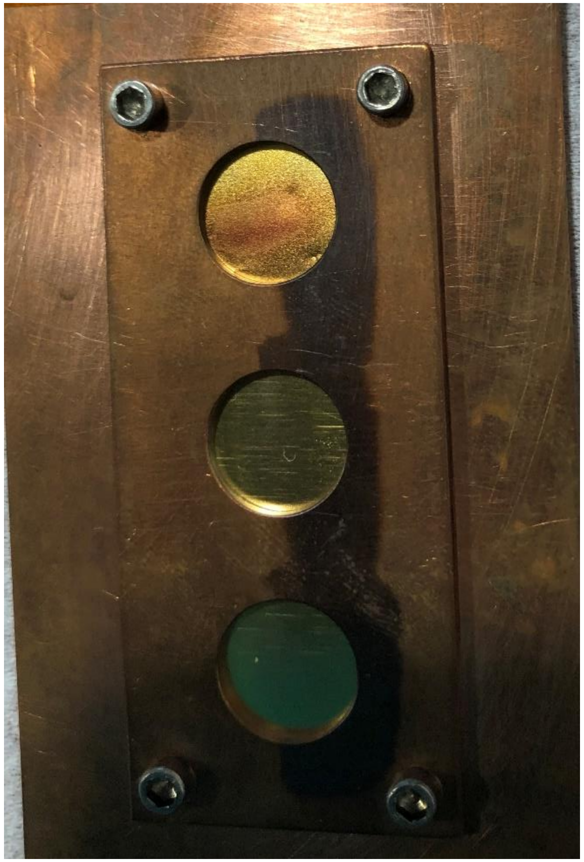
J. Chen *et al.*, Nucl. Data Sheets 184, 29 (2022).

γ-ray measurements of ^{31}S states around 6.39 MeV

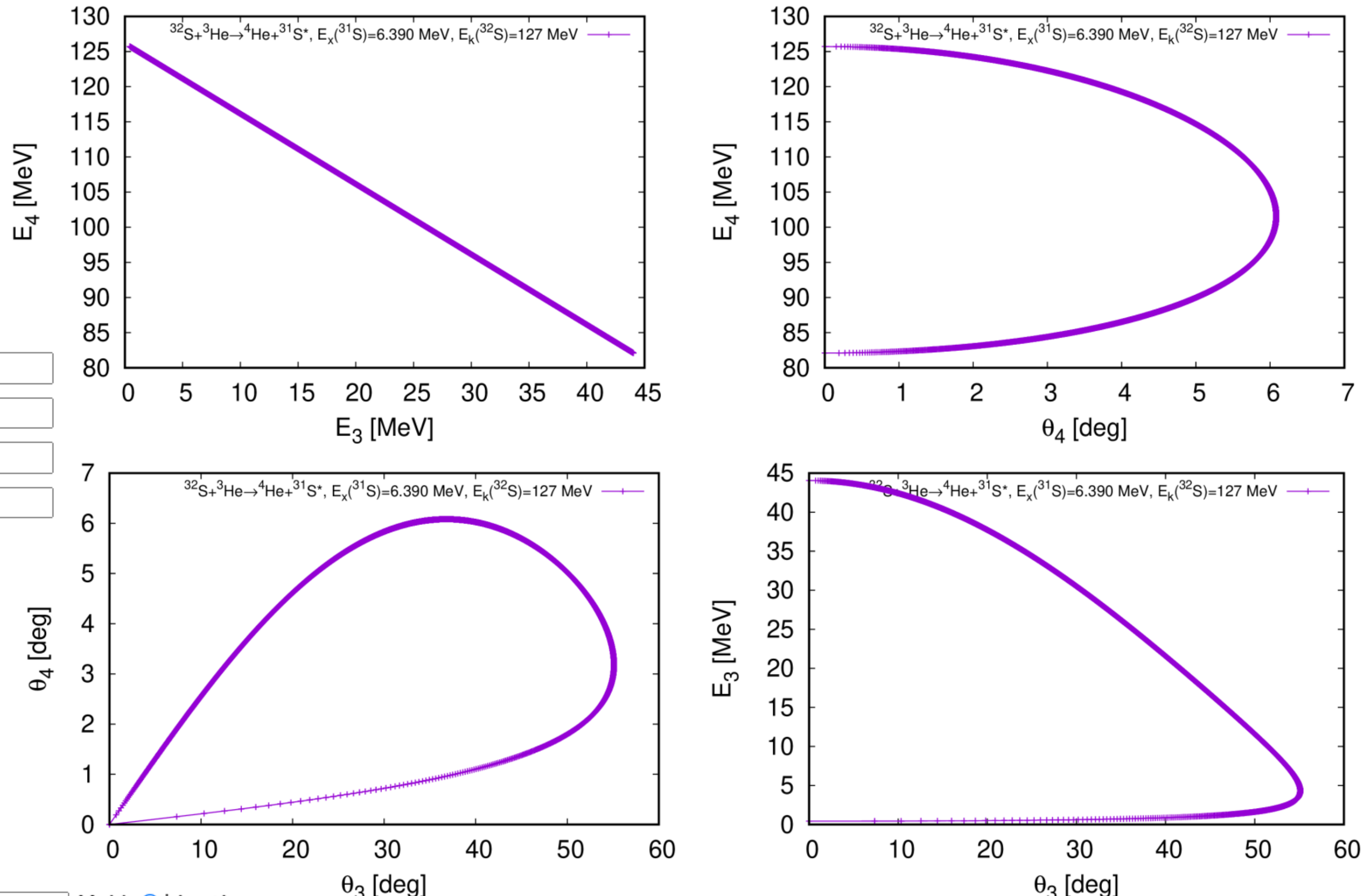
E_x (keV)	$J^{\pi}{}_i$	E_γ (keV)	E_f (keV)	$J^{\pi}{}_f$	Reaction / Decay	Reference
6393.7(5)	$11/2^+$	1090.7(10)	*5301*	$9/2^+$	^{12}C(^{20}Ne,*n*)^{31}S	Jenkins
		3042.4(4)	*3351*	$7/2^+$		
6394.2(2)	$11/2^+$	1091.2(4)	5301.7(3)	$9/2^+$	^{28}Si(^{4}He,*n*)^{31}S	Doherty
		3042.9(1)	3351.3(2)	$7/2^+$		
6393	$11/2^+$	1090.5(7)	*5301*	$9/2^+$	^{24}Mg(^{12}C,αn)^{31}S	Testov
		3042.2(10)	*3351*	$7/2^+$		
6392.5(2)	$5/2^+$	5143.1(2)	1248.5(1)	$3/2^+$	^{28}Si(^{4}He,*n*)^{31}S	Doherty
6392.5(2)	$5/2^+$	5145(3)	*1248*	$3/2^+$	^{2}H(^{30}P,*n*)^{31}S	Kankainen
6390.2(7)	$3/2^+$	2182.52(25)	4207.7(31)	$3/2^+$	^{31}Cl($\beta^+\gamma$)^{31}S	Bennett
		3106.28(31)	3283.76(31)	$5/2^+$		
		3313.56(33)	3076.40(31)	$1/2^+$		
		4155.84(31)	2234.06(20)	$5/2^+$		
		5141.3(6)	1248.43(20)	$3/2^+$		
		6389.5(7)	0	$1/2^+$		

