

# Spectroscopy for Astrophysics in the Janssens Era (and Beyond!)

K.A. Chipps

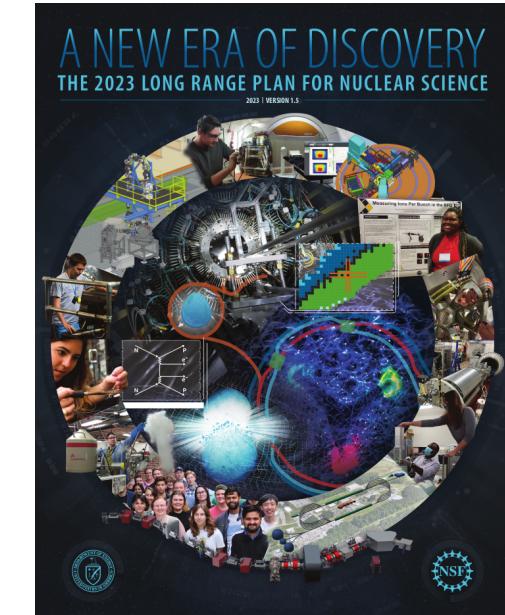
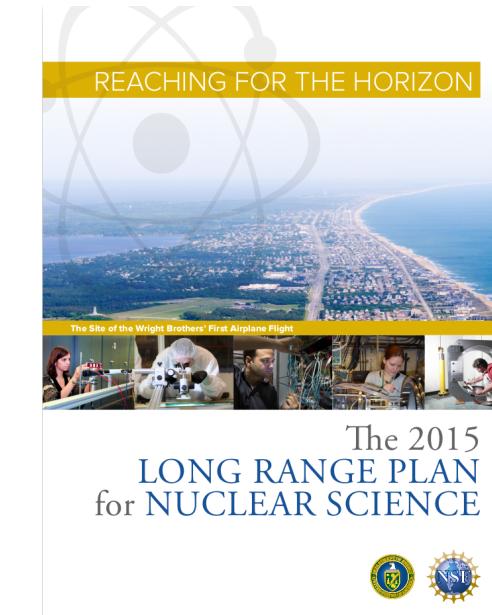
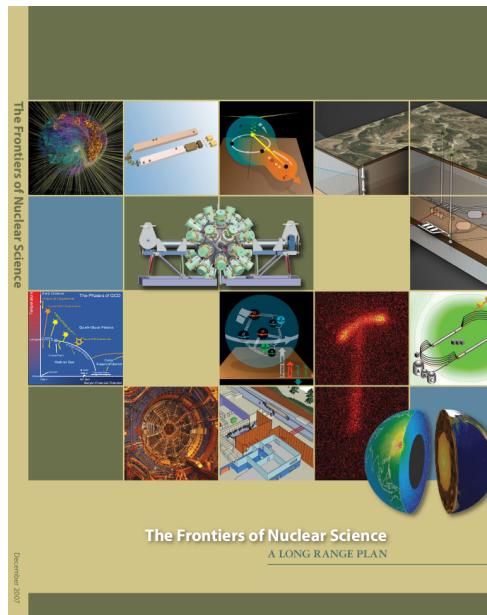
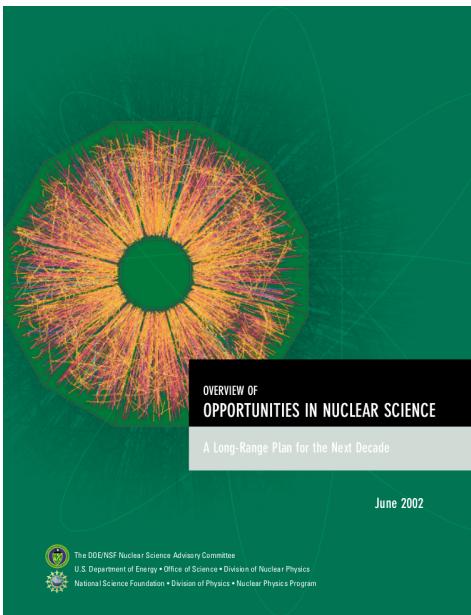
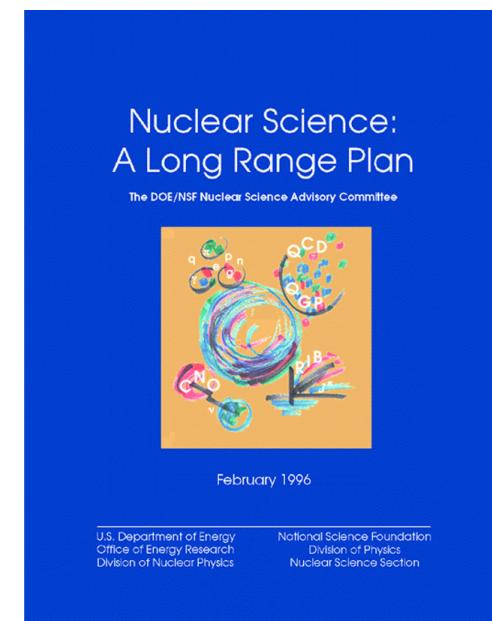
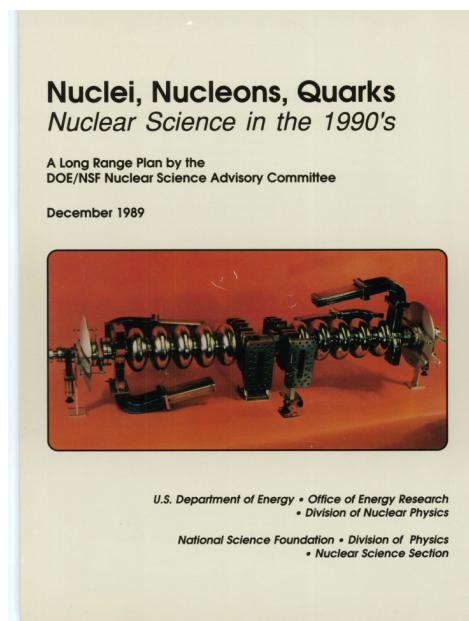
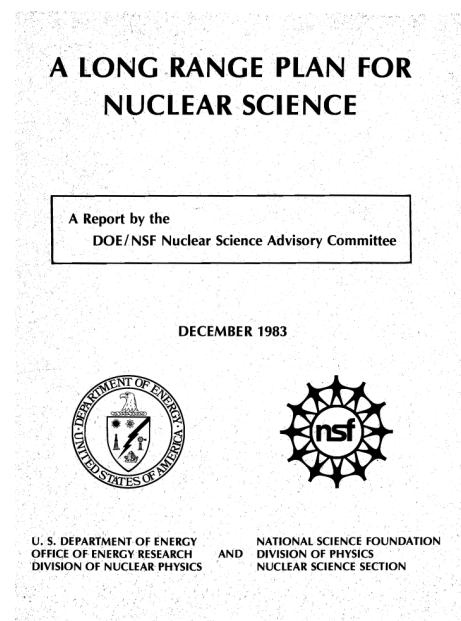
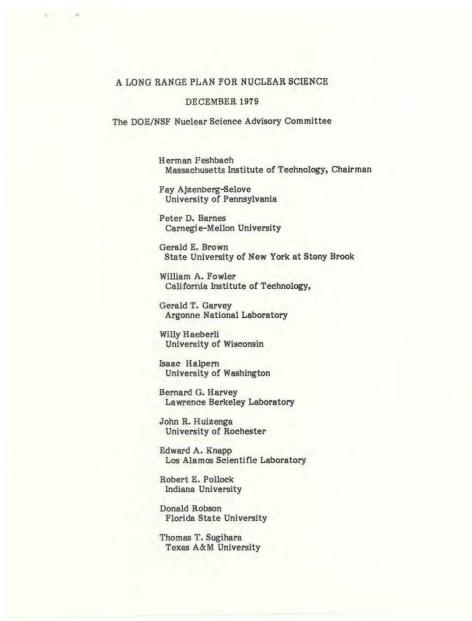
Oak Ridge National Laboratory



ORNL is managed by UT-Battelle LLC for the US Department of Energy

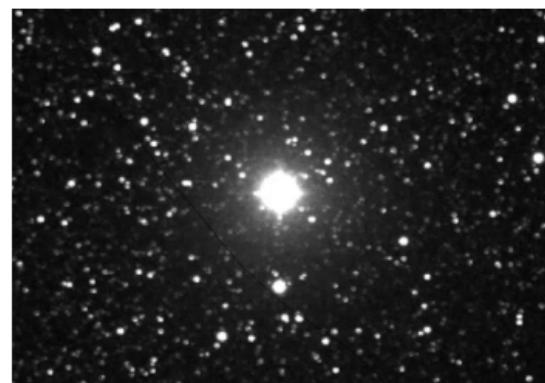


RVFJ career spans 1981-present. In that time, we determined the r-process is universal and then determined it isn't



