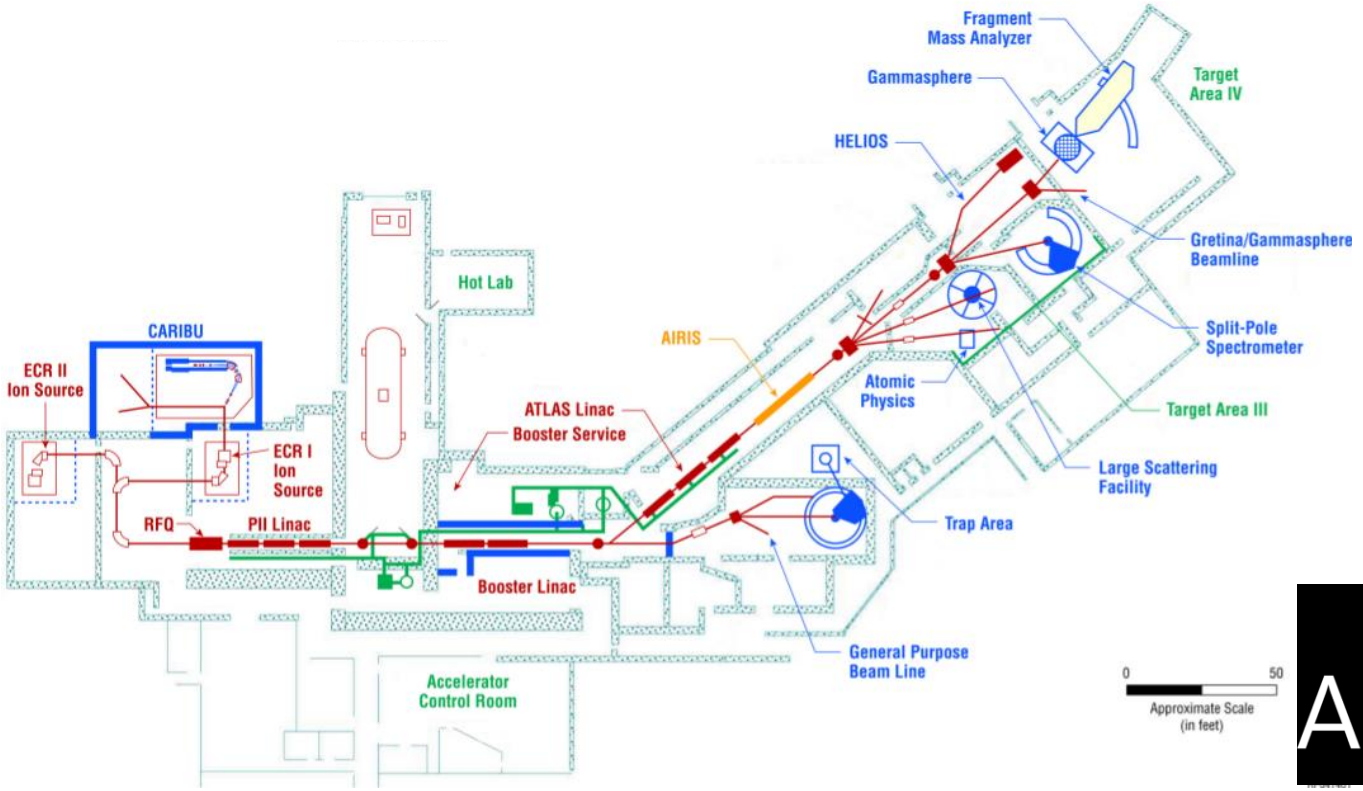
Research Opportunities with Isomer beams

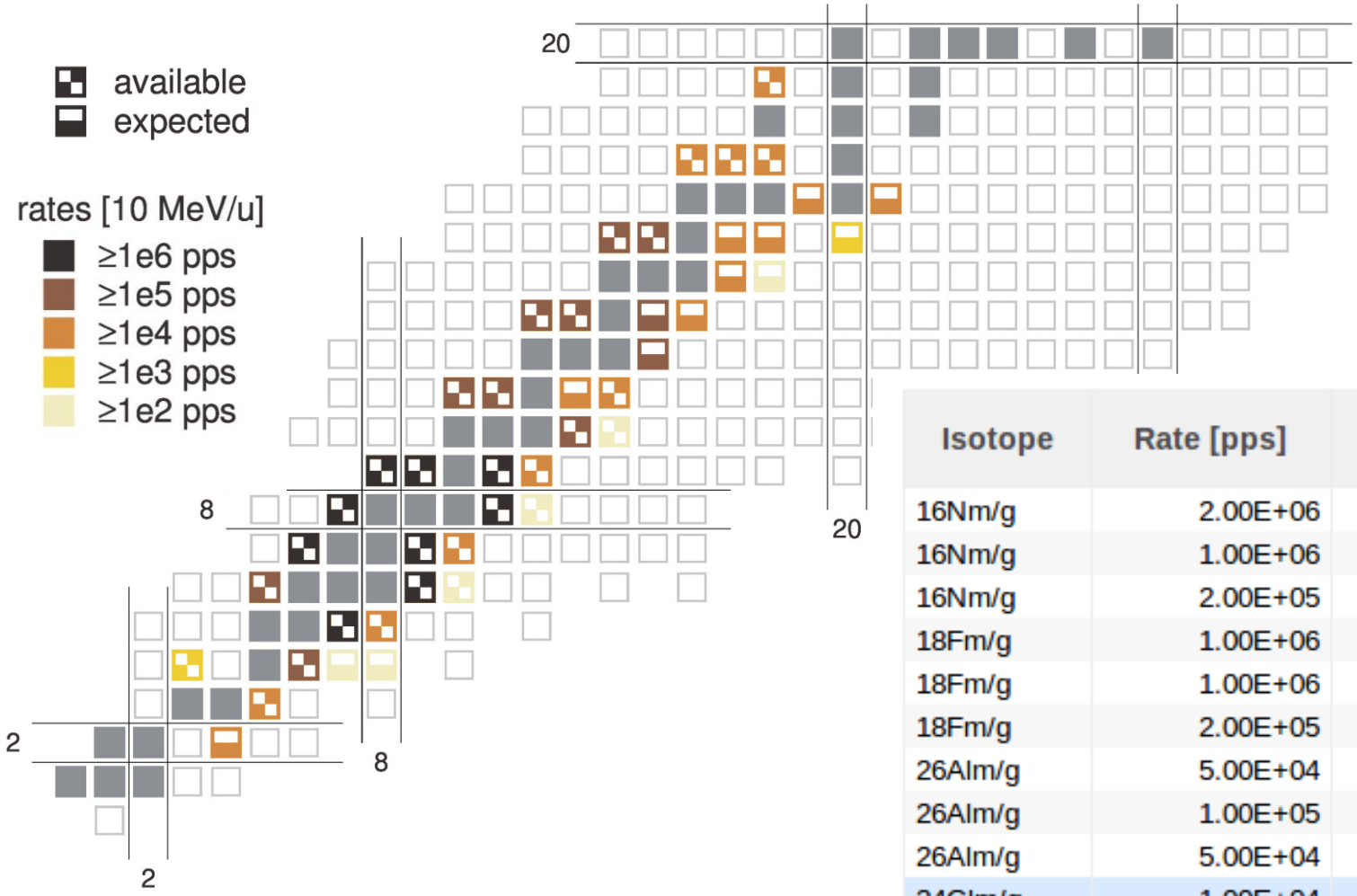
Sergio Almaraz-Calderon
Florida State University

Workshop on Nuclear Astrophysics Opportunities at ATLAS 2019



12–13 July 2019, Physics Division, Argonne National Laboratory

Available in-flight radioactive beams at ATLAS as of January 2019

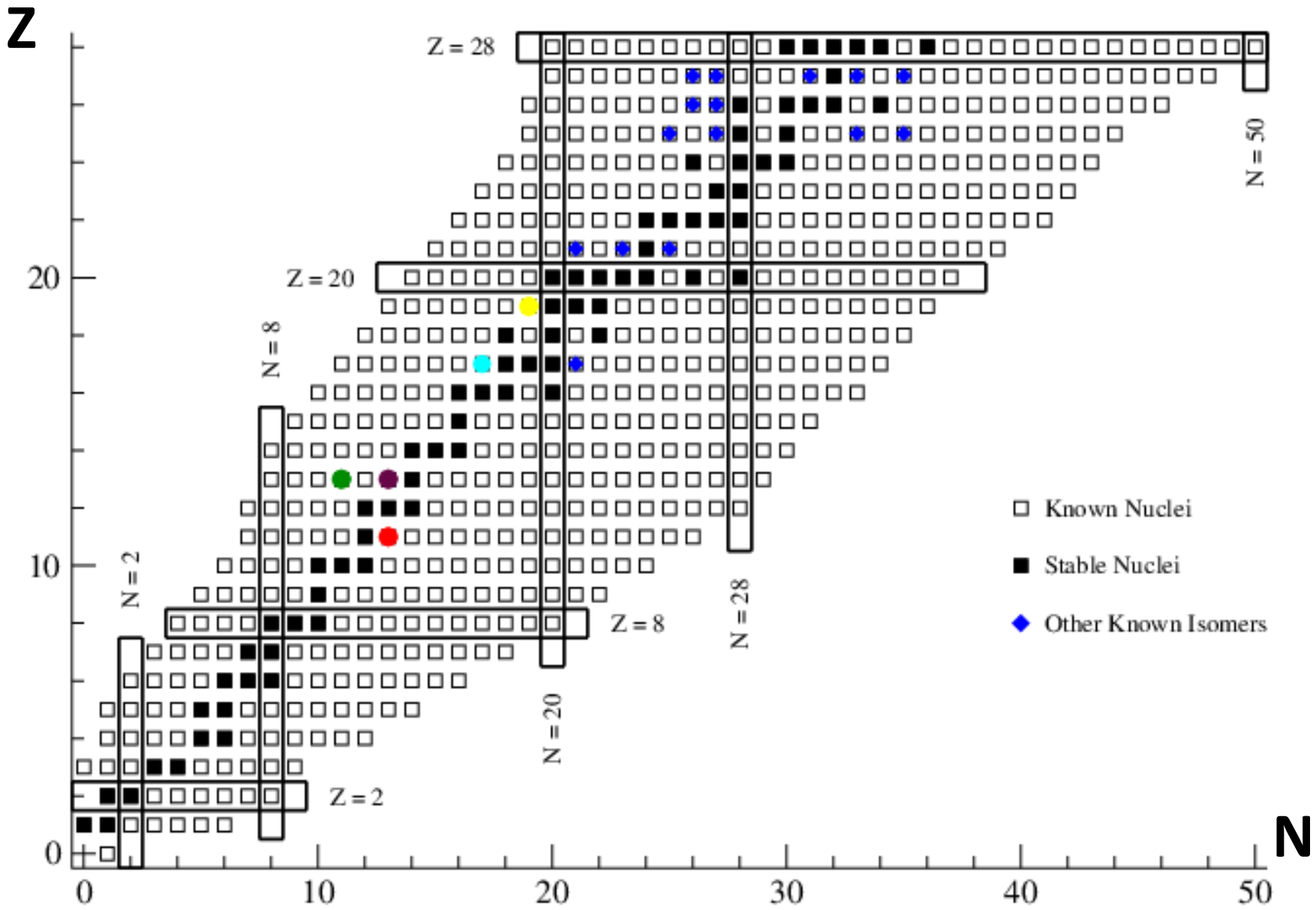


www.anl.gov/atlas/inflight-radioactive-beams

Isomeric beams:

Isotope	Rate [pps]	Energy [MeV/u]	Purity [%]	Designation
16Nm/g	2.00E+06	6	20	Available
16Nm/g	1.00E+06	10	20	Available
16Nm/g	2.00E+05	14	20	Available
18Fm/g	1.00E+06	6	20	Available
18Fm/g	1.00E+06	10	50	Available
18Fm/g	2.00E+05	14	50	Available
26Alm/g	5.00E+04	6	10	Available
26Alm/g	1.00E+05	10	20	Available
26Alm/g	5.00E+04	14	20	Available
34Clm/g	1.00E+04	6	2	Available
34Clm/g	2.00E+04	10	4	Available
34Clm/g	1.00E+04	14	4	Expected

Isomers $Z<28$ and $t_{1/2}>10$ ms



Isomers $Z<28$ and $t_{1/2}>10$ ms

Ground and isomeric state information for $^{26}_{13}Al$

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	5+	-12.2101	$7.17\times10^{+05}$ y *24*	ε : 100.00 %
0.2283	0+	-11.9818	6.3460 s *8*	ε : 100.00 %

Ground and isomeric state information for $^{38}_{19}K$

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	3+	-28.8007	7.636 m *18*	ε : 100.00 %
0.1304	0+	-28.6703	924.3 ms *3*	ε : 99.97 % IT : 0.03 %

Ground and isomeric state information for $^{24}_{13}Al$

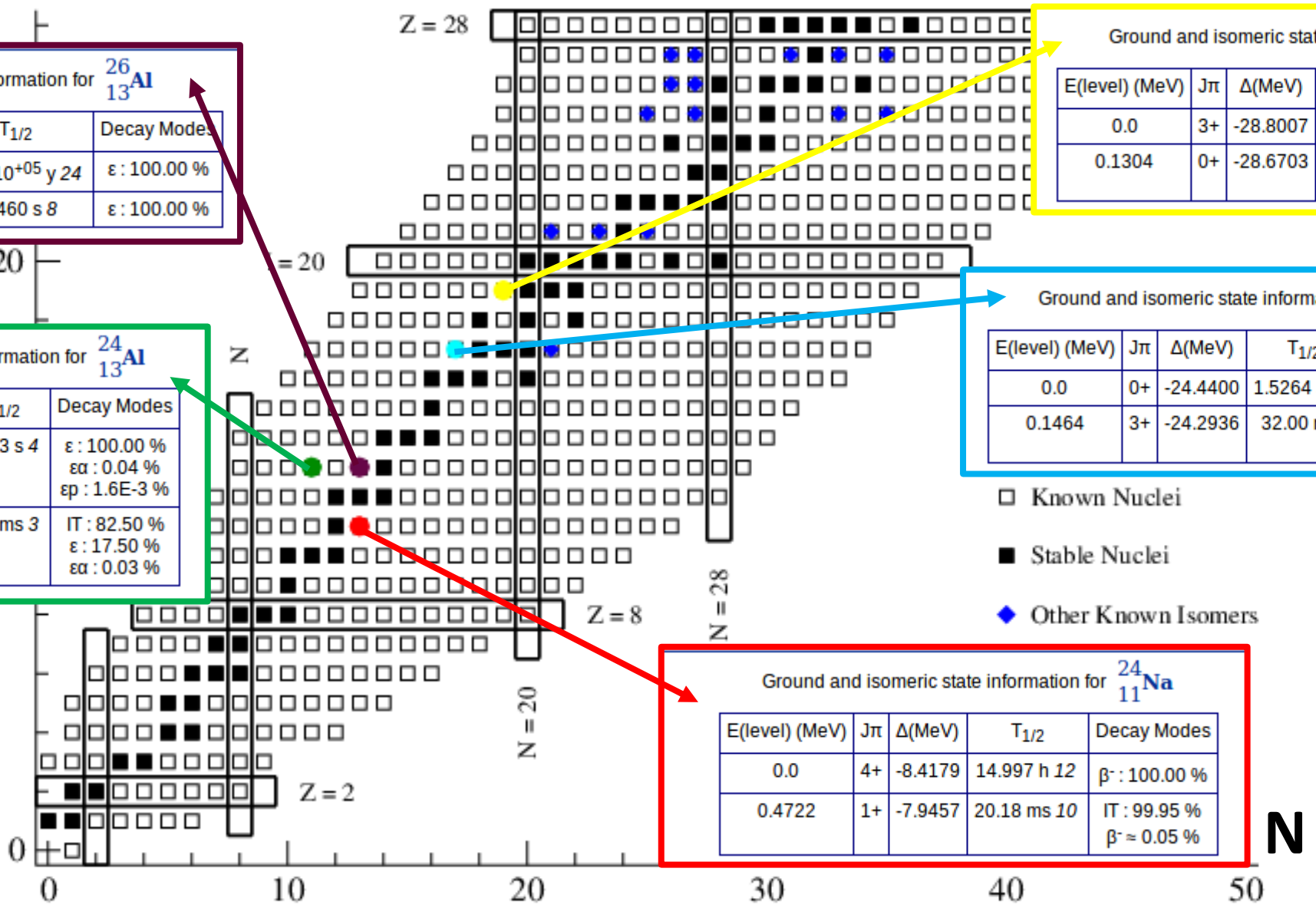
E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	4+	-0.0488	2.053 s *4*	ε : 100.00 % εα : 0.04 % εp : 1.6E-3 %
0.4258	1+	0.3769	130 ms *3*	IT : 82.50 % ε : 17.50 % εα : 0.03 %

Ground and isomeric state information for $^{34}_{17}Cl$

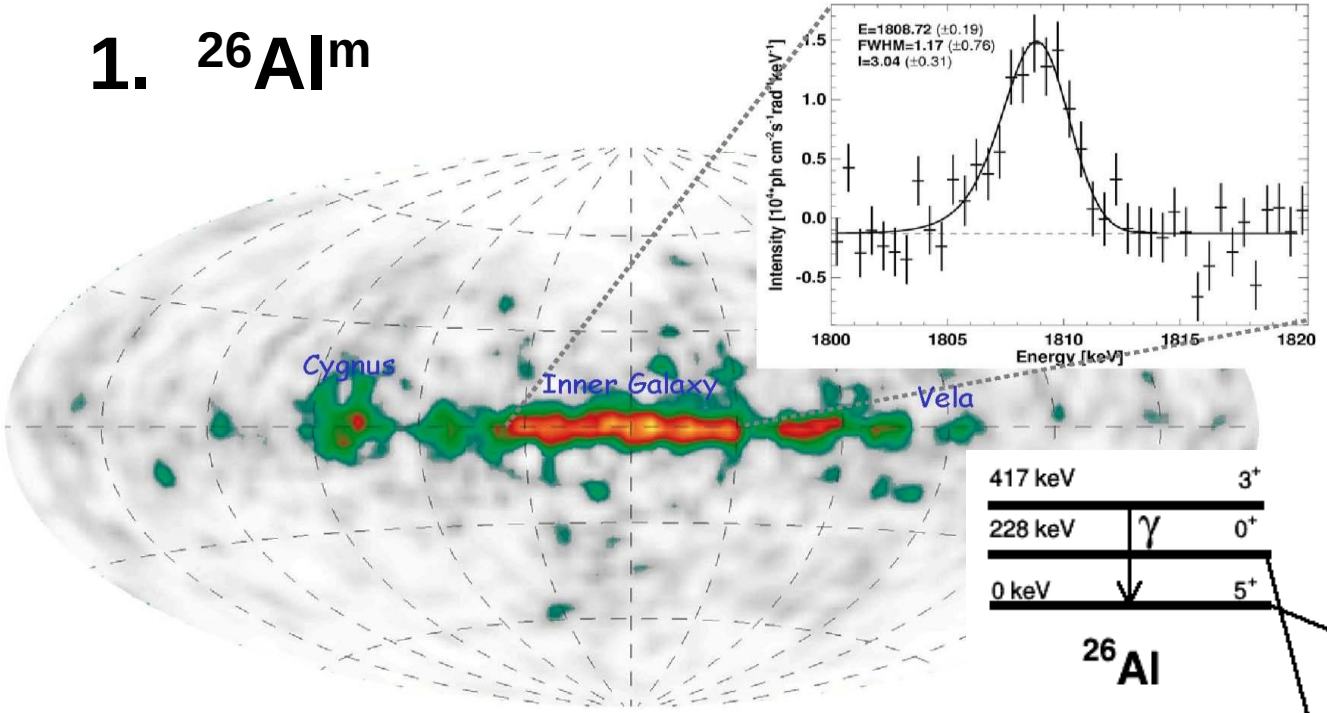
E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	0+	-24.4400	1.5264 s *14*	ε : 100.00 %
0.1464	3+	-24.2936	32.00 m *4*	ε : 55.40 % IT : 44.60 %