^{3}He Implanted Target





Reaction Kinematics



Projectile (m_1): 32S

Target (m_2): 3He

Ejectile (m_3): 4He

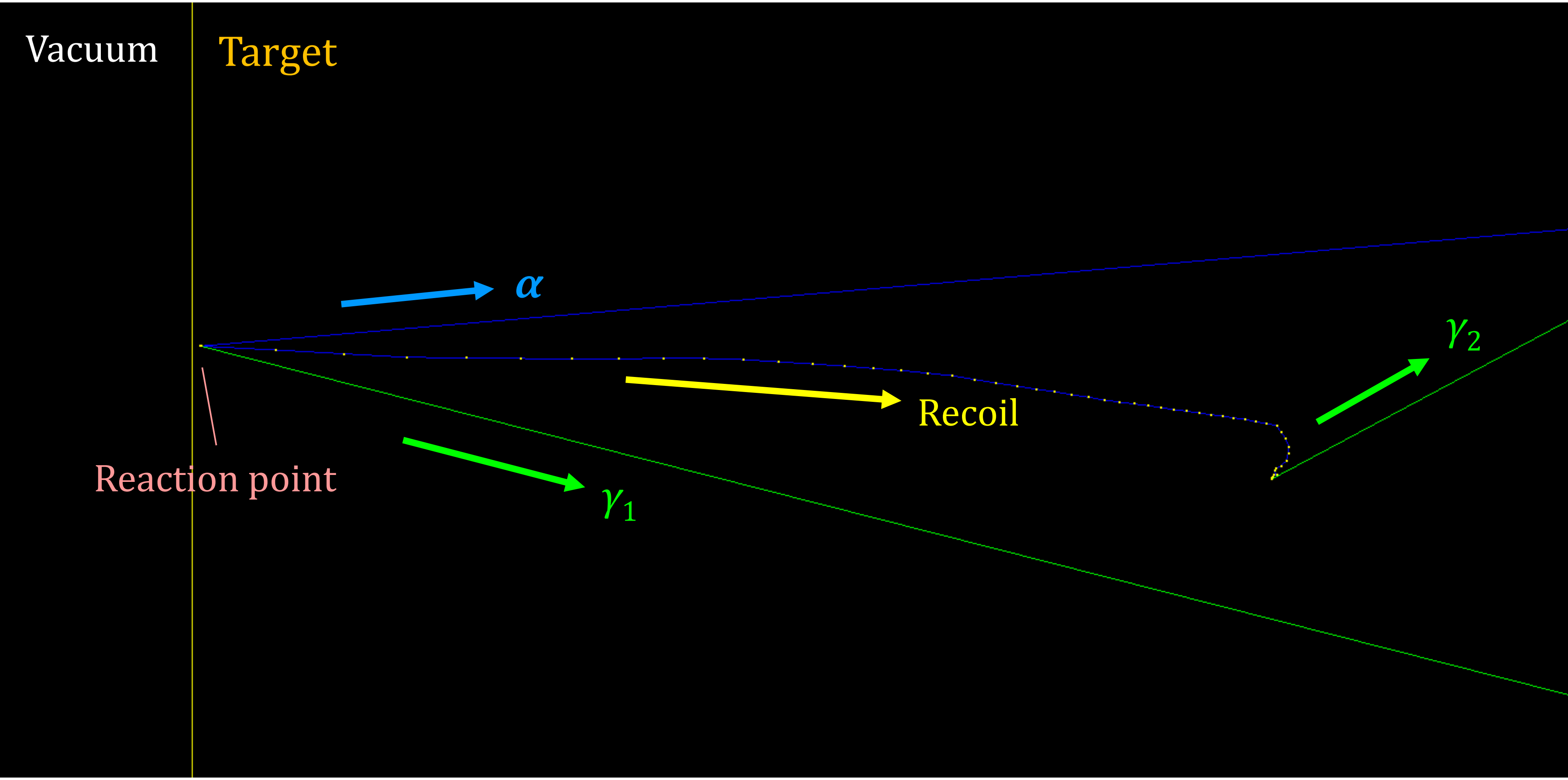
Recoil (m_4): 31S

Projectile Energy: 127 MeV ◉ kinetic

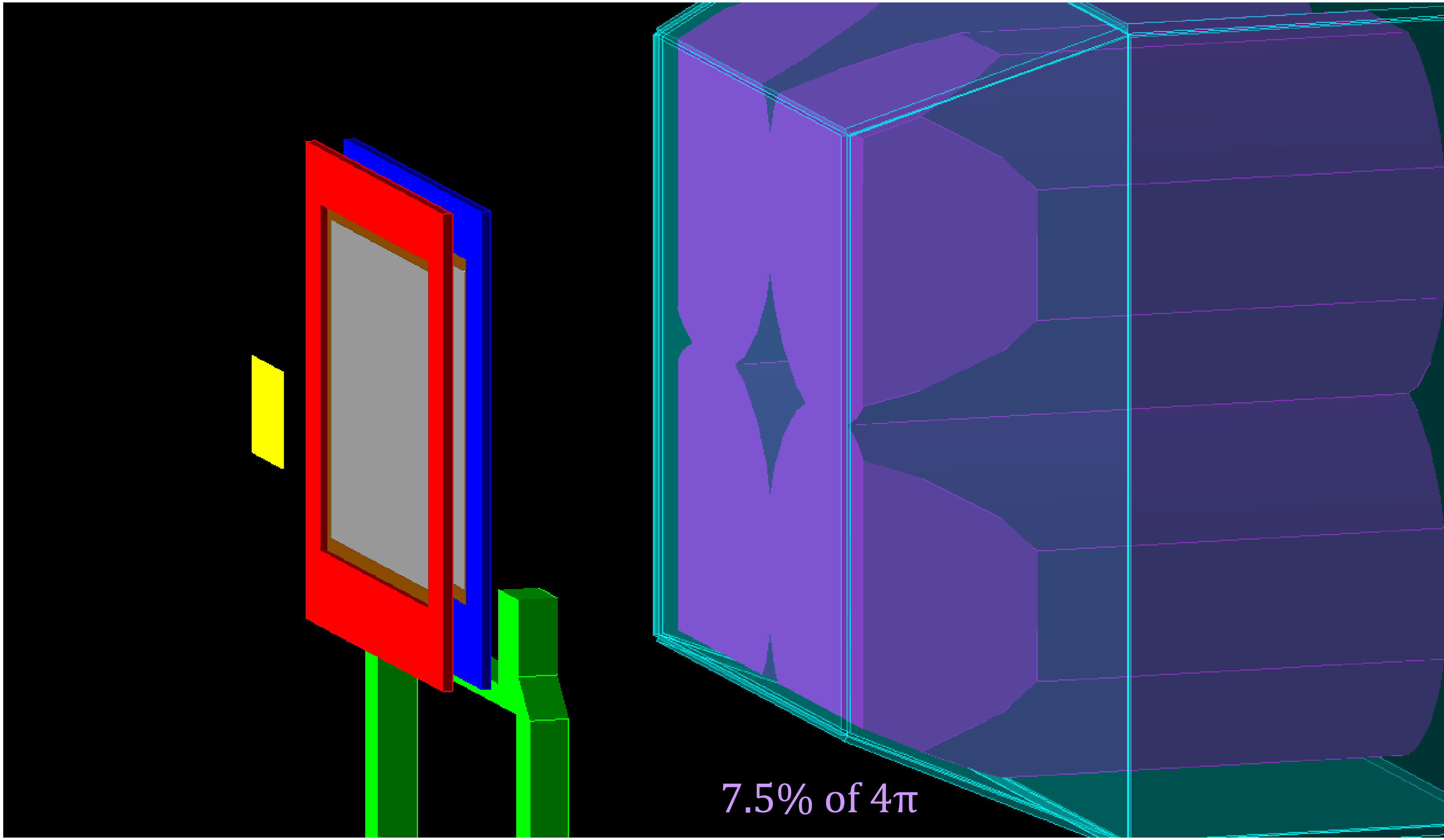
FRIB

Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science | Michigan State University
640 South Shaw Lane • East Lansing, MI 48824, USA
frib.msu.edu