# Explosive Astrophysical Environments are Unique and Fascinating Multi-Physics Laboratories

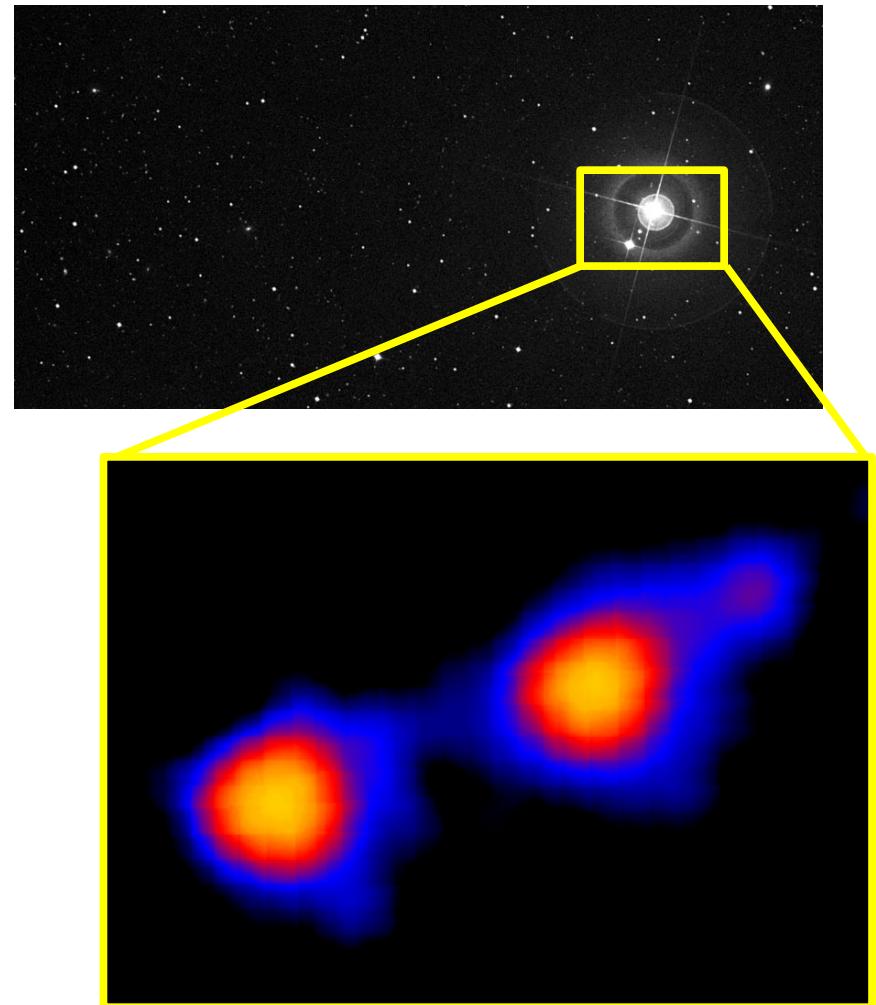
Novae, X-Ray Bursts, Supernovae, Mergers...



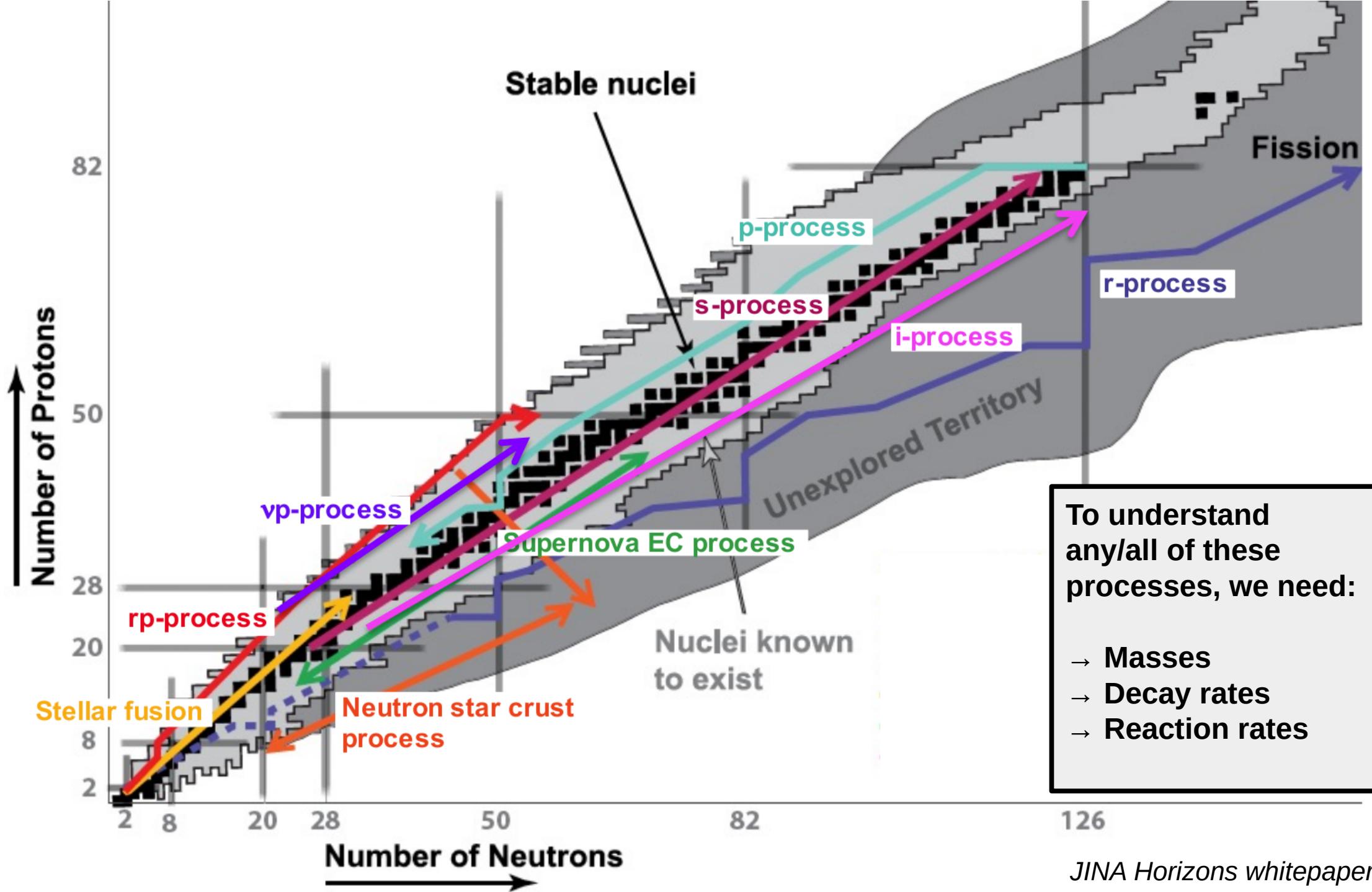
The recurrent nova RS Ophiuchi just went into outburst — its first burst in 15 years — and it's bright enough to see with the naked eye.

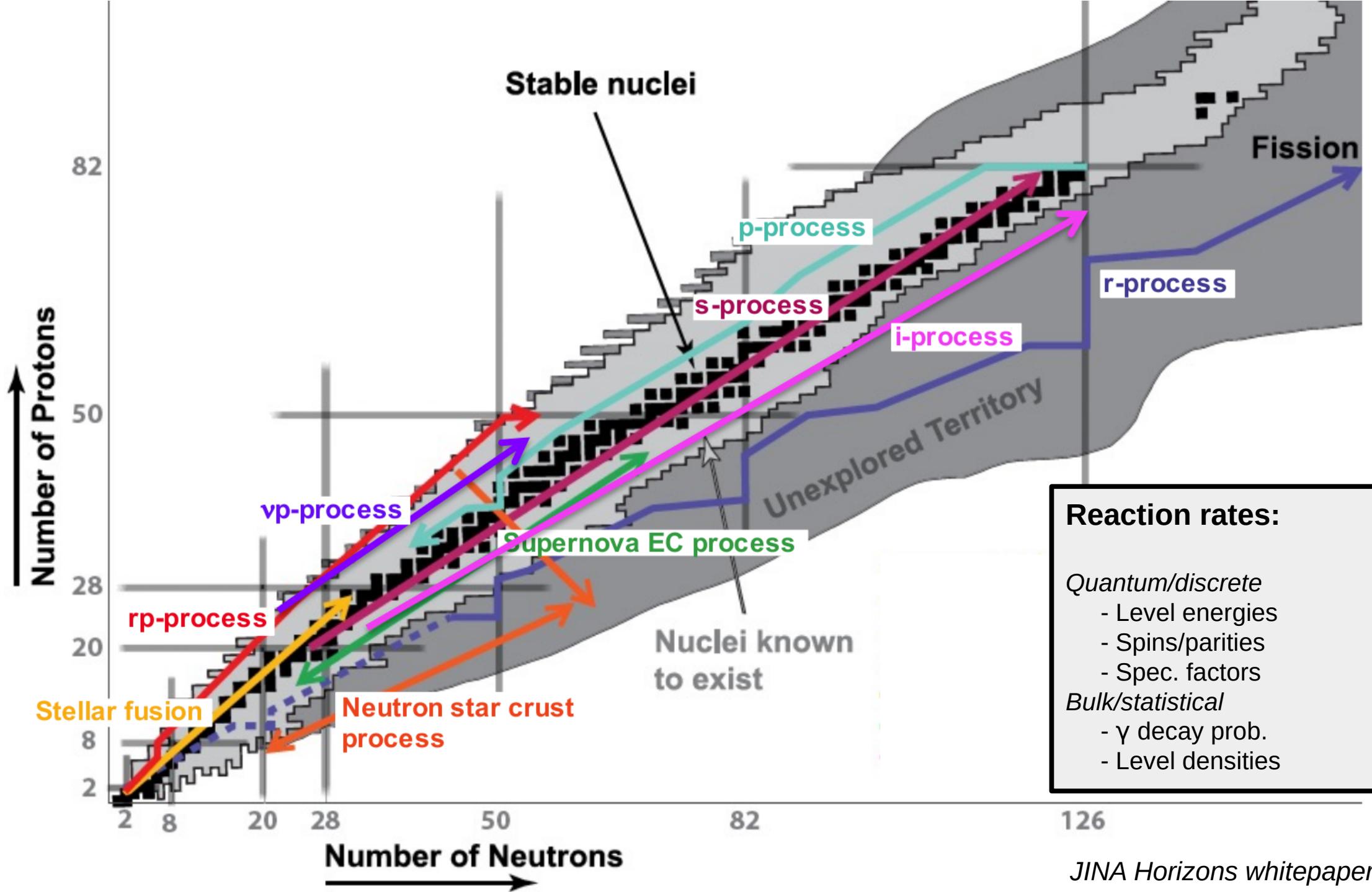
The recurrent nova RS Ophiuchi dramatically brightened from magnitude 11.2 to 4.8 over August 8-9, 2021. The outburst image was taken on August 9.42 UT and paired with an older photo from the Palomar Observatory Sky Survey (POSS) from July 1989 when the star was at minimum. Ernesto Guido, Marco [Rocchetto & Adriano Valvasori](#) / [telescope.live](#)