Ground and isomeric state information for $^{24}_{11}Na$

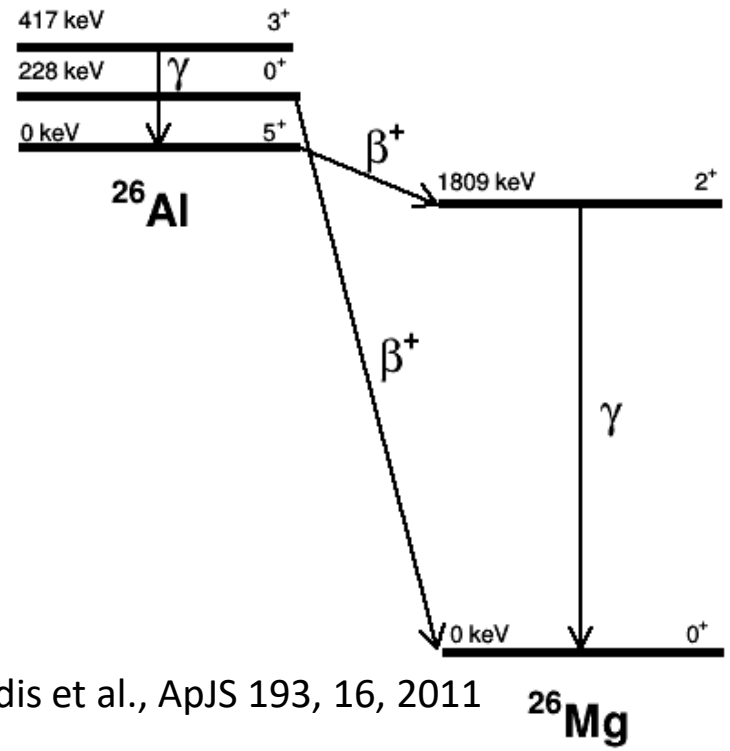
E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	4+	-8.4179	14.997 h *12*	β⁻ : 100.00 %
0.4722	1+	-7.9457	20.18 ms *10*	IT : 99.95 % β⁻ ≈ 0.05 %

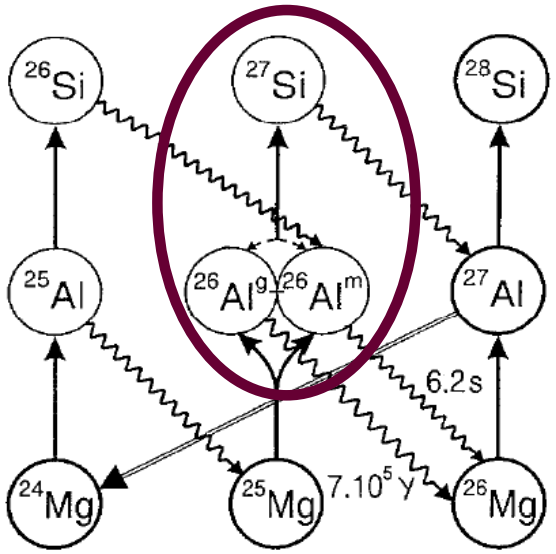


1. $^{26}Al^{m}$



Diehl et al, AA 298, 445 (1995), Nature 439, 45 (2006)





N. Prantzos et al., Phys. Rep. 267, 1 (1996)

$$^{26}Al^{m}(d,p)^{27}Al \rightarrow {}^{26}Al^{m}(p,\gamma)^{27}Si$$

Mirror symmetry $^{27}Al/^{27}Si$

C. Iliadis et al., ApJS 193, 16, 2011

Ground and isomeric state information for $^{26}_{13}Al$

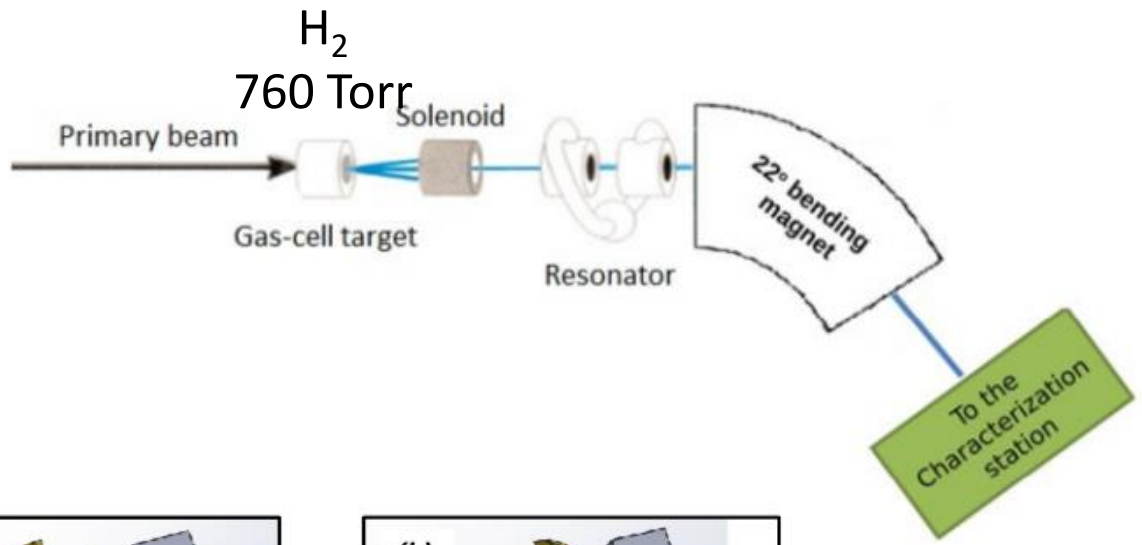
E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	5+	-12.2101	$7.17\times10^{+05}$ y *24*	ε : 100.00 %
0.2283	0+	-11.9818	6.3460 s *8*	ε : 100.00 %

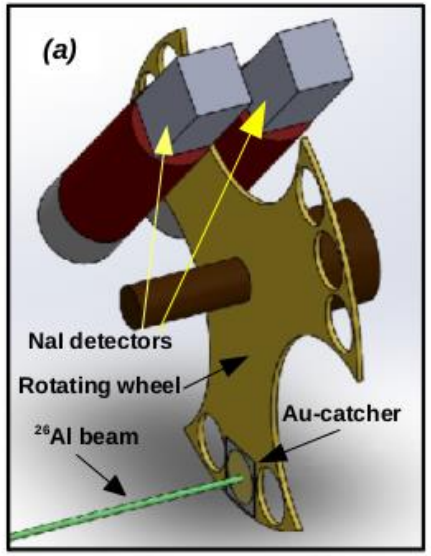
1. $^{26}Al^{m}$

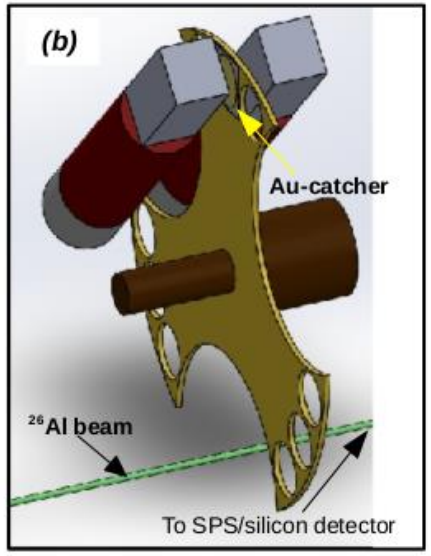
In-flight production of $^{26}Al^{m}$

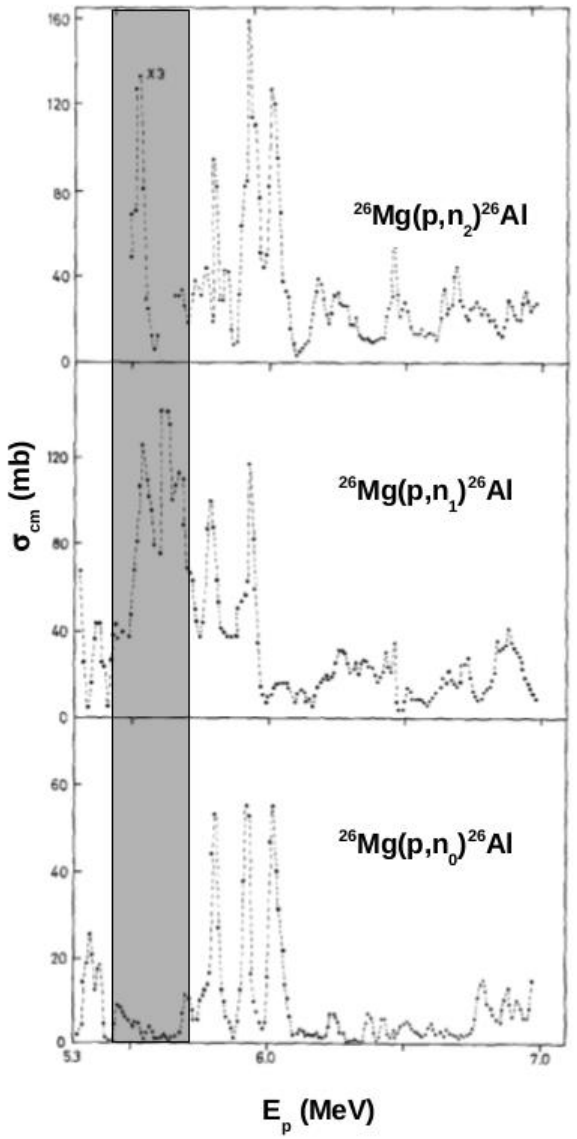
$^{26}Mg(p,n)^{26}Al$

^{26}Mg
158.5 MeV





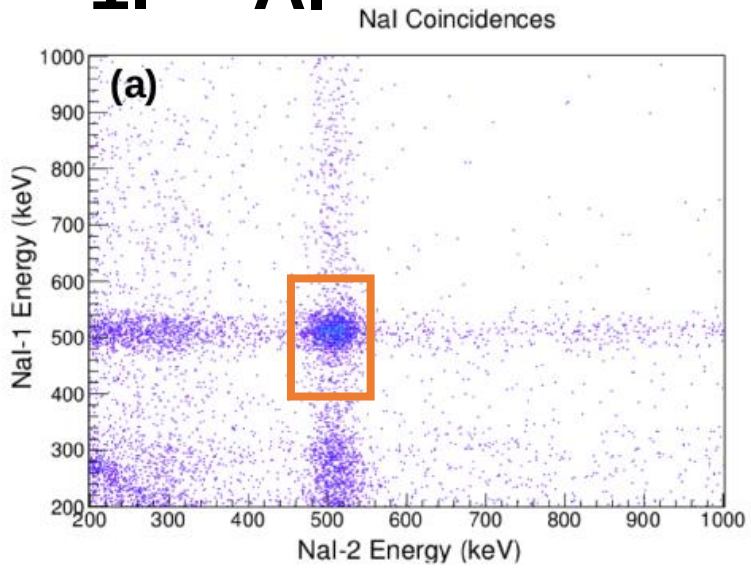


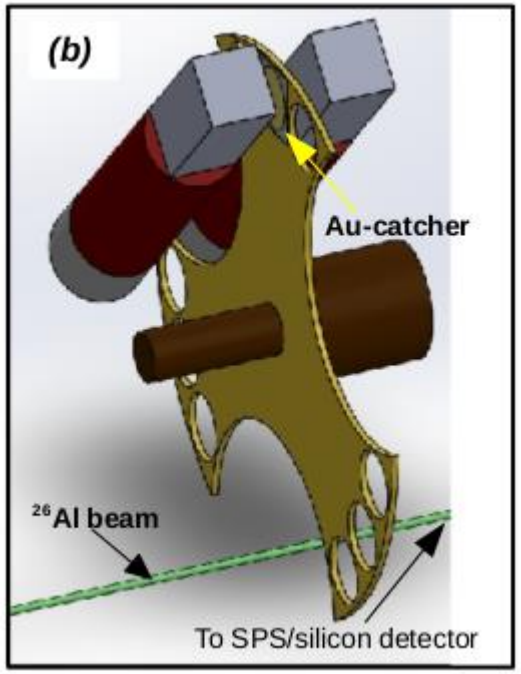


Doukellis et al., NPA 467, 511 (1987)