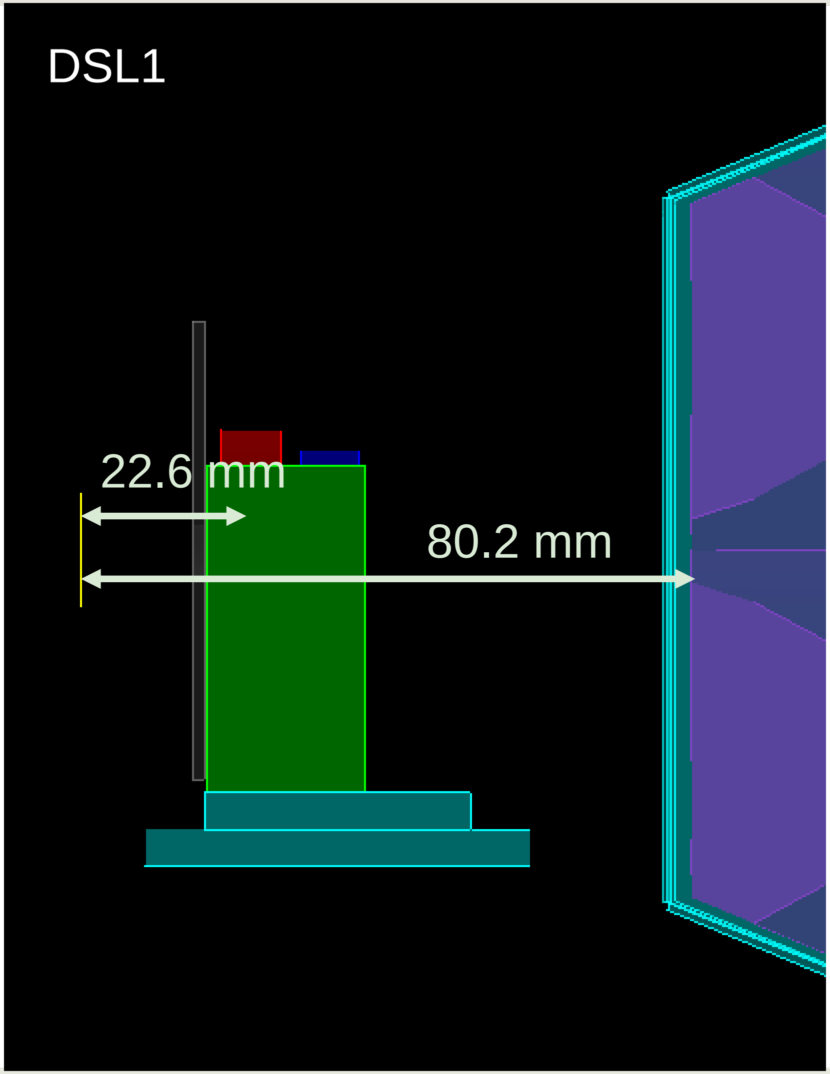
Geant4 Simulation

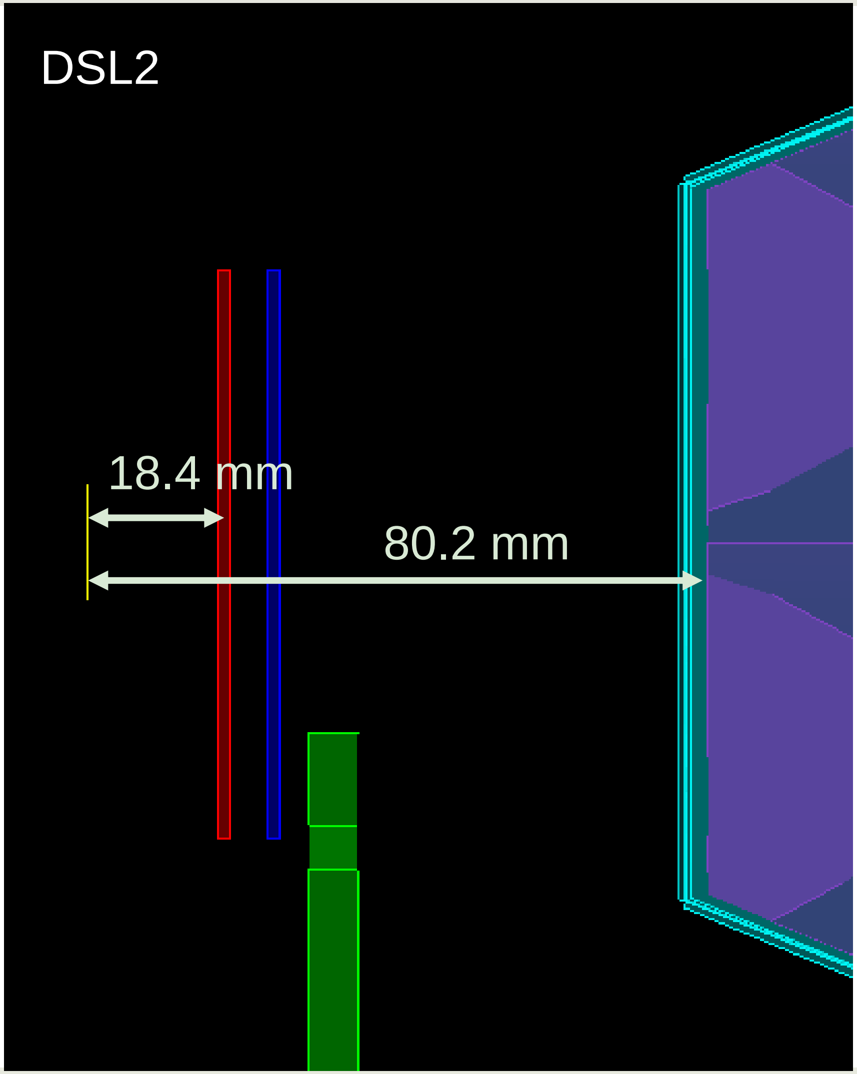


Geant4 Simulation

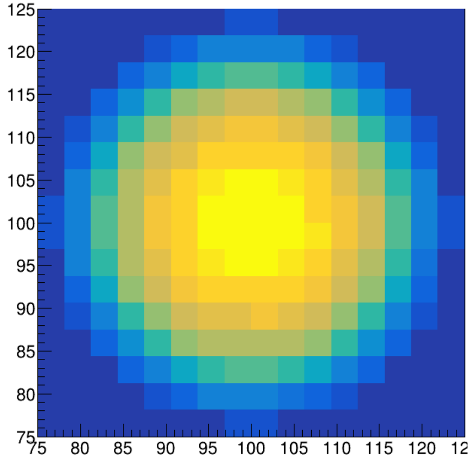


Solid Angle



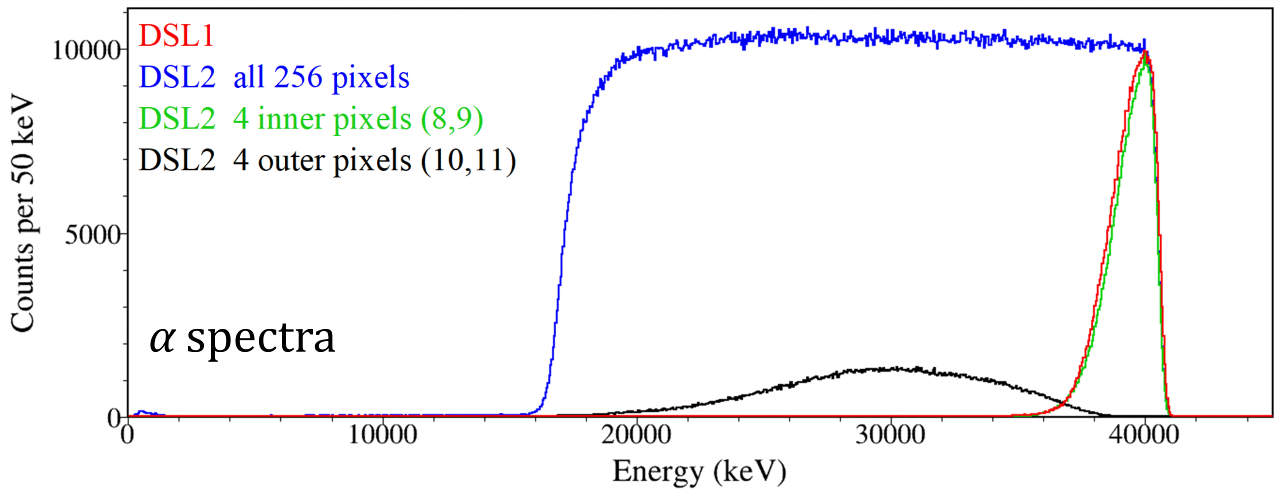


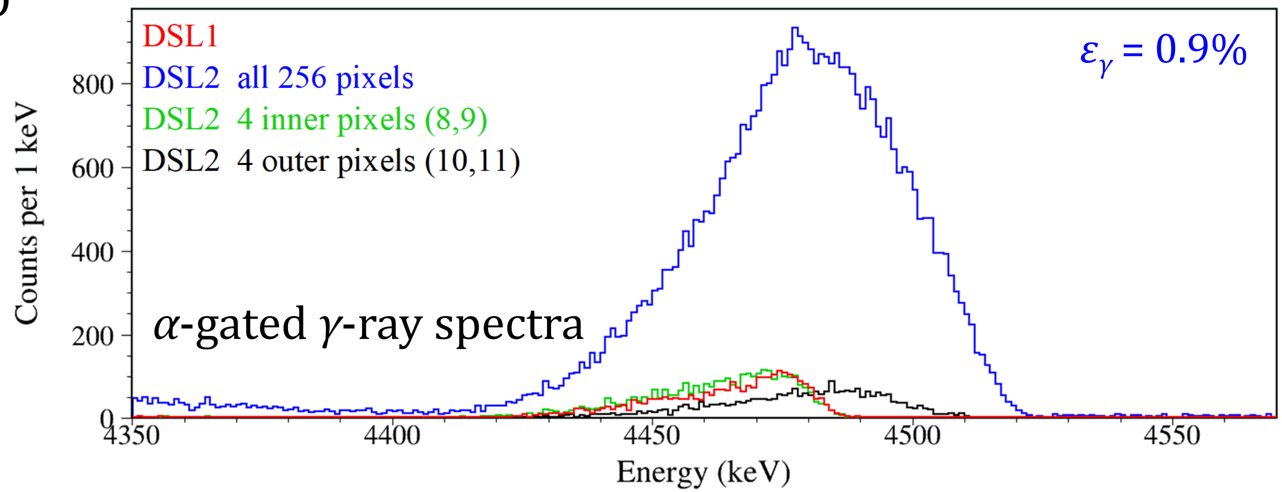
Geant4 Simulation



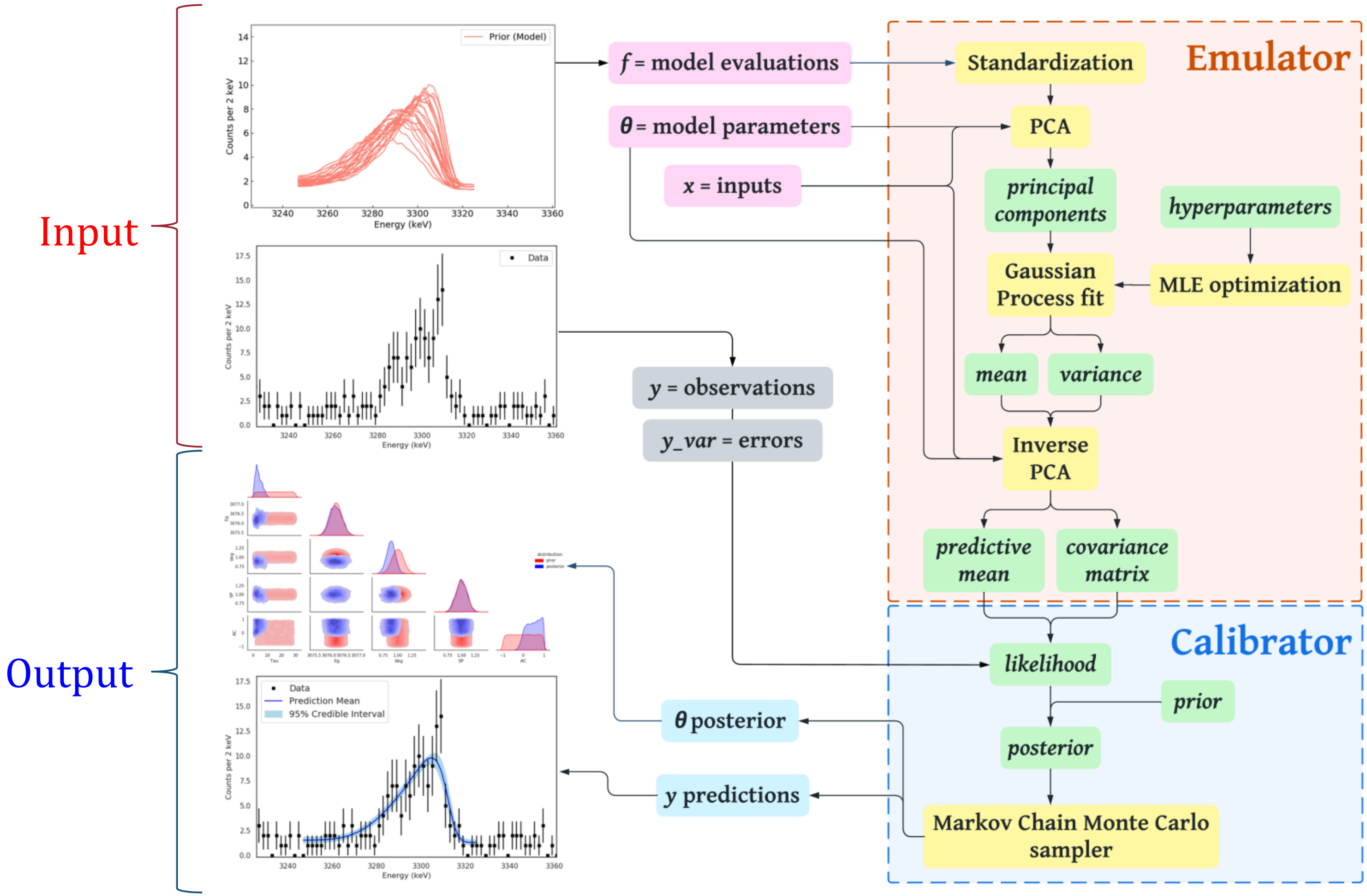
α particle heatmap on DSSD

1 pixel: 0.21% of 4π



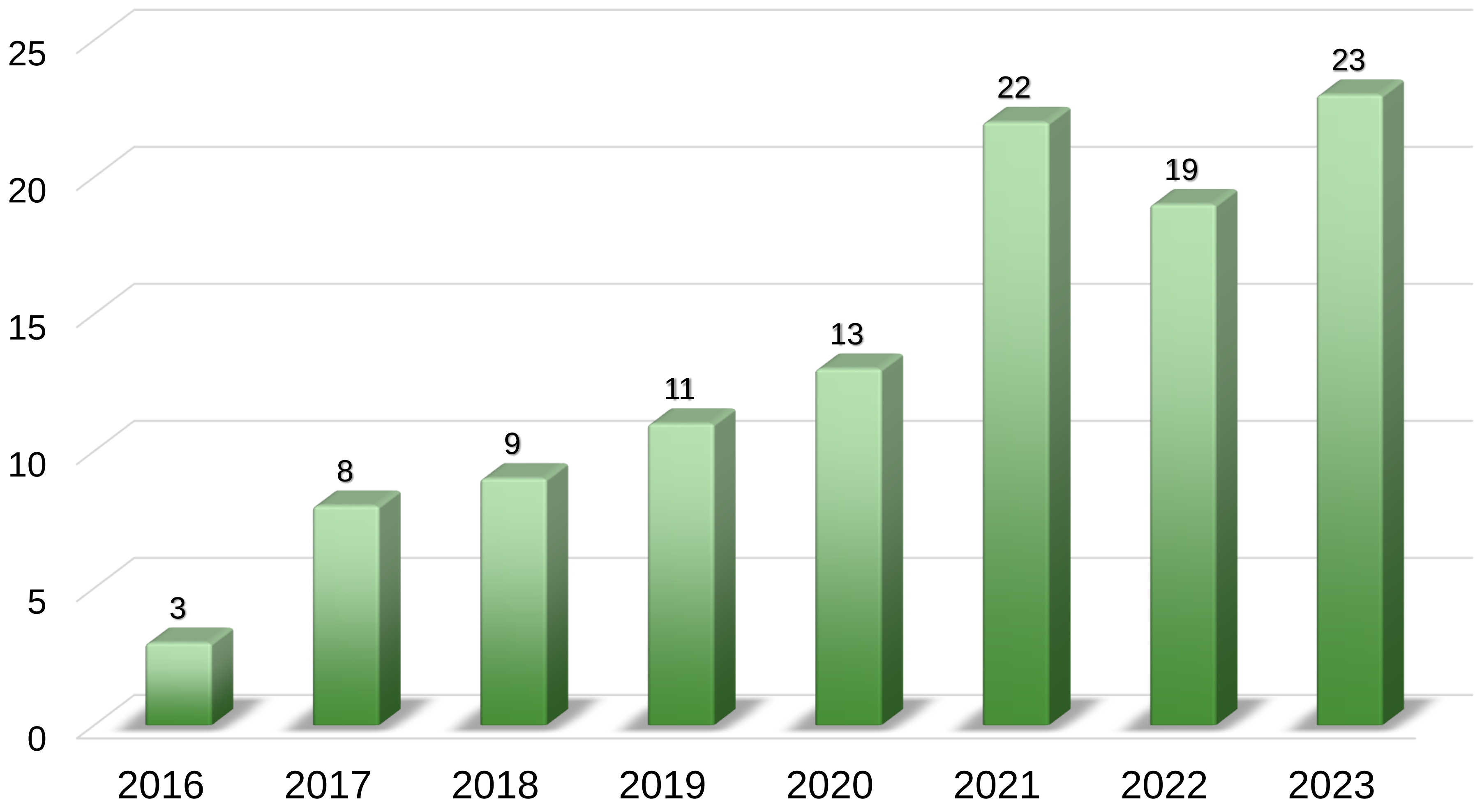


Bayesian Model Emulation & Model Calibration



Ö. Sürer *et al.*, Phys. Rev. C 106, 024607 (2022).

Bayesian-related talks at each APS DNP Meeting



Advantages of Inverse Kinematics

While DSAM can in principle be done in either normal or inverse kinematics, there are several advantages to inverse kinematics, where a heavy beam impinges on a light target, including:

- Recoils tend to be in the electronic stopping power regime. Electronic stopping powers are both more easily measured and have smaller angular scattering, leading to smaller uncertainties in the extracted lifetimes.

- Velocity change can be larger, due to a maximum in stopping powers for typical systems around recoil energies of tens of MeV for nuclei with mass number $20 < A < 40$. This is particularly helpful for extracting finite lifetimes for short-lived states.

- Higher recoil velocities ($\beta = 0.074$) lead to larger Doppler shifts, making it easier to distinguish unshifted peaks from shifted peaks, particularly at low energies, where the absolute shift is small.