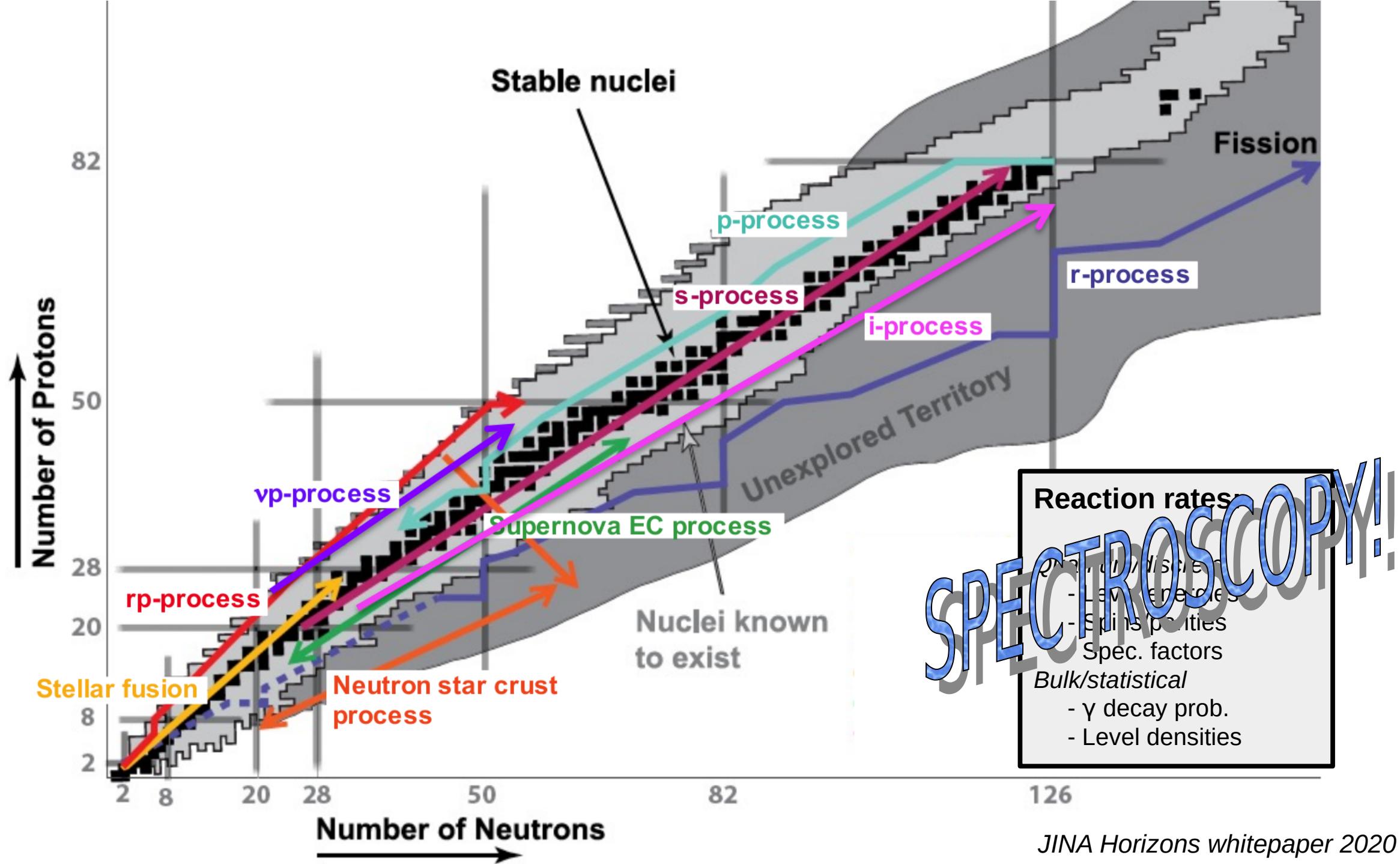
A star that normally slumbers around 12th magnitude suddenly "woke up" seven magnitudes brighter this past weekend. Now you can see it with the naked eye!



all are driven by nuclear reactions and decays involving proton-rich, radioactive nuclei







# Novae endpoint nucleosynthesis: $^{38}\text{K}(\text{p},\gamma)$

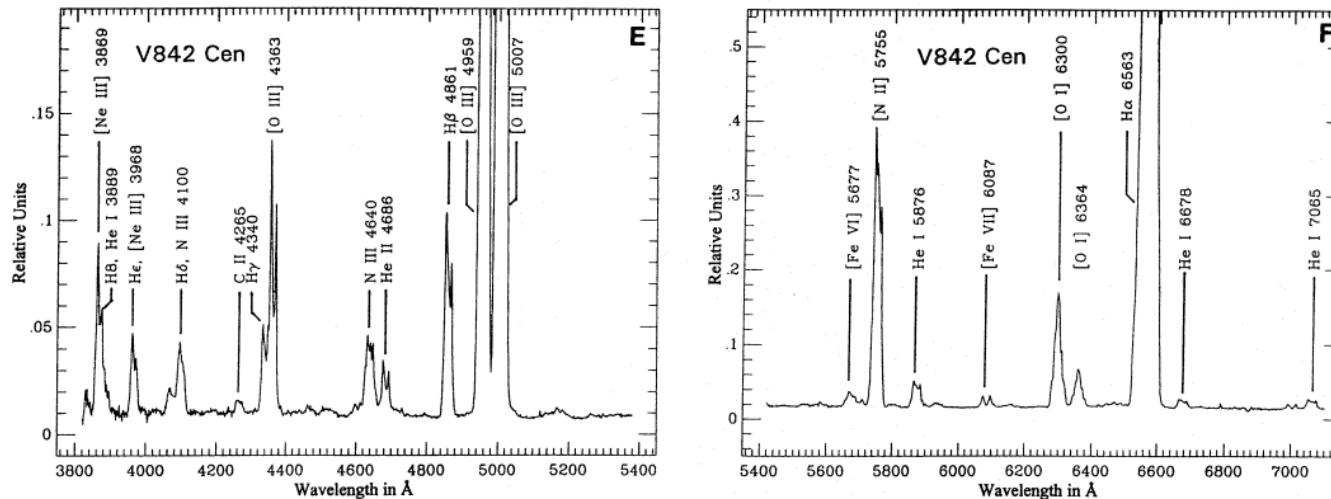


Fig. 1a-n. Examples of optical spectra of novae in nebular stage

Element	Sun	QV Vul (1987)	V2214 Oph (1988)	V977 Sco (1989)	V443 Sct (1989)
H	1.00		1.00	1.00	1.00
He	1.0 e-1	1.1 e-1	1.9 e-1	1.9 e-1	2.3 e-1
N	9.5 e-5	1.1 e-3	6.4 e-2	5.9 e-3	7.8 e-3
O	8.1 e-4	3.8 e-3	1.1 e-3	3.7 e-3	9.0 e-4
Ne	1.1 e-4	7.3 e-5	2.5 e-3	2.5 e-3	1.4 e-5
S	1.7 e-5	4.1 e-6	9.7 e-5	-	2.4 e-5
Ar	3.7 e-6	-	5.5 e-5	5.3 e-5	1.8 e-5
Ca	2.2 e-6	-	9.4 e-5	1.6 e-5	1.0 e-5
Fe	4.2 e-5	2.3 e-5	6.5 e-4	4.8 e-5	2.8 e-5
Z	0.019	0.05	0.37	0.08	0.06

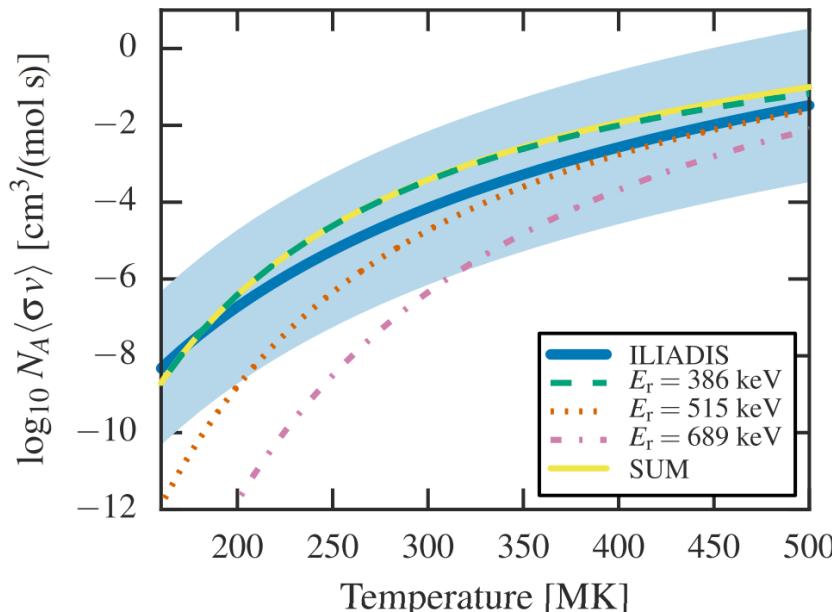
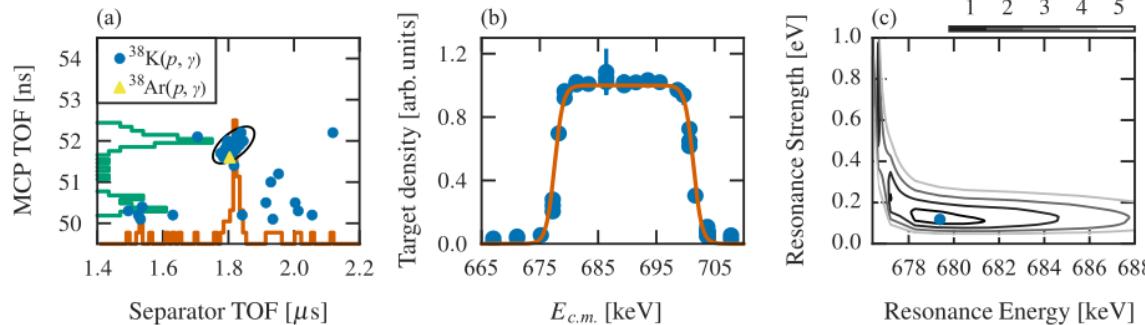
Andrea et al, A&A 291, 869