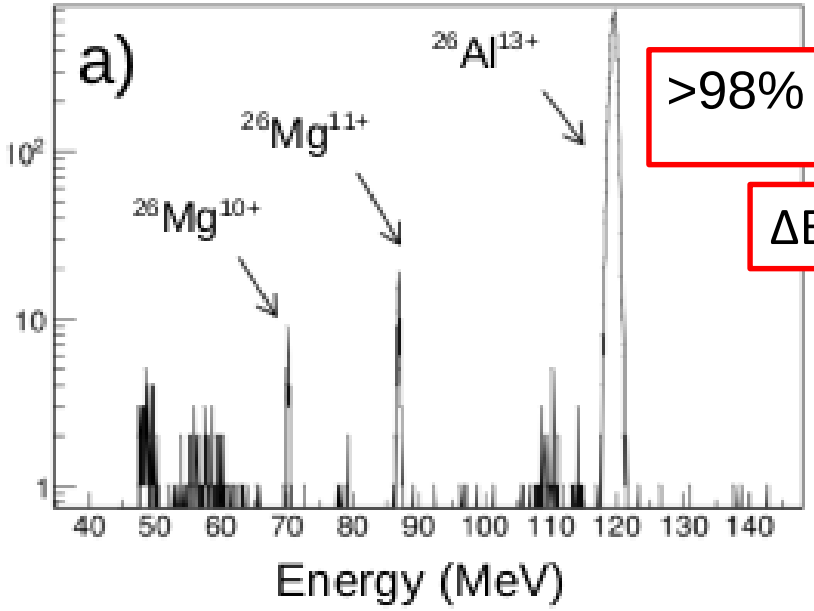
1. $^{26}Al^{m}$

"High quality" $^{26}Al^{m}$ beam



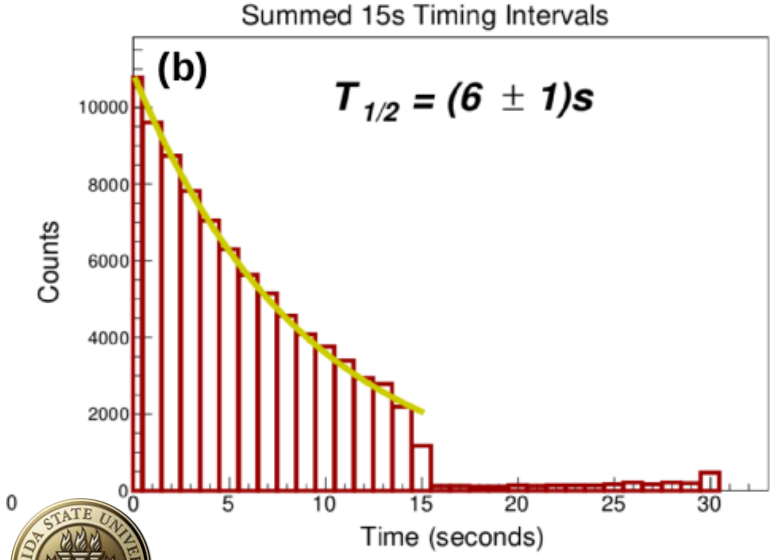


120 MeV ^{26}Al beam



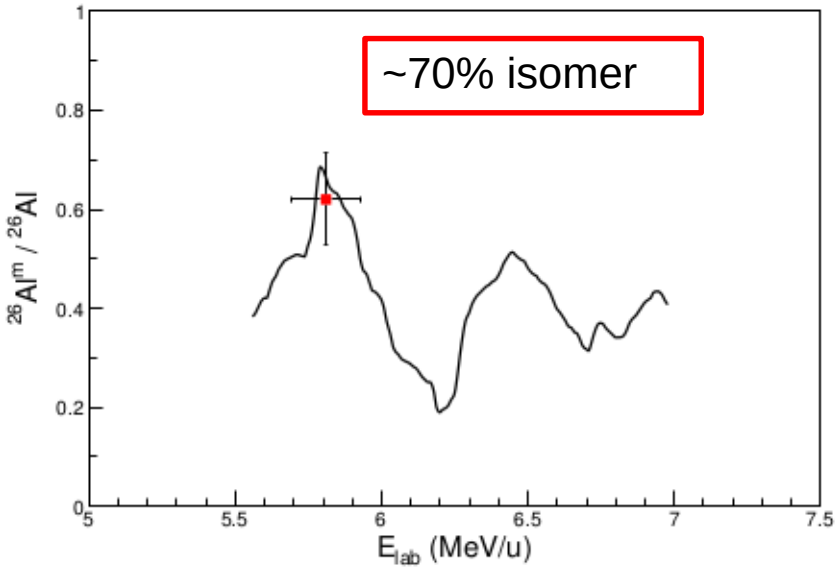
>98% purity

ΔE~1%



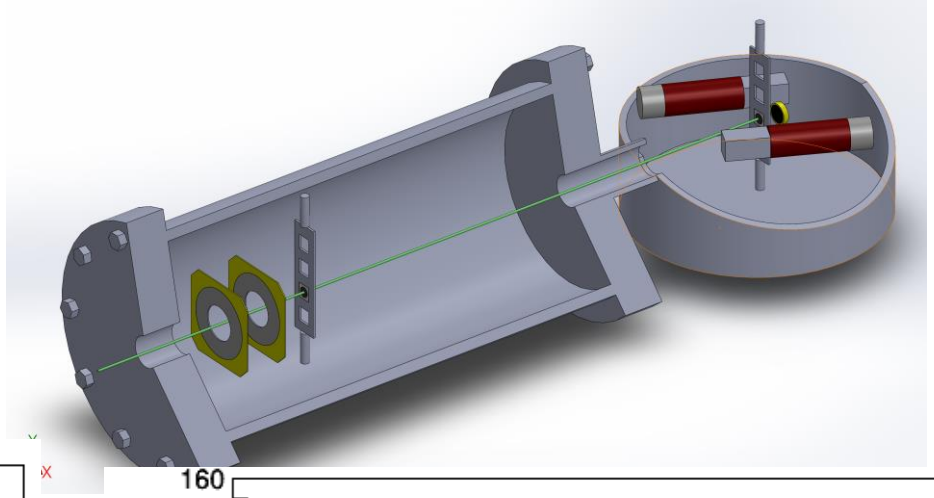
I ~ 2.5x10^{5} pps

BWA, SAC, KER, et al, NIMA 899, 6 (2018)