C. Fry, Ph.D. Thesis, Michigan State University, USA, 2018.

Readiness

S2373 **Lifetime of the key $^{30}P(p,\gamma)^{31}S$ resonance in novae (DSL)**

Spokespersons: B. Davids, L.J. Sun, C. Wrede

Isotope	Minimum Intensity (s-1)	Requested Intensity (s-1)	Target & Ion Source	Energy	Comment
^{32}S	0.6E+10	1.8E+10	OLIS	128 MeV	

Comments: ^{32}S 7+ was already delivered to DSL in Aug 2018 at 1E+11 pps, with acceptable contaminant levels. Thus this is feasible. However the new OLIS team (C. Charles) has not yet had experience of producing this beam so some practice time with OLIS should be taken into account well in advance of experiment.

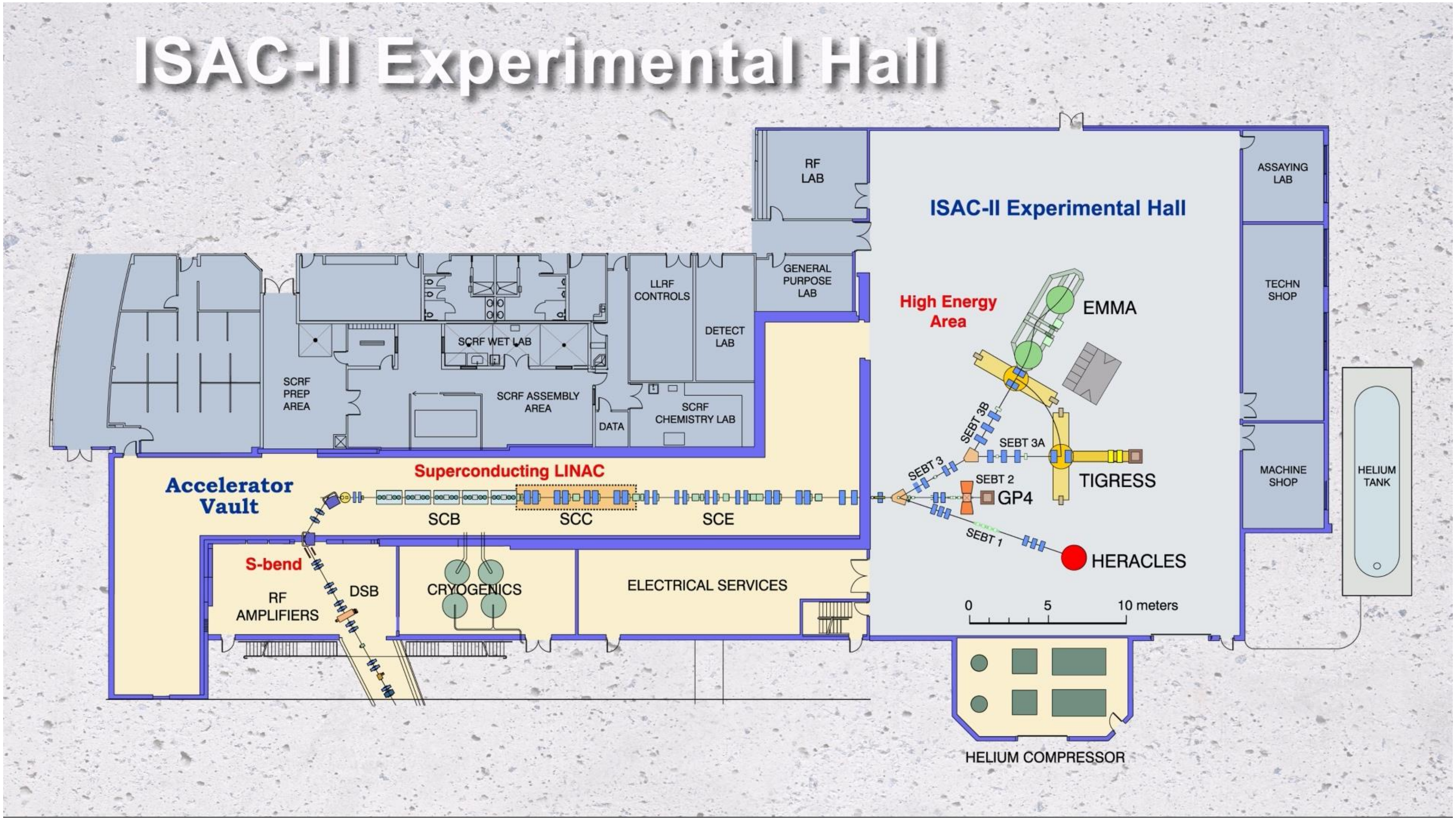
Classification for Beam Delivery or Development

Proposals or Progress Reports:
☒ feasible ☐ marginal ☐ infeasible

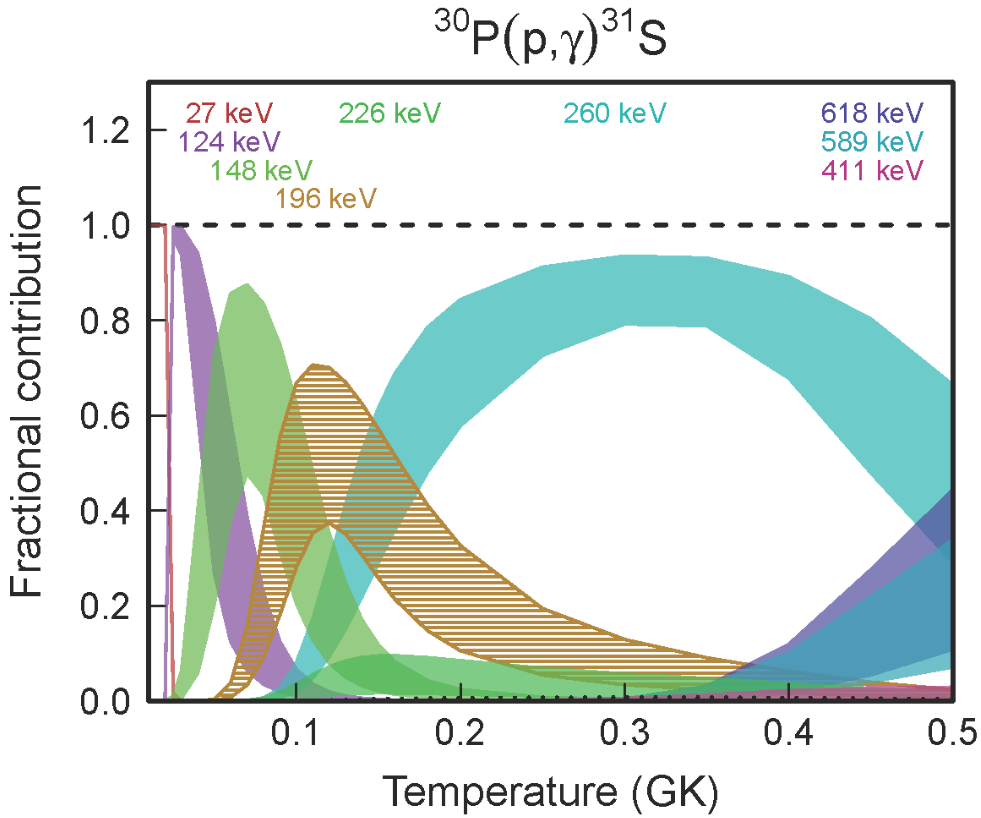
Letters of Intent:
☐ trivial ☐ complex ☐ major