Sc	36Sc	37Sc	38Sc	39Sc	40Sc	41Sc	42Sc	43Sc	
Ca	34Ca Jpi=0+	35Ca T1/2s=5.000E Jpi=0+ T1/2s=1.020E	36Ca Jpi=3/2+ T1/2s=1.811E	37Ca Jpi=0+ T1/2s=4.400E	38Ca Jpi=3/2+ T1/2s=8.596E	39Ca Jpi=3/2+ T1/2s=1.000E	40Ca Jpi=0+ T1/2s=1.000E	41Ca Jpi=0+ T1/2s=3.250E	42Ca Jpi=0+ T1/2s=1.000E
32K	33K	34K Jpi=3/2+ T1/2s=1.900E	35K Jpi=2+ T1/2s=3.420E	36K Jpi=3/2+ T1/2s=1.226E	37K Jpi=3+ T1/2s=4.582E	38K Jpi=3+ T1/2s=1.000E	39K Jpi=3/2+ T1/2s=4.030E	40K Jpi=3/2+ T1/2s>1.000E	41K Jpi=0+ T1/2s>1.000E
31Ar	32Ar Jpi=0+ T1/2s=9.800E	33Ar Jpi=1/2+ T1/2s=1.730E	34Ar Jpi=0+ T1/2s=8.445E	35Ar Jpi=3/2+ T1/2s=1.775E	36Ar Jpi=3/2+ T1/2s>1.000E	37Ar Jpi=0+ T1/2s=3.027E	38Ar Jpi=0+ T1/2s>1.000E	39Ar Jpi=7/2+ T1/2s=8.489E	40Ar Jpi=0+ T1/2s>1.000E
30Cl	31Cl T1/2s=1.500E	32Cl Jpi=1+ T1/2s=2.980E	33Cl Jpi=3/2+ T1/2s=2.511E	34Cl Jpi=0+ T1/2s=1.526E	35Cl Jpi=3/2+ T1/2s>1.000E	36Cl Jpi=2+ T1/2s=9.499E	37Cl Jpi=3/2+ T1/2s>1.000E	38Cl Jpi=2- T1/2s=2.234E	39Cl Jpi=3/2+ T1/2s=3.336E
29S	30S Jpi=0+ T1/2s=1.178E	31S Jpi=1/2+ T1/2s=2.572E	32S Jpi=0+ T1/2s<1.000E	33S Jpi=3/2+ T1/2s<1.000E	34S Jpi=0+ T1/2s>1.000E	35S Jpi=3/2+ T1/2s=7.561E	36S Jpi=0+ T1/2s>1.000E	37S Jpi=7/2- T1/2s=3.030E	38S Jpi=0+ T1/2s=1.022E
28P	29P Jpi=3+ T1/2s=2.703E	30P Jpi=1/2+ T1/2s=4.140E	31P Jpi=1/2+ T1/2s<1.000E	32P Jpi=1+ T1/2s=1.232E	33P Jpi=1/2+ T1/2s=2.189E	34P Jpi=1+ T1/2s=1.243E	35P Jpi=1/2+ T1/2s=4.730E	36P Jpi=1/2+ T1/2s=5.600E	37P Jpi=1/2+ T1/2s=2.310E
27Si	28Si Jpi=0+ T1/2s>1.000E	29Si Jpi=1/2+ T1/2s>1.000E	30Si Jpi=0+ T1/2s>1.000E	31Si Jpi=3/2+ T1/2s=9.438E	32Si Jpi=0+ T1/2s=5.428E	33Si T1/2s=6.180E	34Si Jpi=0+ T1/2s=2.770E	35Si T1/2s=7.800E	36Si Jpi=0+ T1/2s=4.500E
26Al	27Al Jpi=5+ T1/2s=2.335E	28Al Jpi=5/2+ T1/2s>1.000E	29Al Jpi=3+ T1/2s=3.135E	30Al Jpi=3+ T1/2s=3.936E	31Al Jpi=(3/2,5/2)+ T1/2s=3.600E	32Al Jpi=11+ T1/2s=6.400E	33Al T1/2s=3.300E	34Al T1/2s=6.000E	35Al T1/2s=1.500E

Iliadis et al, ApJSS 142, 105

$^{38}\text{K}(\text{p},\gamma)^{39}\text{Ca}$ .....	$^{38}\text{Ar}$	0.11
	$^{39}\text{K}$	9.5
	$^{40}\text{Ca}$	5.1

# Spectroscopy of $^{38}\text{K}(p,\gamma)^{39}\text{Ca}$ : putting the cart before the horse



Christian et al, PRC97, 025802

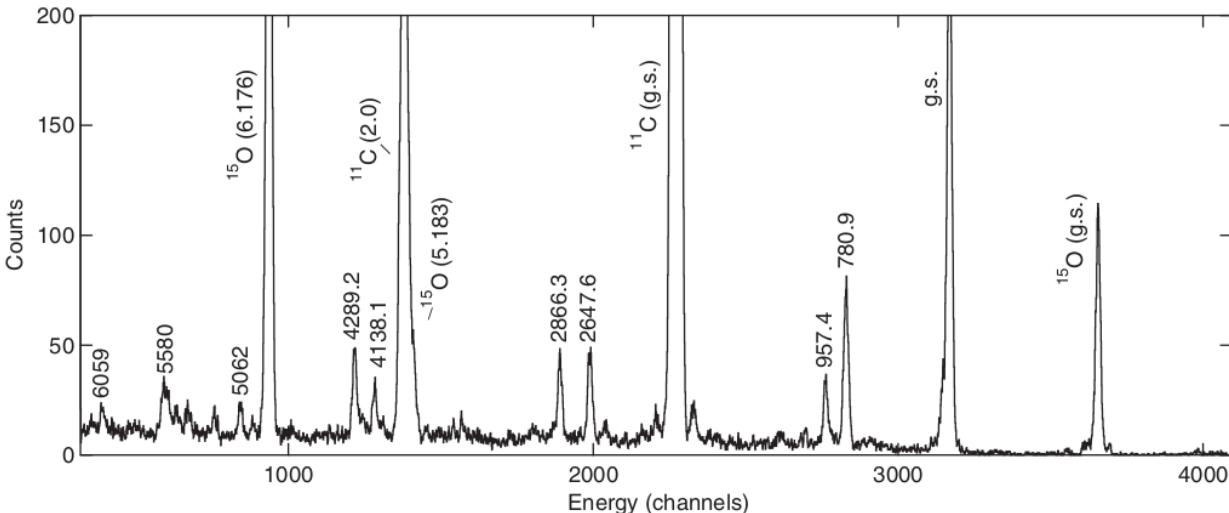
Ref.	$E_x$ (keV)	$E_r$ (keV)	$\omega\gamma$ (meV)
Christian et al. [7]	6157(10)	386(10)	$\leq 2.54$
	6286(10)	515(10)	$\leq 18.4$
	6450(2)	679(2)	120(25)

The chosen beam energies cover respective center-of-mass energies in the DRAGON gas target of  $386 \pm 13$ ,  $515 \pm 13$ , and  $689 \pm 13$  keV. The resonances in question were previously identified as  $5/2^+$   $^{39}\text{Ca}$  states through  $^{40}\text{Ca}(^3\text{He},\alpha)^{39}\text{Ca}$  [18],  $^{40}\text{Ca}(d,t)^{39}\text{Ca}$  [19], and  $^{40}\text{Ca}(p,d)^{39}\text{Ca}$  [20] transfer reaction studies. Their recommended excitation energies are  $6157 \pm 10$ ,  $6286 \pm 10$ , and  $6460 \pm 10$  keV, corresponding to  $^{38}\text{K} + p$  resonances at  $386 \pm 10$ ,  $515 \pm 10$ , and  $689 \pm 10$  keV, respectively [21]. The respective  $(p,\gamma)$  cone angles for mea-

...what's 10 keV among friends?

# Spectroscopy of $^{38}\text{K}(\text{p},\gamma)^{39}\text{Ca}$ : pointing out the horse/cart situation

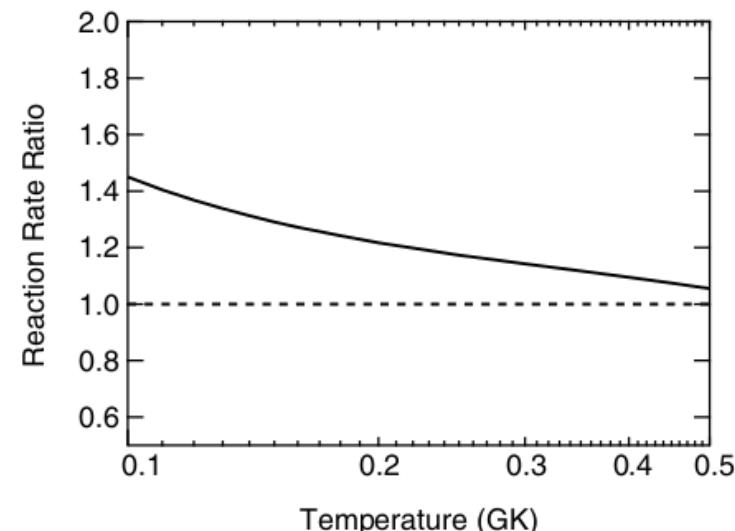
Setoodehnia et al, PRC98, 055804



$^{40}\text{Ca}(\text{He}^3, \alpha)^{39}\text{Ca}$  using Enge  
spectrograph to constrain energies and  
spins

701 keV would have been on the edge  
of the DRAGON target!