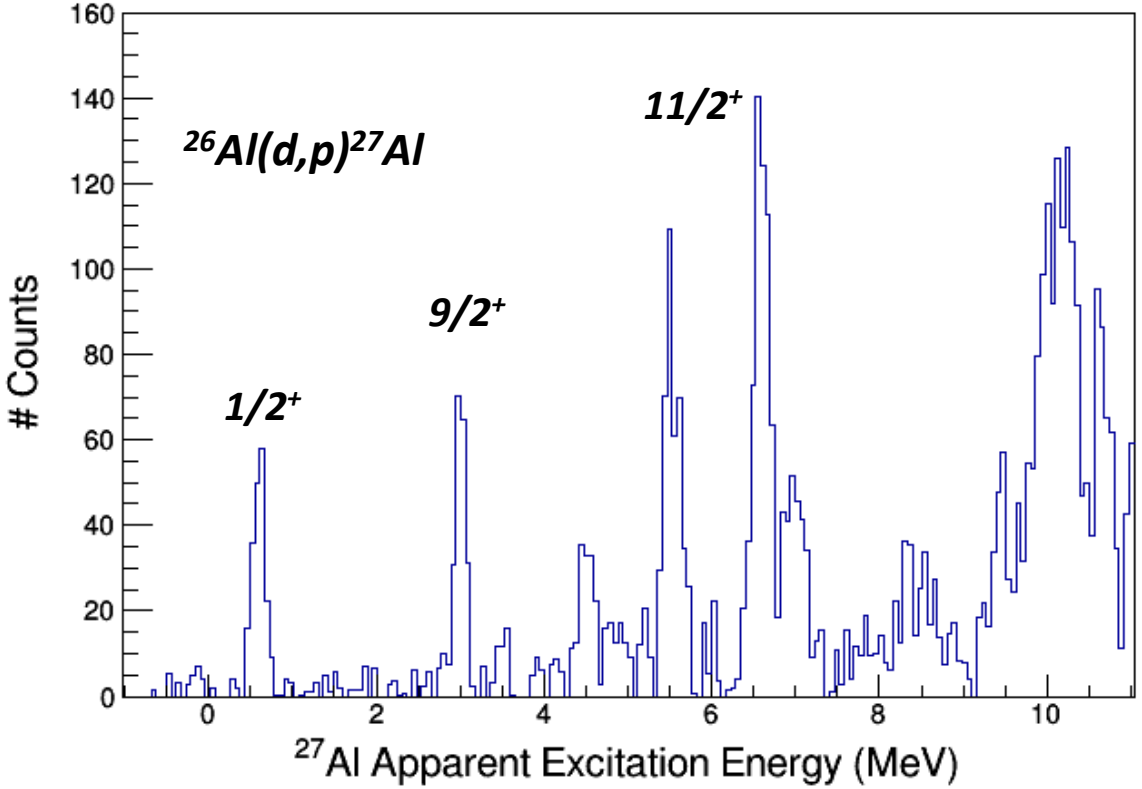


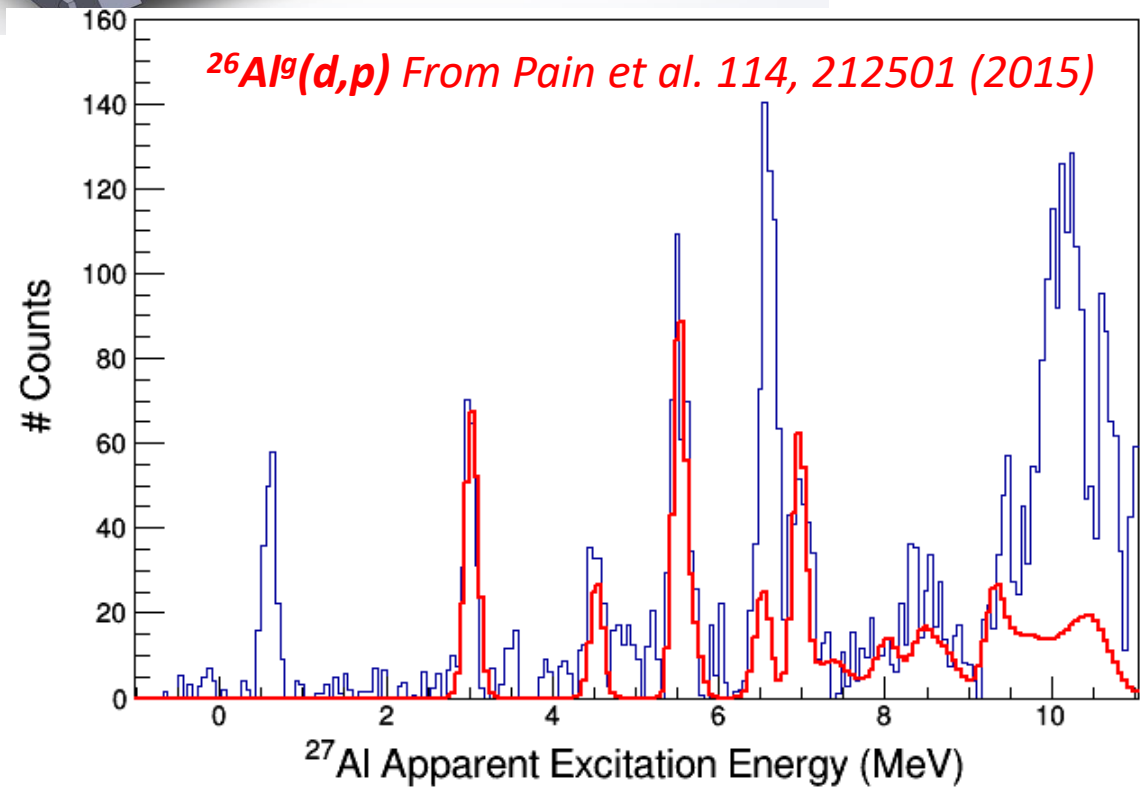
1. $^{26}Al^{m}$

Study of the $^{26}Al^{m}(d,p)$ reaction



θ_{cm} ~ 6° – 12°

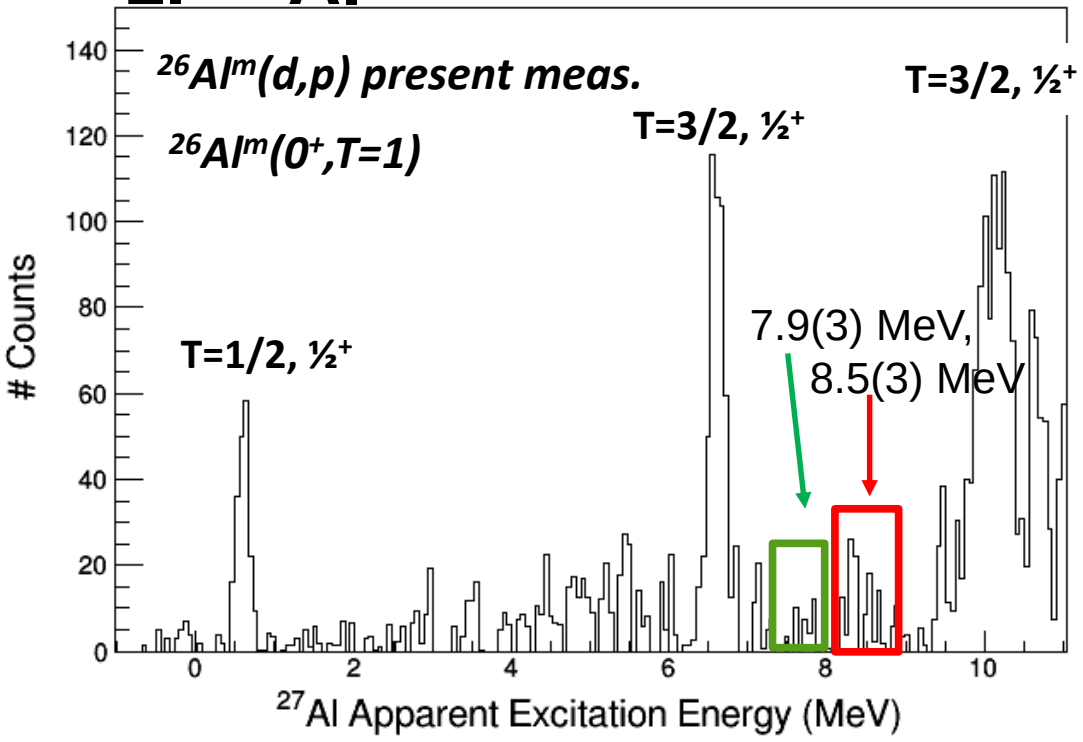


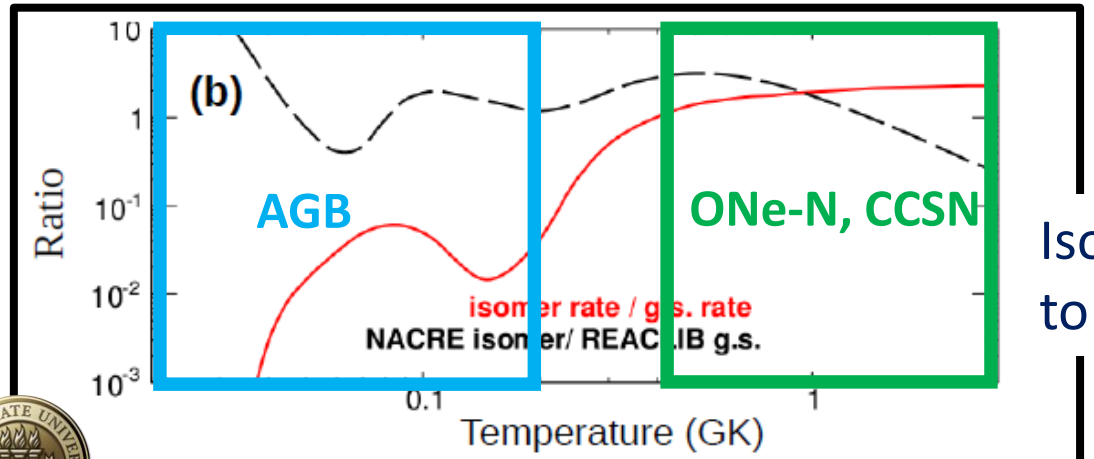


SAC, K.E Rehm et al., PRL 119, 072701 (2017)

Astrophysical Implications

1. $^{26}Al^m$



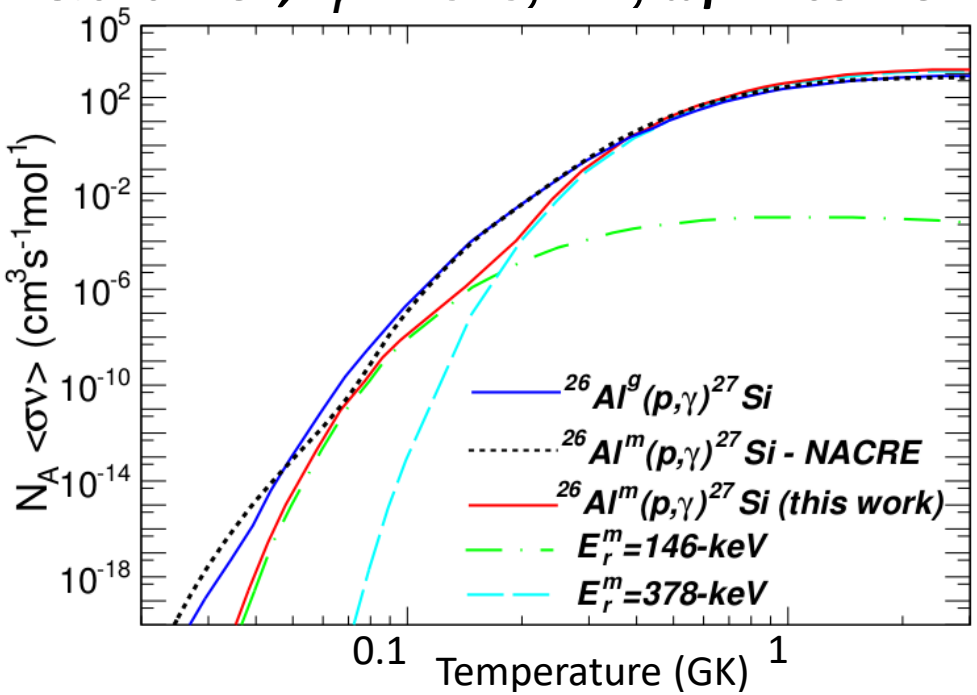


SF ≤ 0.025

$^{26}Al^m(p,\gamma)^{27}Si$

$E_x(^{27}Si) = 7.838$ MeV, $E_r^m = 146$ keV, $l=2$, $\omega\gamma \leq 0.03$ μeV

$E_x(^{27}Si) = 8.070$ MeV, $E_r^m = 378$, $l=1$, $\omega\gamma \leq 165$ meV



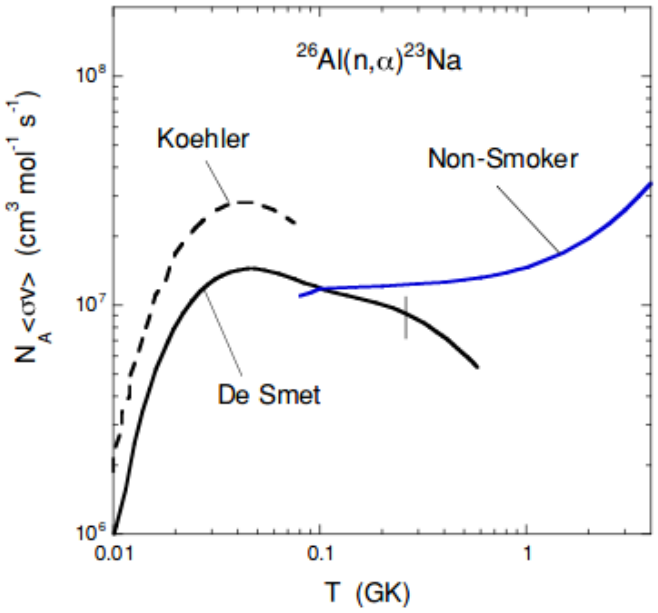
Isomer contribution is very different than g.s. contribution to the astrophysical reaction rate!