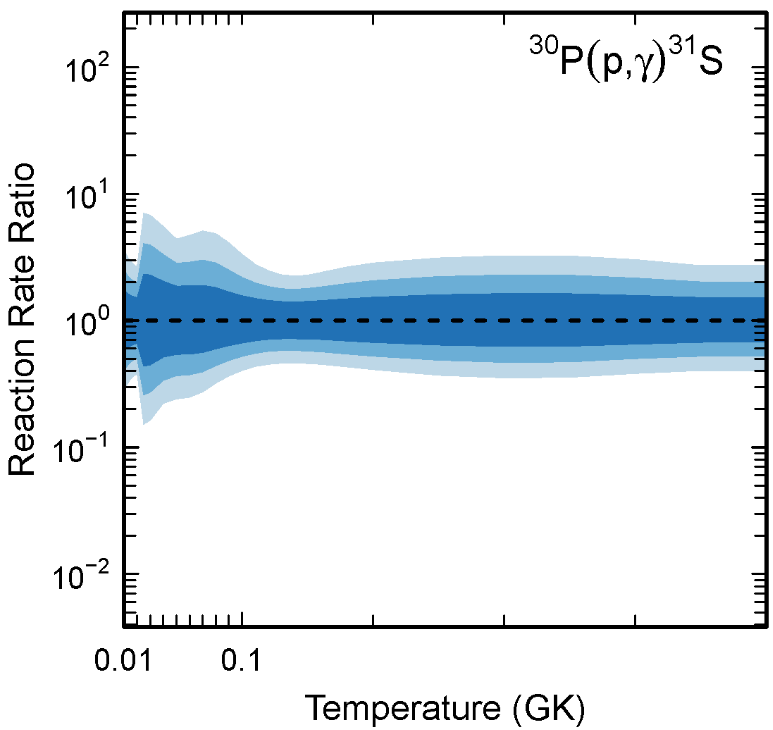
We possess all the equipment and targets needed for the experiment at TRIUMF.