Ref.	$E_x$ (keV)	$E_r$ (keV)	$\omega\gamma$ (meV)
Christian <i>et al.</i> [7]	6157(10)	386(10)	$\leq 2.54$
	6286(10)	515(10)	$\leq 18.4$
	6450(2)	679(2)	120(25)
Setoodehnia <i>et al.</i> [11]	6154(5)	383(5)	$\leq 2.6$
	6286(10)	515(10)	$\leq 18.4$
	6472.2(24)	701.3(25)	126(39)



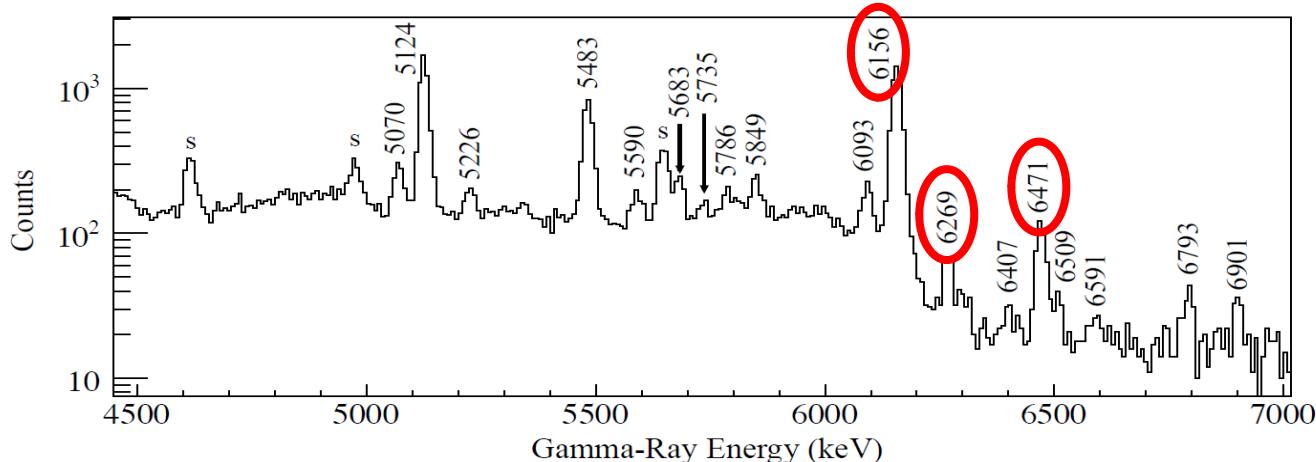
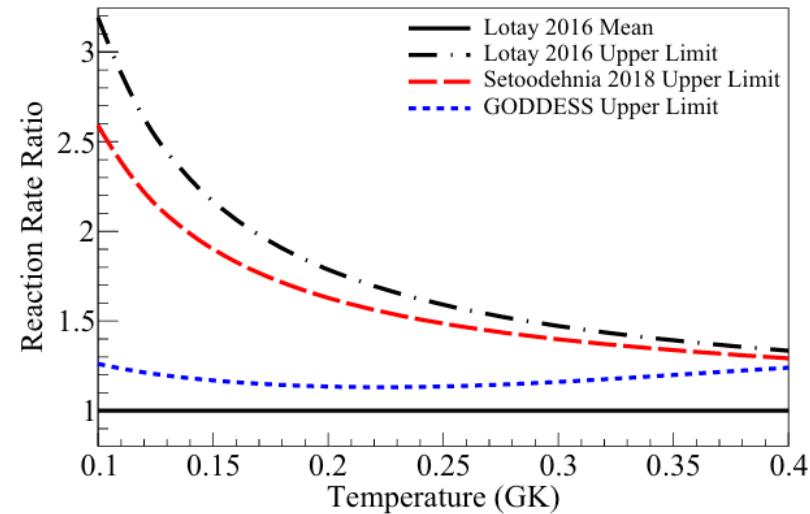
(b) Ratio of the new over old reaction rate.

# Spectroscopy of $^{38}\text{K}(\text{p},\gamma)^{39}\text{Ca}$ : careful spectroscopy with



## solves the problem

Hall et al, PRC101, 015804



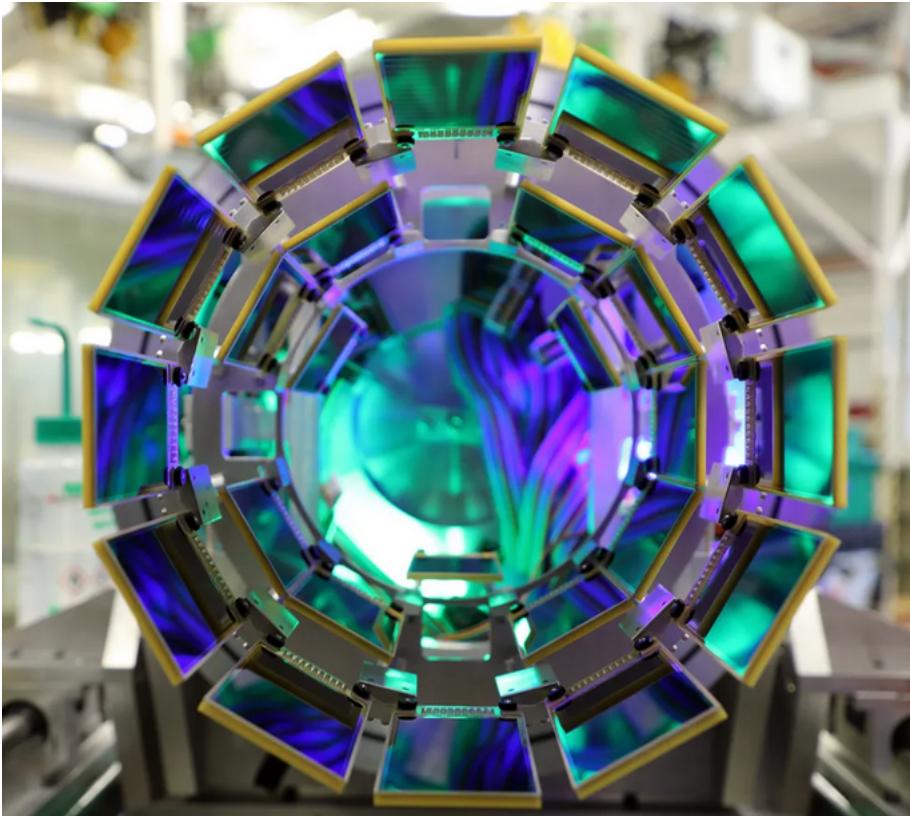
Ref.	$E_x$ (keV)	$E_r$ (keV)	$\omega\gamma$ (meV)
Lotay 2016 Mean	6157(10)	386(10)	$\leq 2.54$
Lotay 2016 Upper Limit	6286(10)	515(10)	$\leq 18.4$
Setoodehnia 2018 Upper Limit	6450(2)	679(2)	120(25)
GODDESS Upper Limit	6154(5)	383(5)	$\leq 2.6$
Christian <i>et al.</i> [7]	6286(10)	515(10)	$\leq 18.4$
Setoodehnia <i>et al.</i> [11]	6472.2(24)	701.3(25)	126(39)
Present Work	6156.7(16)	386(2)	$\leq 2.54$
	6269.3(22)	498(2)	2.47 - 24.7
	6471.4(19)	701(2)	126(39)

- Constrain level energies to 2 keV
  - Good agreement for 6157-keV level
- Reduced reaction rate uncertainties
- Confirms 701-keV energy from SPS expt
  - places this resonance at edge of DRAGON target
- Suggests middle resonance is lower by 1-2  $\sigma$ 
  - outside DRAGON target?

clearly hard at work during the 2019 GODDESS campaign...



# Spectroscopy of $^{38}\text{K}(\text{p},\gamma)^{39}\text{Ca}$ : constraining resonance strengths



$^{38}\text{K}(\text{d},\text{p})$  spectroscopic transfer reaction study undertaken with



**ORNL**

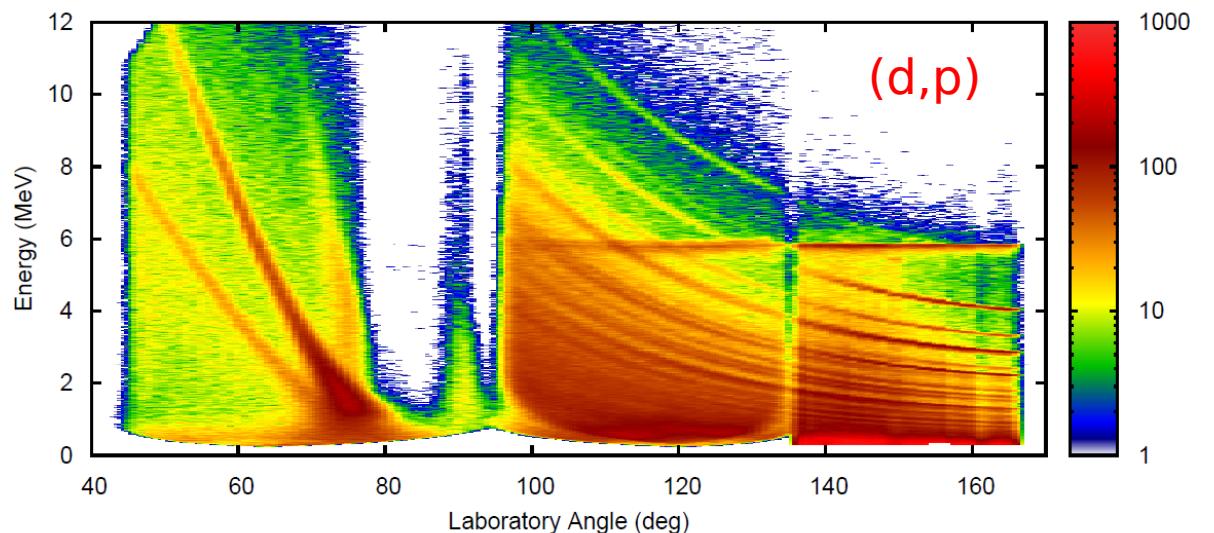
**Proton single particle spectroscopic factors can be tricky:**