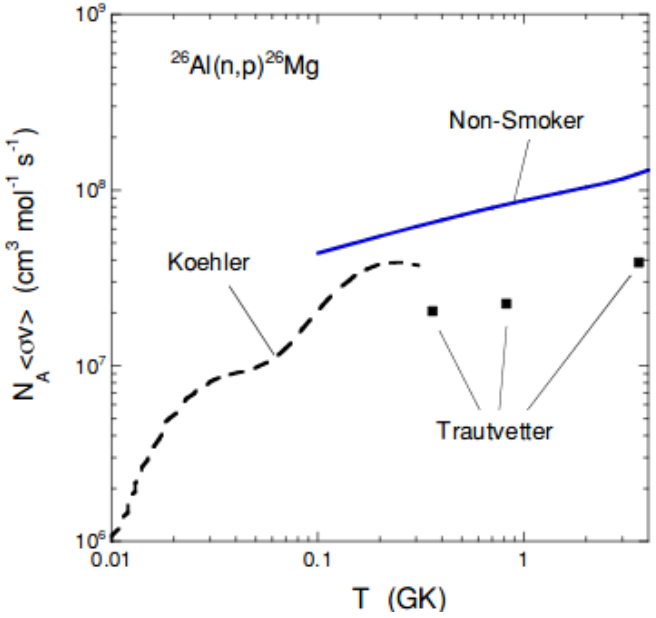
SAC, KER et al., PRL 119, 072701 (2017)

1. $^{26}Al^{m}$

What else can we do with a $^{26}Al^{m}$ beam?

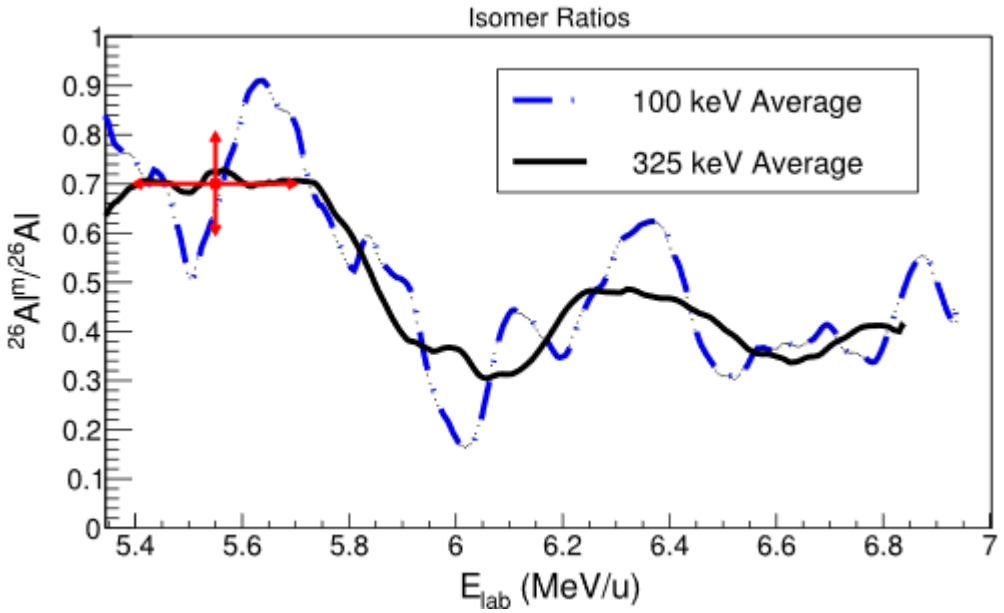
$^{26}Al(n,p)^{26}Mg$ and $^{26}Al(n,\alpha)^{23}Na$





"… It is currently difficult to estimate rate uncertainties, and new measurements are urgently needed."

C. Iliadis et al., AJSS 193, 16 (2011)



Populate resonances in ^{27}Al and look at their charge-particle decay

$$^{26}Al^{m/g}(d,p)^{27}Al \rightarrow p,\alpha$$

2. $^{34}Cl^{m}$

Astrophysical reaction of interest: $^{34}Cl^{m/g}(p,\gamma)^{35}Ar$

Ground and isomeric state information for $^{34}_{17}Cl$

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	0+	-24.4400	1.5264 s *14*	ε : 100.00 %
0.1464	3+	-24.2936	32.00 m *4*	ε : 55.40 % IT : 44.60 %

- Relevant in novae nucleosynthesis and rp-process nucleosynthesis.
- Uncertainties in these rates translate to uncertainties in ^{34}S production in novae relevant for classification of presolar grains.

PHYSICAL REVIEW C **91**, 015803 (2015)

Discovery of $^{34g,m}Cl(p,\gamma)^{35}Ar$ resonances activated at classical nova temperatures

C. Fry,[1,2,*] C. Wrede,[1,2,†] S. Bishop,[3] B. A. Brown,[1,2] A. A. Chen,[4] T. Faestermann,[3] R. Hertenberger,[5] A. Parikh,[6,7]

PHYSICAL REVIEW C **87**, 034621 (2013)

Nuclear model calculations of charged-particle-induced reaction cross section data for the production of the radiohalogen $^{34}Cl^{m}$

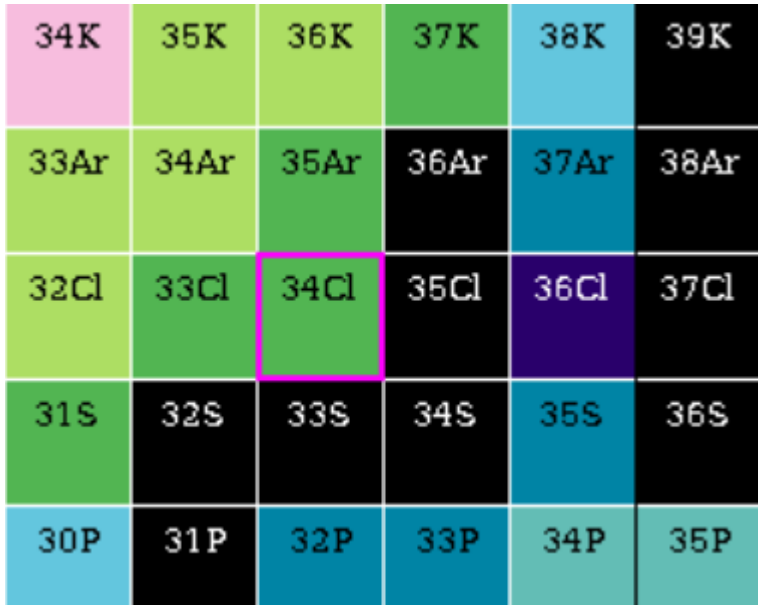
W.A. Richter and B.A. Brown, **Shell-model studies of the $^{34g,m}Cl(p,\gamma)^{35}Ar$ reaction rates**, IOP Conf. Ser., JoP 966, 01226 (2018)