Beam Delivery



RatesMC

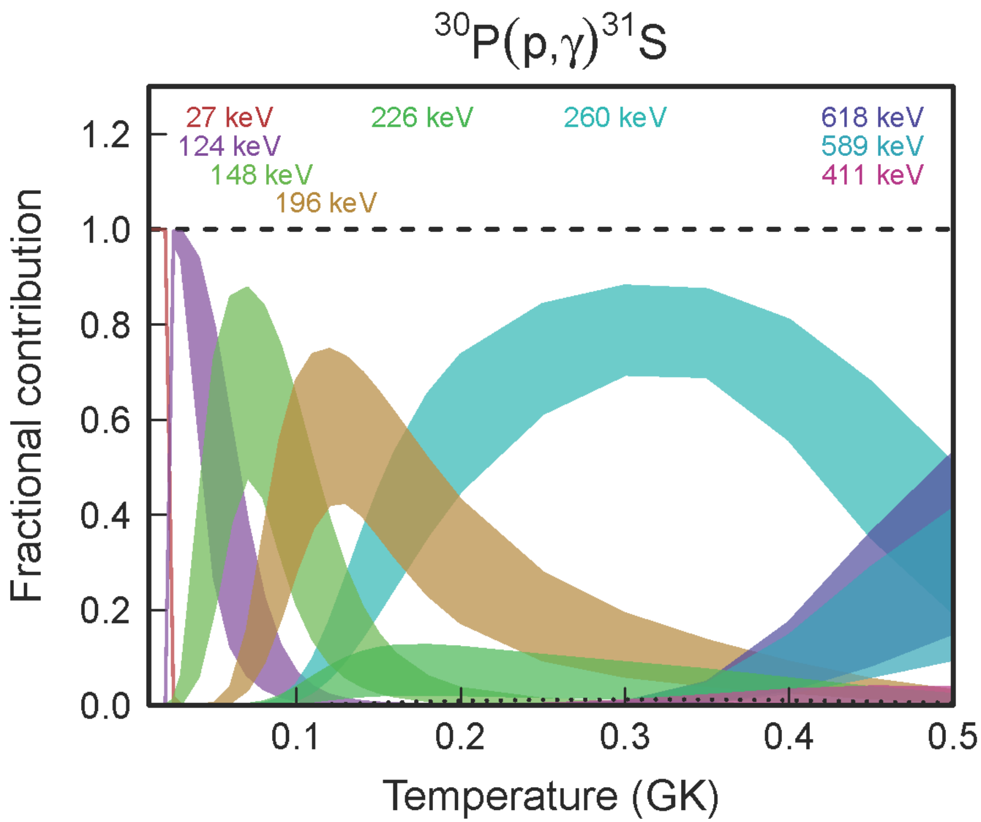


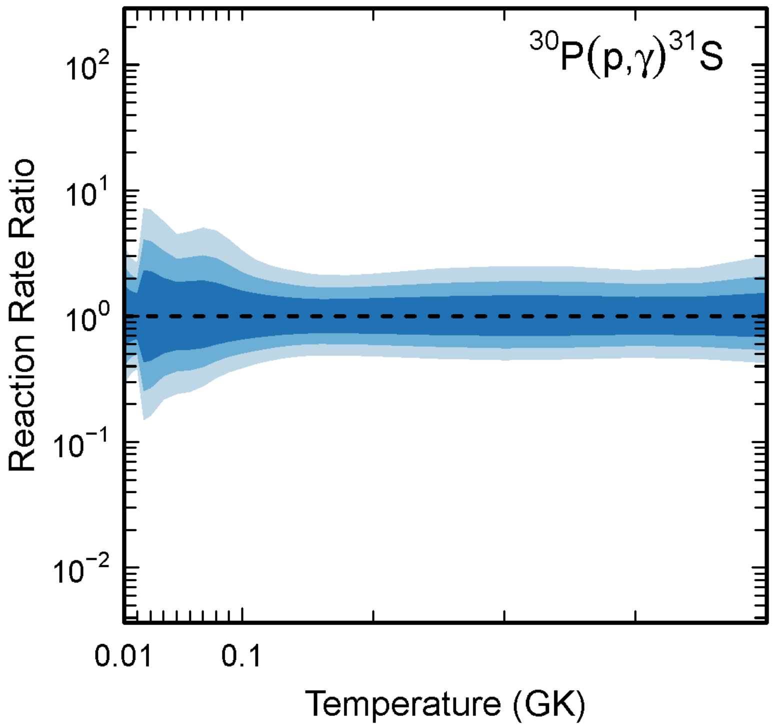


$\omega\gamma_{260} = 80(48)\ \mu\text{eV}$

T. Budner *et al.*, Phys. Rev. Lett. 128, 182701 (2022).

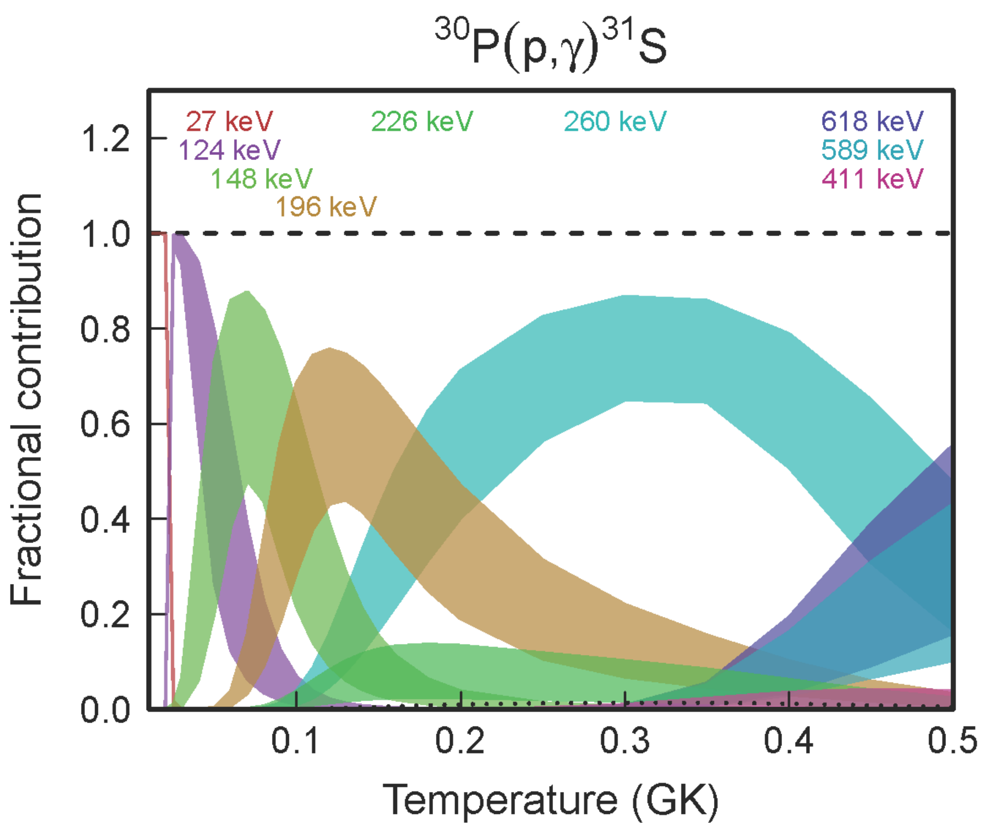
RatesMC

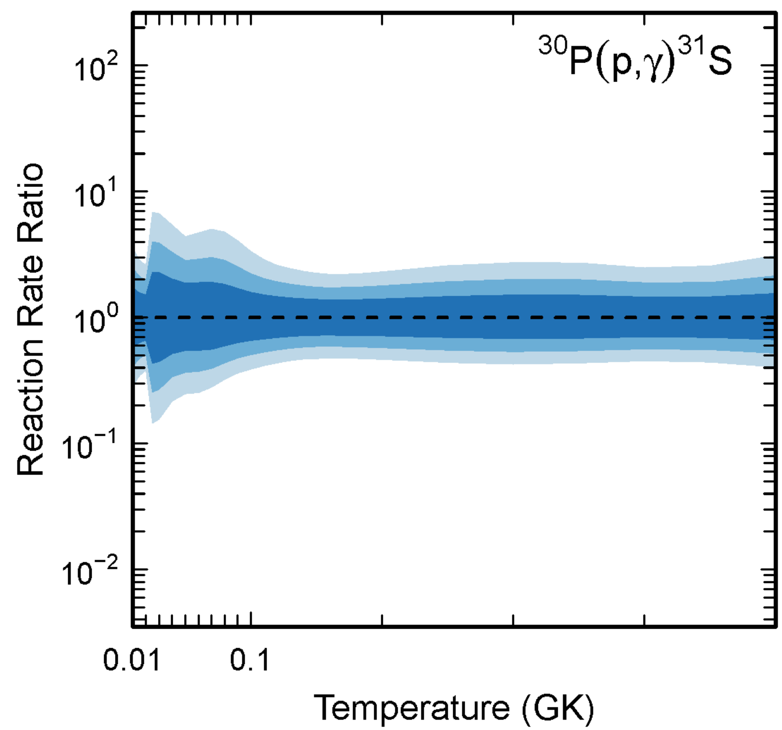




$\omega\gamma_{260} = 22 - 62\ \mu\mathrm{eV}$ 1000 counts τ = 3 fs

RatesMC





$\omega\gamma_{260} = 18 - 57\ \mu\text{eV}$ 500 counts τ = 3 fs

RatesMC

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***************************************************************************************************
Resonant Contribution
Note: G1 = entrance channel, G2 = exit channel, G3 = spectator channel !! Ecm, Exf in (keV); wg, Gx in (eV) !
Note: if Er<0, theta^2=C2S*theta_sp^2 must be entered instead of entrance channel partial width
Ecm     DEcm    wg      Dwg     J    G1      DG1     L1   G2     DG2     L2   G3   DG3  L3   Exf   Int   Corr/Frac
 27.05  0.38  1.1e-33 0.4e-33 3.5 0 0 0 0 0 0 0 0 0 0.0 0
124.45  0.38  9.5e-12 9.5e-12 0.5 0 0 0 0 0 0 0 0 0 0.0 0
148.45  0.27  2.1e-9 2.1e-9 1.5 0 0 0 0 0 0 0 0 0 0.0 0
196.15  0.55  5.1e-7 2.7e-7 1.5 0 0 0 0 0 0 0 0 0 0.0 0
226.41  0.33  0.7e-6 0.7e-6 2.5 0 0 0 0 0 0 0 0 0 0.0 0
244.95  0.38  6.1e-8 2.1e-8 4.5 0 0 0 0 0 0 0 0 0 0.0 0
259.81  0.29  8.0e-5 4.8e-5 1.5 0 0 0 0 0 0 0 0 0 0.0 0
261.51  0.33  5.8e-7 2.5e-7 2.5 0 0 0 0 0 0 0 0 0 0.0 0
262.28  0.31  1.0e-30  1.0e-30  5.5 0 0 0 0 0 0 0 0 0 0.0 0
271.35  2.01  1.0e-30  1.0e-30  3.5 0 0 0 0 0 0 0 0 0 0.0 0
410.95  0.47  0.85e-4 0.85e-4 1.5 0 0 0 0 0 0 0 0 0 0.0 0
451.75  2.01  1.0e-30  1.0e-30  3.5 0 0 0 0 0 0 0 0 0 0.0 0
503.99  0.33  1.0e-30  1.0e-30  4.5 0 0 0 0 0 0 0 0 0 0.0 0
589.35  1.03  0.072  0.072  2.5 0 0 0 0 0 0 0 0 0 0.0 0
618.35  2.01  0.200  0.200  1.5 0 0 0 0 0 0 0 0 0 0.0 0
***************************************************************************************************
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$$\omega\gamma = 80(48)\ \mu\text{eV}$$