- getting good resolution with (d,n)
- getting good res and sufficient target density for ( $^3\text{He},\text{d}$ )

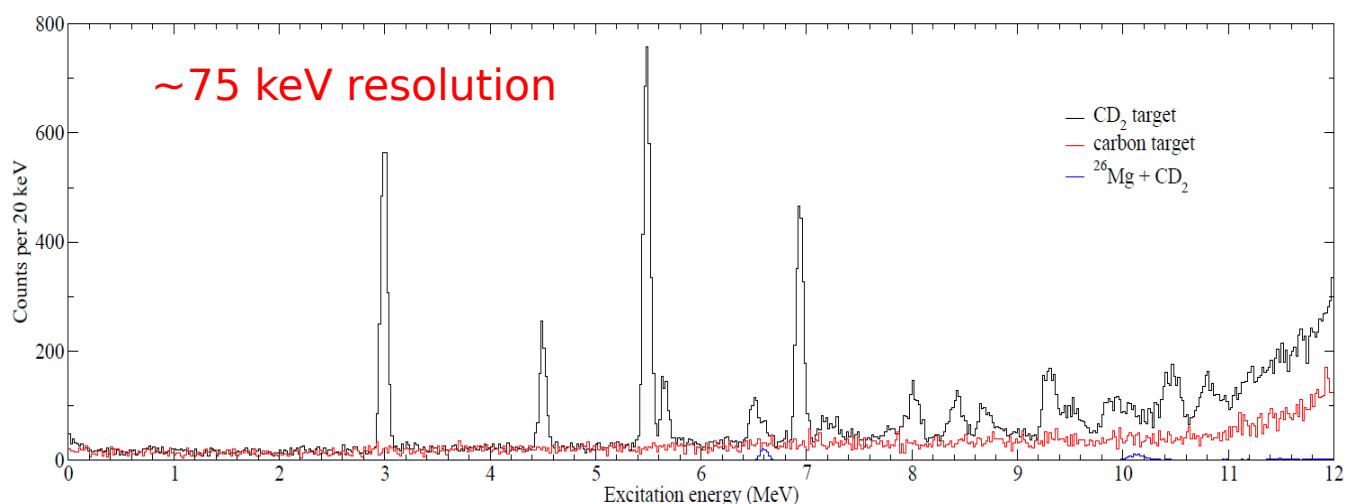
**For these  $\text{N}=\text{Z}$  nuclei, let's measure *neutron* single particle spectroscopic factors:**

- mirror assignments and MED shifts from fusion evaporation studies  
(with Gammasphere and GRETINA!)
- (d,p) angular distributions straightforward to measure/interpret  
( $\text{J}\pi$  and spectroscopic factors)
- shell model embedded in the continuum corrections  
(neutron SF  $\rightarrow$  proton SF)

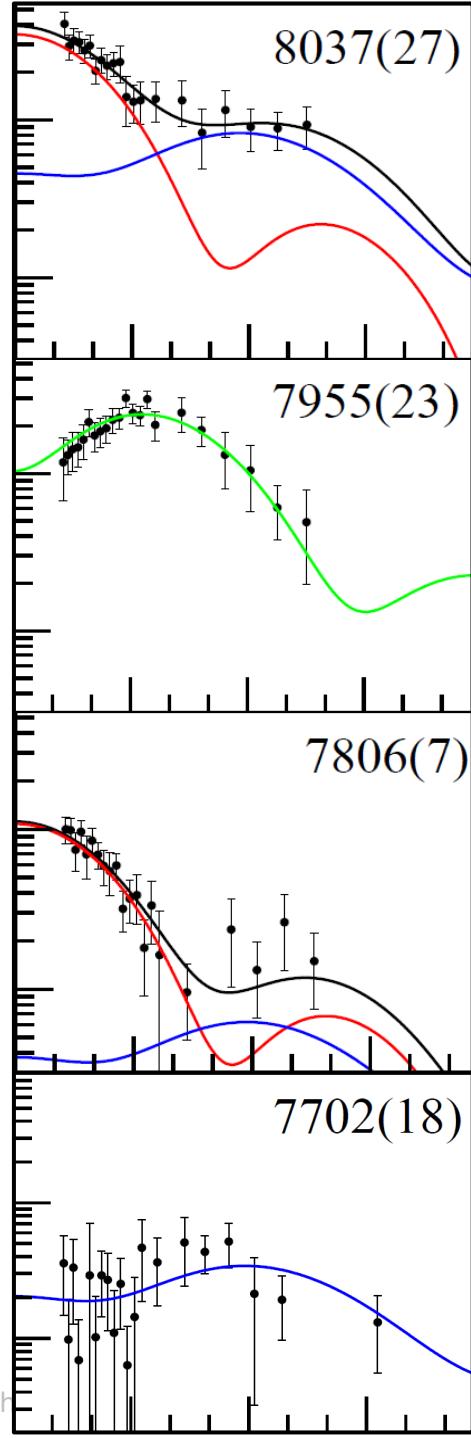
# For example: $^{26}\text{Al}(\text{d},\text{p})^{27}\text{Al}$ experiment



- 4.5 MeV/u  $^{26}\text{Al}$  (HRIBF tandem)
- $5 \times 10^6$  pps
- $150 \mu\text{g}/\text{cm}^2 \text{CD}_2$
- MCP normalization



Pain et al, PRL114, 212501



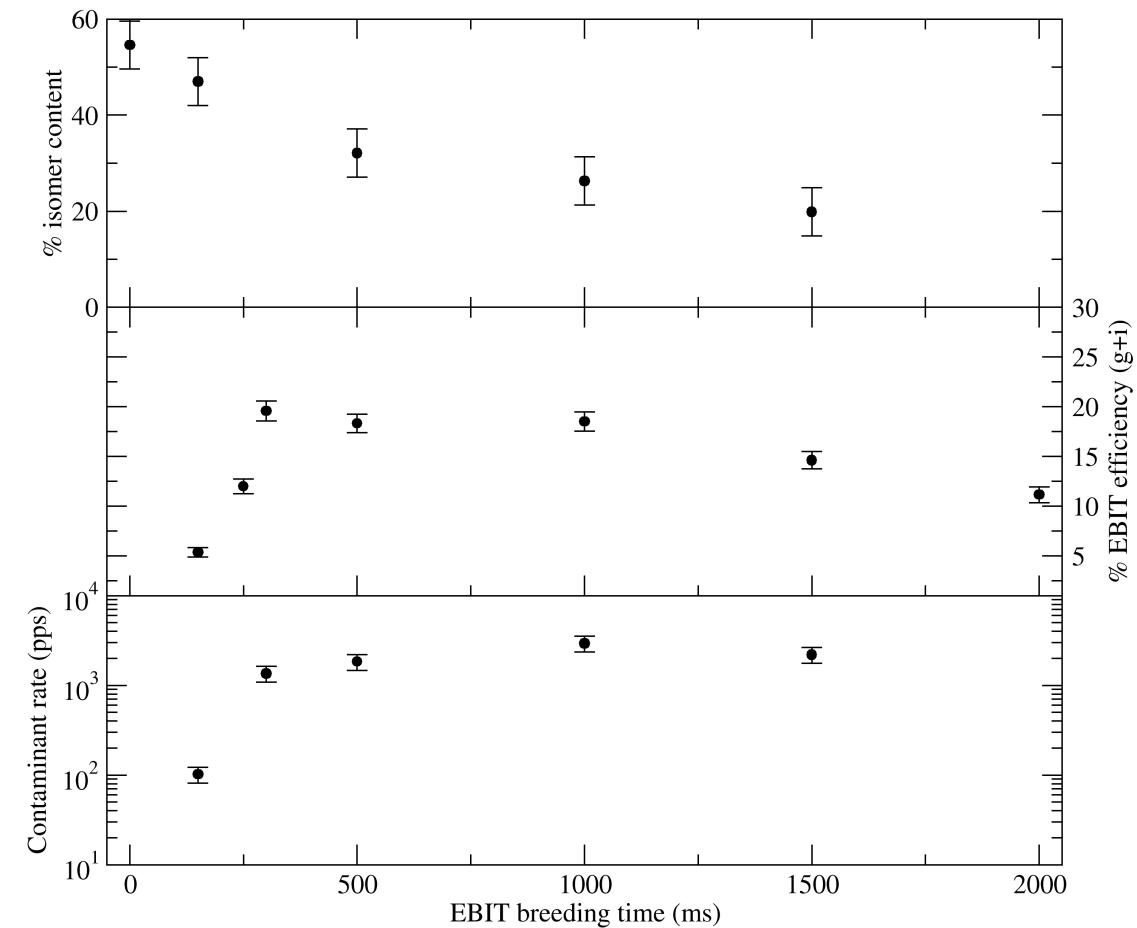
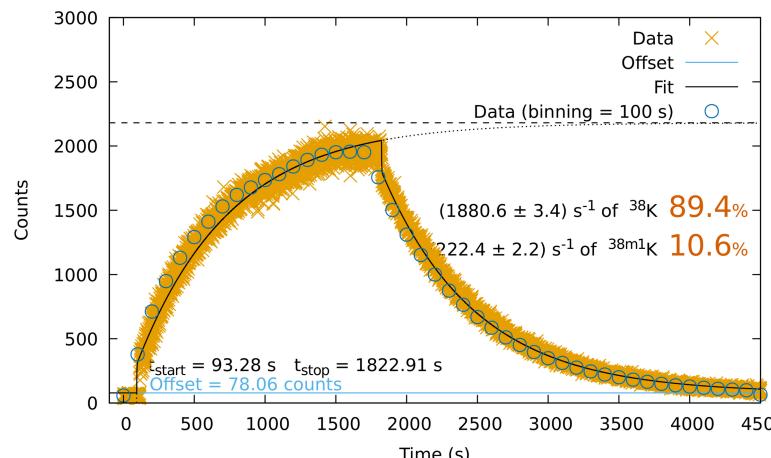
K.A. Ch

# Spectroscopy of $^{38}\text{K}(\text{p},\gamma)^{39}\text{Ca}$ : don't forget the isomer!

$^{38}\text{K}$  has a low-lying, large  $\Delta J$ , long-lived isomer  
→ just like  $^{26}\text{Al}$ !