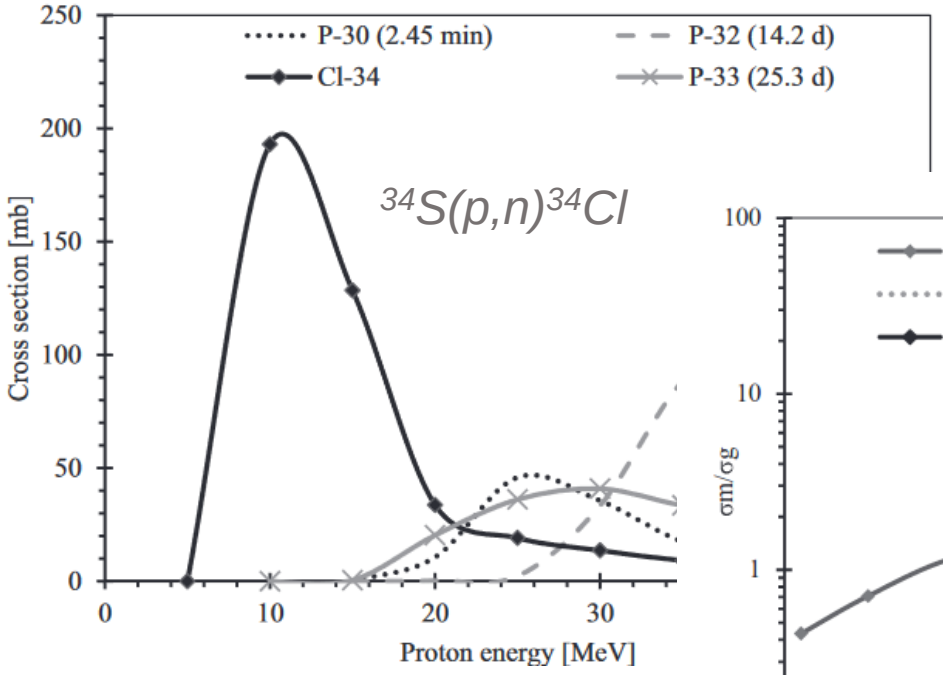
2. $^{34}Cl^{m}$

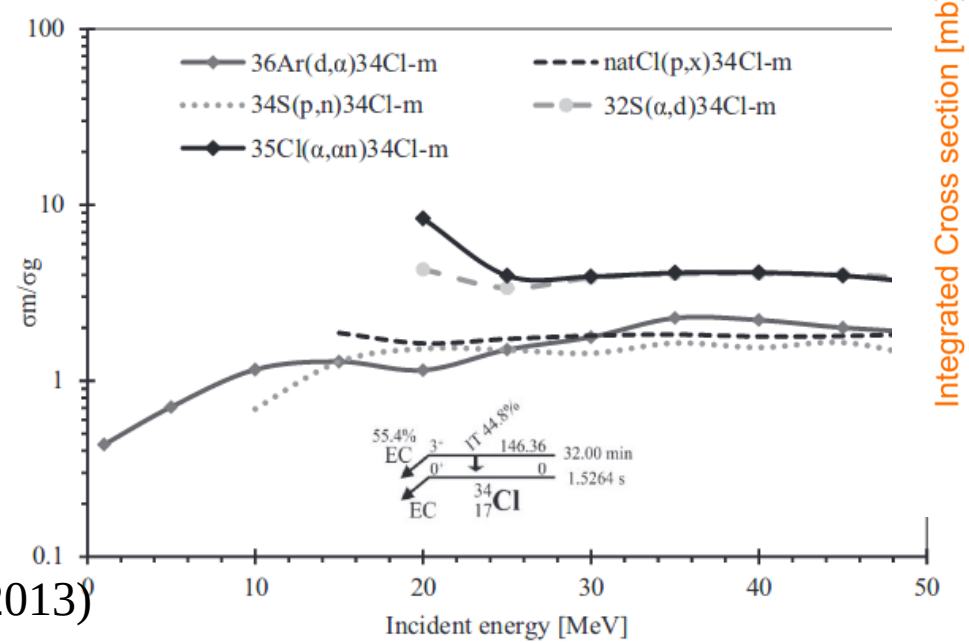
Astrophysical reaction of interest:

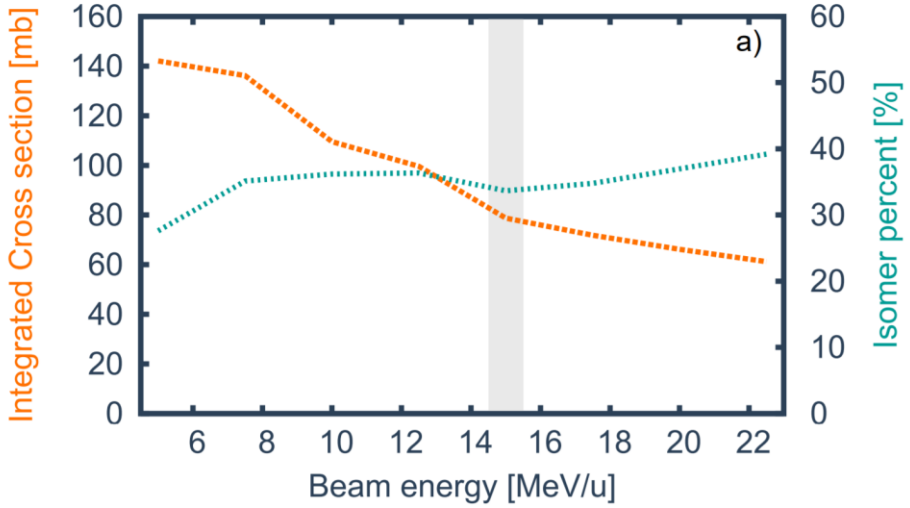
$^{34}Cl^{m/g}(p,\gamma)^{35}Ar$

Study $^{34}Cl^{m}(d,p)^{35}Cl$ **→ mirror symmetry** $^{35}Ar/^{35}Cl$









$^{33}S(d,n)^{34}Cl$

C.R.Hoffman Argonne Proposal

Bakhtiari et al, PRC87, 034621 (2013)

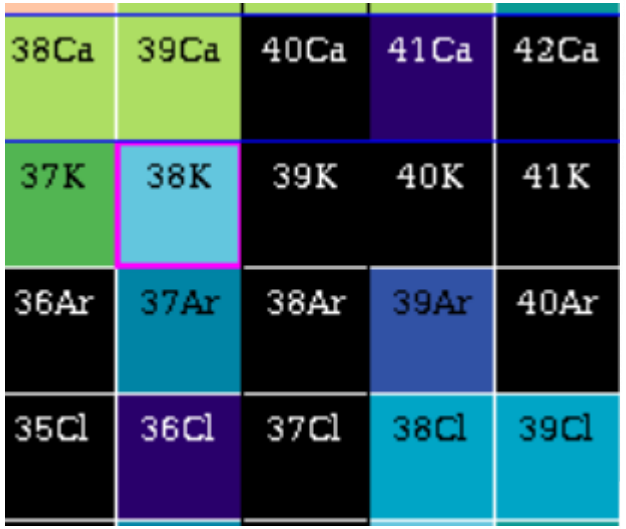
3. $^{38}K^{m}$

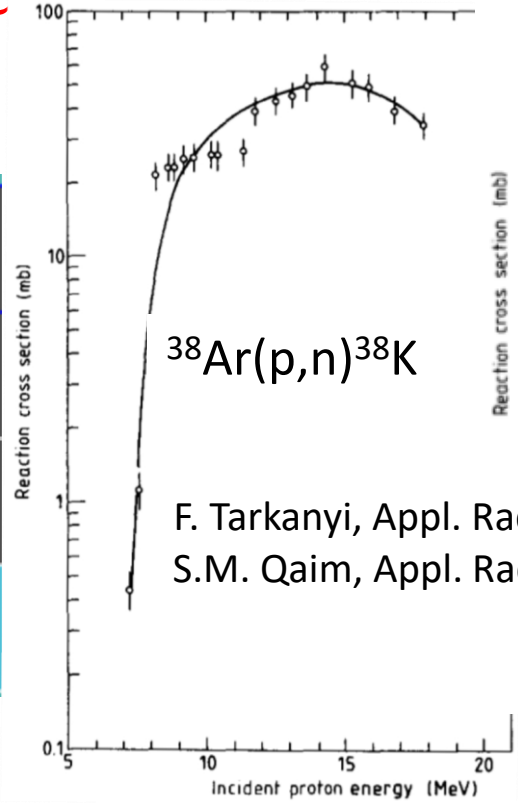
Astrophysical reaction of interest:

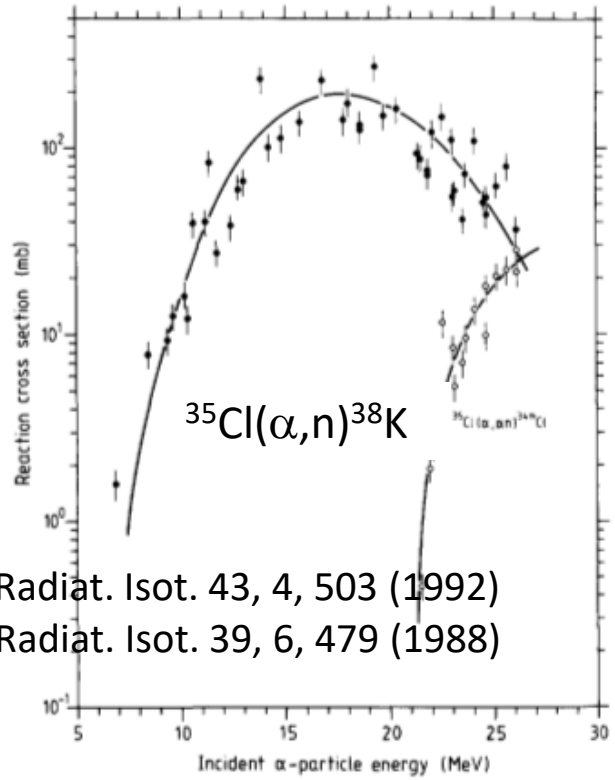
$^{38}K^{m/g}(p,\gamma)^{39}Ca$

- End point of Nova nucleosynthesis
- Strong disagreement between the observations of Ar and Ca abundances in nova ejecta and model predictions.

$^{38m}K(d,p)^{39}K$







F. Tarkanyi, Appl. Radiat. Isot. 43, 4, 503 (1992)
S.M. Qaim, Appl. Radiat. Isot. 39, 6, 479 (1988)

Ground and isomeric state information for $^{38}_{19}K$

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	3+	-28.8007	7.636 m 18	ε : 100.00 %
0.1304	0+	-28.6703	924.3 ms 3	ε : 99.97 % IT : 0.03 %

PHYSICAL REVIEW ACCELERATORS AND BEAMS **21,** 121301 (2018)

^{38}K isomer production via fast fragmentation

K. A. Chipps,[1] R. L. Kozub,[2] C. Sumithrarachchi,[3] T. Ginter,[3] T. Baumann,[3] K. Lund,[3] A. Lapierre,[3] A. Villari,[3] F. Montes,[4,3] S. Jin,[4,3,5] K. Schmidt,[4,3] S. Ayoub,[4,3] S. D. Pain,[1] and D. Blankstein[6]

4. $^{24}Al^{m}$

Astrophysical reaction of interest: $^{24}Al^{m/g}(p,\gamma)^{25}Si$

Relevant in rp-process, variations in the proton capture rate could lead to variations in the abundance of several Si, S and Ar isotopes during novae nucleosynthesis.