Need to run  $^{38}\text{K}(\text{d},\text{p})$  with two different beam settings:  
*mostly gs* and *mostly isomer*  
so that we can differentiate the strength built on each...

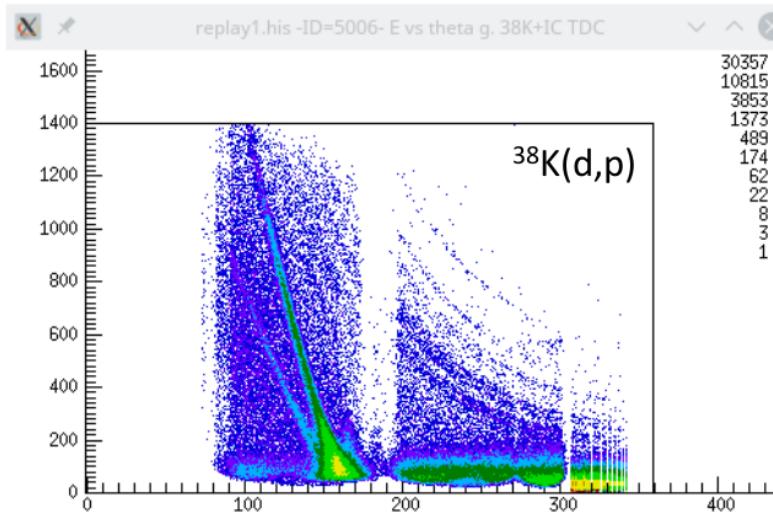
These isomers can be populated thermally in an astrophysical environment, or as the endpoint of beta decay  
(in the case of  $^{38}\text{K}^m$ , it's almost 80%)!



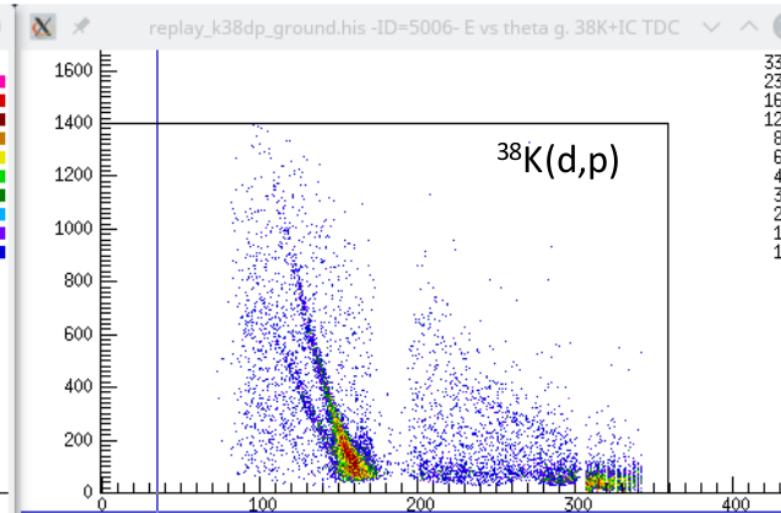
Chipp et al, PRAB 21, 121301

# Spectroscopy of $^{38}\text{K}(\text{p},\gamma)^{39}\text{Ca}$ : don't forget the isomer!

Short breeding time (March)

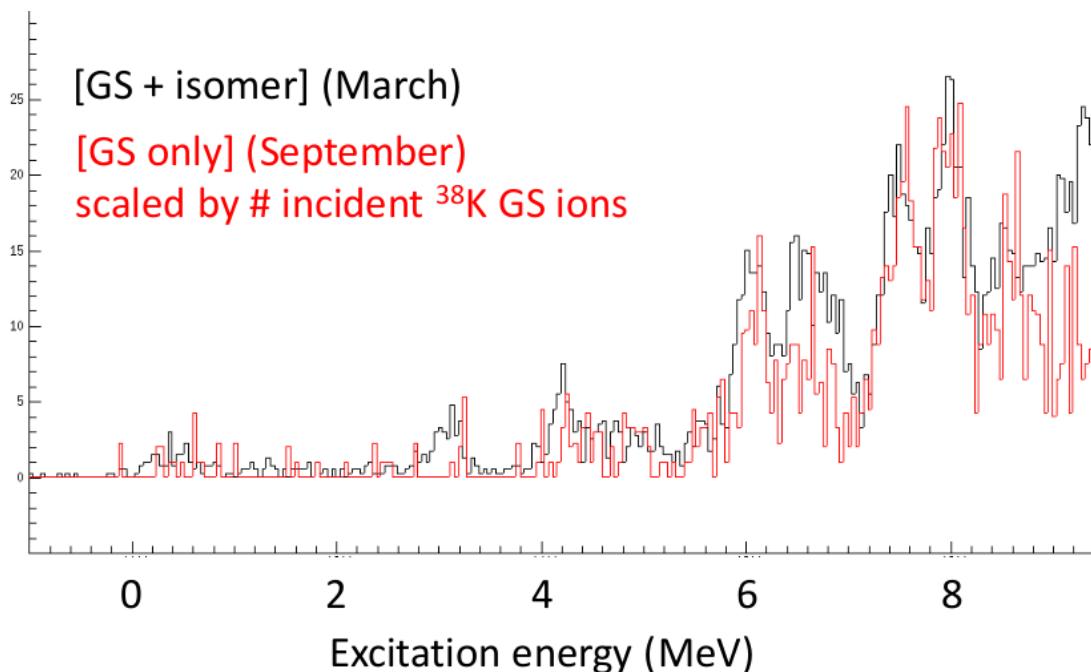


Long breeding time (September)

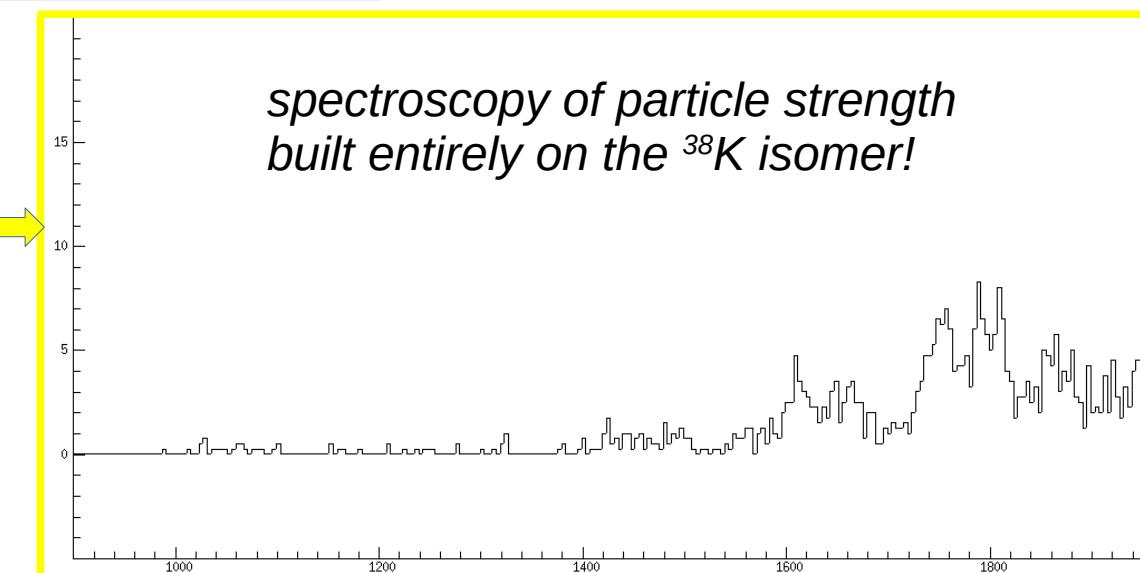


multiple ways to vary the isomer content of a beam – can be done at ATLAS and FRIB

[GS + isomer] (March)  
[GS only] (September)  
scaled by # incident  $^{38}\text{K}$  GS ions



spectroscopy of particle strength built entirely on the  $^{38}\text{K}$  isomer!



# Novae endpoint nucleosynthesis: $^{38}\text{K}(\text{p},\gamma)$ and the necessity for spectroscopy in astro

$^{38}\text{K}(\text{p},\gamma)^{39}\text{Ca}$ .....		$^{38}\text{Ar}$	0.11
		$^{39}\text{K}$	9.5
		$^{40}\text{Ca}$	5.1



$^{38}\text{K}^m(\text{p},\gamma)^{39}\text{Ca}$ .....		$^{38}\text{Ar}$
		$^{39}\text{K}$
		$^{40}\text{Ca}$

	<b>Sc</b>	<b>36Sc</b>	<b>37Sc</b>	<b>38Sc</b>	<b>39Sc</b>	<b>40Sc</b>	<b>41Sc</b>	<b>42Sc</b>	<b>43Sc</b>
<b>Ca</b>	<b>34Ca</b>	<b>35Ca</b>	<b>36Ca</b>	<b>37Ca</b>	<b>38Ca</b>	<b>39Ca</b>	<b>40Ca</b>	<b>41Ca</b>	<b>42Ca</b>
	Jpi=0+	T1/2s=5.000E	Jpi=0+ T1/2s=1.020E	Jpi=3/2+ T1/2s=1.811E	Jpi=0+ T1/2s=4.400E	Jpi=3/2+ T1/2s=8.596E	Jpi=0+ T1/2s=1.000E	Jpi=7/2- T1/2s=3.250E	Jpi=0+ T1/2s>1.000E
<b>32K</b>	<b>33K</b>	<b>34K</b>	<b>35K</b>	<b>36K</b>	<b>37K</b>	<b>38K</b>	<b>39K</b>	<b>40K</b>	<b>41K</b>
	Jpi=3/2+ T1/2s=1.900E	Jpi=3/2+ T1/2s=3.420E	Jpi=3/2+ T1/2s=1.226E	Jpi=3/2+ T1/2s=4.582E	Jpi=3/2+ T1/2s>1.000E	Jpi=4- T1/2s=4.030E	Jpi=3/2+ T1/2s>1.000E		
<b>31Ar</b>	<b>32Ar</b>	<b>33Ar</b>	<b>34Ar</b>	<b>35Ar</b>	<b>36Ar</b>	<b>37Ar</b>	<b>38Ar</b>	<b>39Ar</b>	<b>40Ar</b>
T1/2s=1.510E	Jpi=0+ T1/2s=9.800E	Jpi=1/2+ T1/2s=1.730E	Jpi=0+ T1/2s=8.445E	Jpi=3/2+ T1/2s=1.775E	Jpi=0+ T1/2s>1.000E	Jpi=3/2+ T1/2s=3.027E	Jpi=0+ T1/2s=8.489E	Jpi=0+ T1/2s>1.000E	
<b>30Cl</b>	<b>31Cl</b>	<b>32Cl</b>	<b>33Cl</b>	<b>34Cl</b>	<b>35Cl</b>	<b>36Cl</b>	<b>37Cl</b>	<b>38Cl</b>	<b>39Cl</b>
T1/2s=1.500E	Jpi=1+ T1/2s=2.980E	Jpi=1/2+ T1/2s=2.511E	Jpi=0+ T1/2s=1.526E	Jpi=3/2+ T1/2s>1.000E	Jpi=2+ T1/2s=9.499E	Jpi=3/2+ T1/2s=1.000E	Jpi=2- T1/2s=2.234E	Jpi=3/2+ T1/2s=3.336E	
<b>29S</b>	<b>30S</b>	<b>31S</b>	<b>32S</b>	<b>33S</b>	<b>34S</b>	<b>35S</b>	<b>36S</b>	<b>37S</b>	<b>38S</b>
Jpi=5/2+ T1/2s=1.870E	Jpi=0+ T1/2s=1.178E	Jpi=1/2+ T1/2s=2.572E	Jpi=0+ T1/2s=1.000E	Jpi=3/2+ T1/2s=1.000E	Jpi=0+ T1/2s=1.000E	Jpi=3/2+ T1/2s=7.561E	Jpi=0+ T1/2s=1.000E	Jpi=7/2- T1/2s=3.030E	Jpi=0+ T1/2s=1.022E
<b>28P</b>	<b>29P</b>	<b>30P</b>	<b>31P</b>	<b>32P</b>	<b>33P</b>	<b>34P</b>	<b>35P</b>	<b>36P</b>	<b>37P</b>
Jpi=3+ T1/2s=2.703E	Jpi=1/2+ T1/2s=4.140E	Jpi=1+ T1/2s=1.499E	Jpi=1/2+ T1/2s=1.000E	Jpi=1+ T1/2s=1.232E	Jpi=1/2+ T1/2s=2.189E	Jpi=1+ T1/2s=1.243E	Jpi=1/2+ T1/2s=4.730E	T1/2s=5.600E	T1/2s=2.310E
<b>27Si</b>	<b>28Si</b>	<b>29Si</b>	<b>30Si</b>	<b>31Si</b>	<b>32Si</b>	<b>33Si</b>	<b>34Si</b>	<b>35Si</b>	<b>36Si</b>
Jpi=5/2+ T1/2s=4.160E	Jpi=0+ T1/2s>1.000E	Jpi=1/2+ T1/2s>1.000E	Jpi=0+ T1/2s>1.000E	Jpi=3/2+ T1/2s=9.438E	Jpi=0+ T1/2s=5.428E	T1/2s=6.180E	Jpi=0+ T1/2s=2.770E	Jpi=0+ T1/2s=4.500E	
<b>26Al</b>	<b>27Al</b>	<b>28Al</b>	<b>29Al</b>	<b>30Al</b>	<b>31Al</b>	<b>32Al</b>	<b>33Al</b>	<b>34Al</b>	<b>35Al</b>
Jpi=5+ T1/2s=2.335E	Jpi=5/2+ T1/2s>1.000E	Jpi=3+ T1/2s=1.345E	Jpi=5/2+ T1/2s=3.936E	T1/2s=3.600E	Jpi=3/2+ T1/2s=6.440E	Jpi=1+ T1/2s=3.300E	T1/2s=6.000E	T1/2s=1.500E	



	<b>Sc</b>	<b>36Sc</b>	<b>37Sc</b>	<b>38Sc</b>	<b>39Sc</b>	<b>40Sc</b>	<b>41Sc</b>	<b>42Sc</b>	<b>43Sc</b>
<b>Ca</b>	<b>34Ca</b>	<b>35Ca</b>	<b>36Ca</b>	<b>37Ca</b>	<b>38Ca</b>	<b>39Ca</b>	<b>40Ca</b>	<b>41Ca</b>	<b>42Ca</b>
	Jpi=0+	T1/2s=5.000E	Jpi=0+ T1/2s=1.020E	Jpi=3/2+ T1/2s=1.811E	Jpi=0+ T1/2s=4.400E	Jpi=3/2+ T1/2s=8.596E	Jpi=0+ T1/2s=1.000E	Jpi=7/2- T1/2s=3.250E	Jpi=0+ T1/2s>1.000E
<b>32K</b>	<b>33K</b>	<b>34K</b>	<b>35K</b>	<b>36K</b>	<b>37K</b>	<b>38K</b>	<b>39K</b>	<b>40K</b>	<b>41K</b>
	Jpi=3/2+ T1/2s=1.900E	Jpi=2+ T1/2s=3.420E	Jpi=3/2+ T1/2s=1.226E	Jpi=3/2+ T1/2s=4.582E	Jpi=3/2+ T1/2s>1.000E	Jpi=4- T1/2s=3.027E	Jpi=7/2- T1/2s=8.489E	Jpi=4- T1/2s>1.000E	
<b>31Ar</b>	<b>32Ar</b>	<b>33Ar</b>	<b>34Ar</b>	<b>35Ar</b>	<b>36Ar</b>	<b>37Ar</b>	<b>38Ar</b>	<b>39Ar</b>	<b>40Ar</b>
T1/2s=1.510E	Jpi=0+ T1/2s=9.800E	Jpi=1/2+ T1/2s=1.730E	Jpi=0+ T1/2s=8.445E	Jpi=3/2+ T1/2s=1.775E	Jpi=0+ T1/2s>1.000E	Jpi=3/2+ T1/2s=3.027E	Jpi=0+ T1/2s=8.489E	Jpi=0+ T1/2s>1.000E	
<b>30Cl</b>	<b>31Cl</b>	<b>32Cl</b>	<b>33Cl</b>	<b>34Cl</b>	<b>35Cl</b>	<b>36Cl</b>	<b>37Cl</b>	<b>38Cl</b>	<b>39Cl</b>
T1/2s=1.500E	Jpi=1+ T1/2s=2.980E	Jpi=1/2+ T1/2s=2.511E	Jpi=0+ T1/2s=1.526E	Jpi=3/2+ T1/2s>1.000E	Jpi=2+ T1/2s=9.499E	Jpi=3/2+ T1/2s=1.000E	Jpi=2- T1/2s=2.234E	Jpi=3/2+ T1/2s=3.336E	
<b>29S</b>	<b>30S</b>	<b>31S</b>	<b>32S</b>	<b>33S</b>	<b>34S</b>	<b>35S</b>	<b>36S</b>	<b>37S</b>	<b>38S</b>
Jpi=5/2+ T1/2s=1.870E	Jpi=0+ T1/2s=1.178E	Jpi=1/2+ T1/2s=2.572E	Jpi=0+ T1/2s=1.000E	Jpi=3/2+ T1/2s=1.000E	Jpi=0+ T1/2s=1.000E	Jpi=3/2+ T1/2s=7.561E	Jpi=0+ T1/2s=1.000E	Jpi=7/2- T1/2s=3.030E	Jpi=0+ T1/2s=1.022E
<b>28P</b>	<b>29P</b>	<b>30P</b>	<b>31P</b>	<b>32P</b>	<b>33P</b>	<b>34P</b>	<b>35P</b>	<b>36P</b>	<b>37P</b>
Jpi=3+ T1/2s=2.703E	Jpi=1/2+ T1/2s=4.140E	Jpi=1+ T1/2s=1.499E	Jpi=1/2+ T1/2s=1.000E	Jpi=1+ T1/2s=1.232E	Jpi=1/2+ T1/2s=2.189E	Jpi=1+ T1/2s=1.243E	Jpi=1/2+ T1/2s=4.730E	T1/2s=5.600E	T1/2s=2.310E
<b>27Si</b>	<b>28Si</b>	<b>29Si</b>	<b>30Si</b>	<b>31Si</b>	<b>32Si</b>	<b>33Si</b>	<b>34Si</b>	<b>35Si</b>	<b>36Si</b>
Jpi=5/2+ T1/2s=4.160E	Jpi=0+ T1/2s>1.000E	Jpi=1/2+ T1/2s>1.000E	Jpi=0+ T1/2s>1.000E	Jpi=3/2+ T1/2s=9.438E	Jpi=0+ T1/2s=5.428E	T1/2s=6.180E	Jpi=0+ T1/2s=2.770E	Jpi=0+ T1/2s=4.500E	
<b>26Al</b>	<b>27Al</b>	<b>28Al</b>	<b>29Al</b>	<b>30Al</b>	<b>31Al</b>	<b>32Al</b>	<b>33Al</b>	<b>34Al</b>	<b>35Al</b>
Jpi=5+ T1/2s=2.335E	Jpi=5/2+ T1/2s>1.000E	Jpi=3+ T1/2s=1.345E	Jpi=5/2+ T1/2s=3.936E	T1/2s=3.600E	Jpi=3/2+ T1/2s=6.440E	Jpi=1+ T1/2s=3.300E	T1/2s=6.000E	T1/2s=1.500E	



Teaching spectroscopy to the next generation of nuclear physicists...

2019



2002



Thank you  
(and thanks to Robert for years of  
mentorship!)