Ground and isomeric state information for $^{24}_{13}Al$

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	4+	-0.0488	2.053 s *4*	ε : 100.00 % εα : 0.04 % εp : 1.6E-3 %
0.4258	1+	0.3769	130 ms *3*	IT : 82.50 % ε : 17.50 % εα : 0.03 %

PHYSICAL REVIEW C **97**, 054307 (2018)

Measurement of key resonances for the $^{24}Al(p,\gamma)^{25}Si$ reaction rate using in-beam γ-ray spectroscopy

B. Longfellow,[1,2] A. Gade,[1,2,3] B. A. Brown,[1,2] W. A. Richter,[4,5] D. Bazin,[1] P. C. Bender,[1,*] M. Bowry,[1,†] B. Elman,[1,2] E. Lunderberg,[1,2] D. Weisshaar,[1] and S. J. Williams[1,‡]

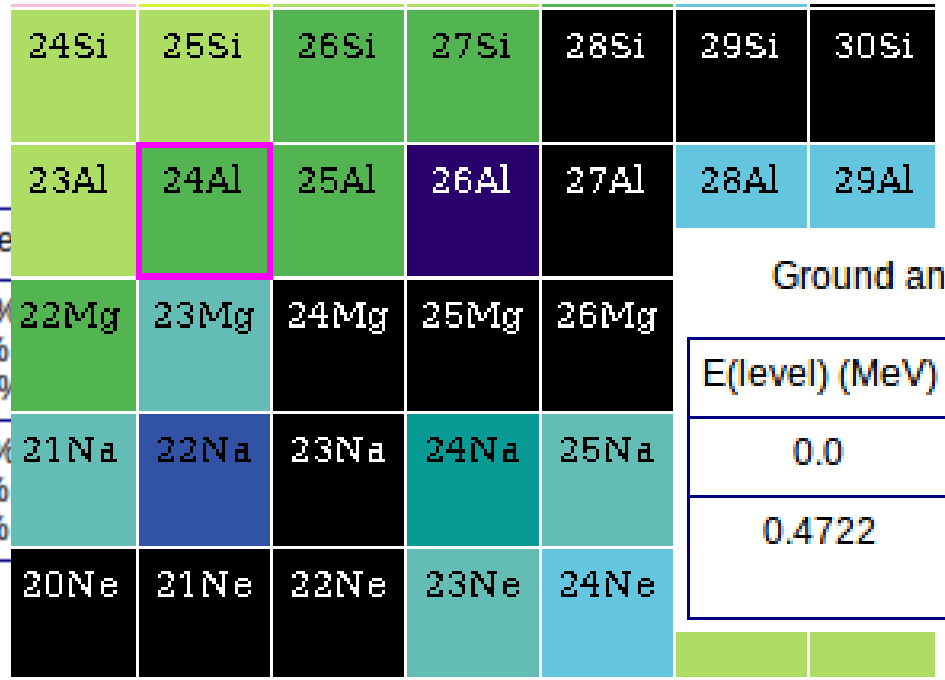
^{24}Al production: $^{24}Mg(p,n)^{24}Al$, Q = -14.667 MeV

Difficult! … but we could look at the mirror system

5. $^{24}Na^{m}$

Ground and isomeric state information for $^{24}_{13}Al$

E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Mode
0.0	4+	-0.0488	2.053 s *4*	ε : 100.00 % εα : 0.04 % εp : 1.6E-3 %
0.4258	1+	0.3769	130 ms *3*	IT : 82.50 % ε : 17.50 % εα : 0.03 %



Ground and isomeric state information for $^{24}_{11}Na$

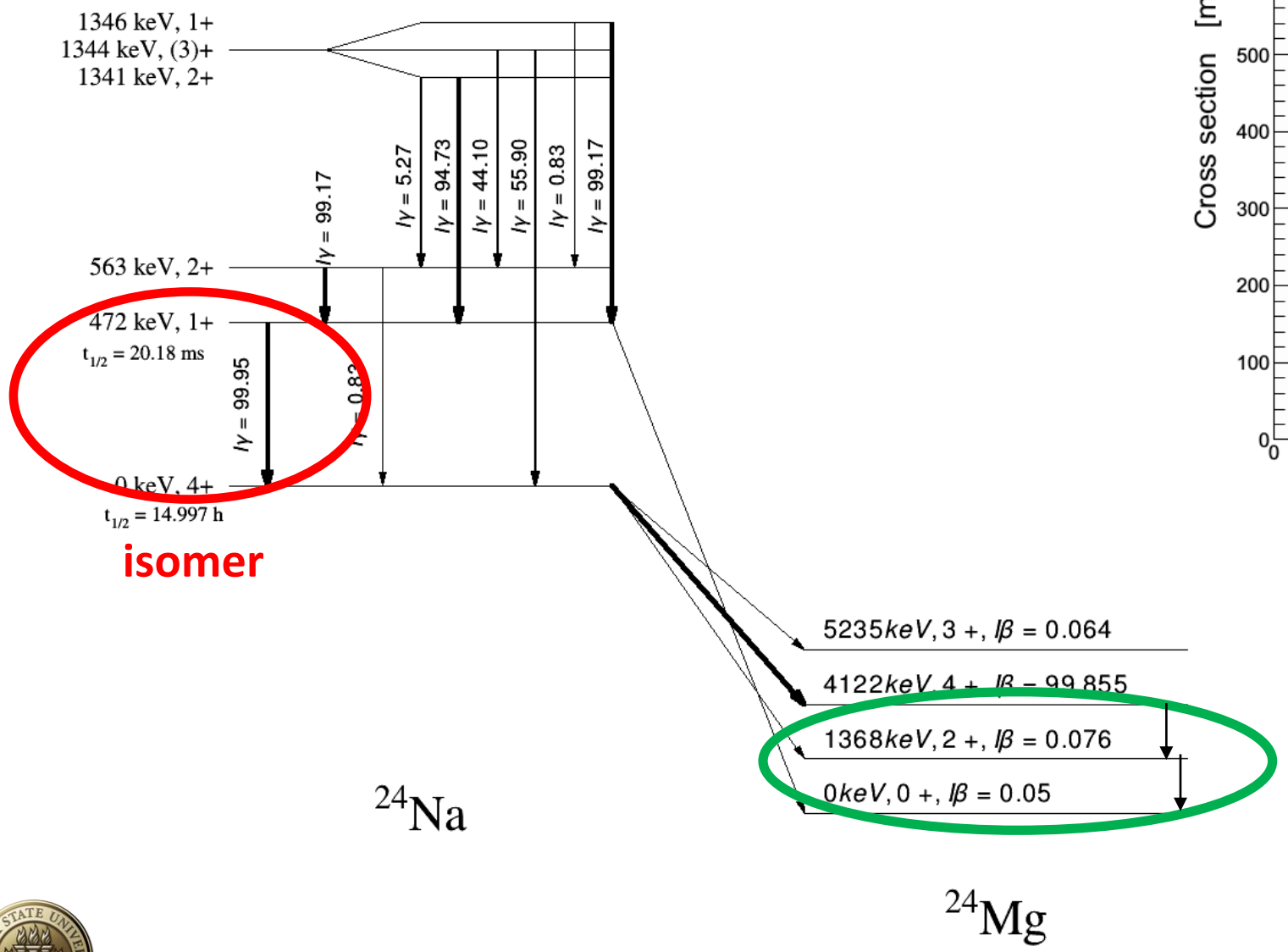
E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
0.0	4+	-8.4179	14.997 h *12*	β^- : 100.00 %
0.4722	1+	-7.9457	20.18 ms *10*	IT : 99.95 % β^- ≈ 0.05 %

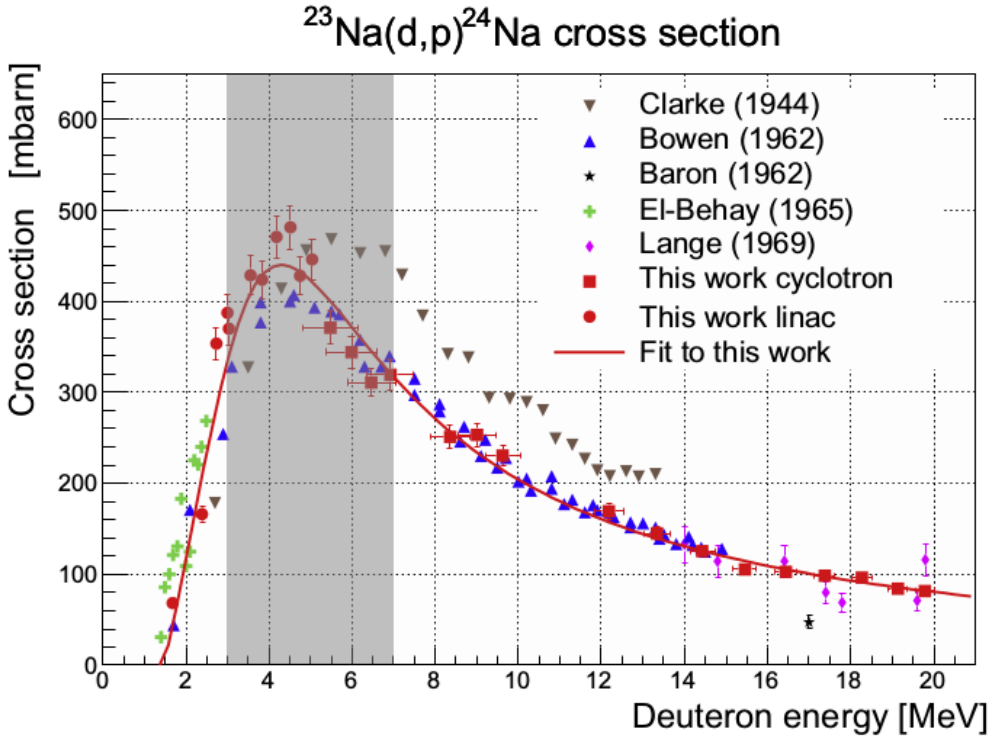
Mirror systems: $^{24}Na/^{24}Al$ and $^{25}Si/^{25}Na$

Easier beam → $^{23}Na(d,p)^{24}Na$, Q = 4.7 MeV

$^{24}Na^{m/g}(d,p)^{25}Na$ to study $^{24}Al^{m/g}(p,\gamma)^{25}Si$

5. $^{24}Na^{m}$

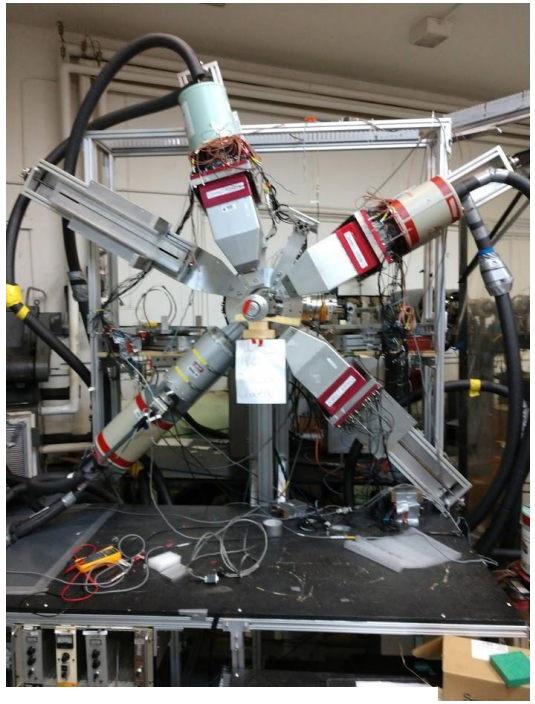


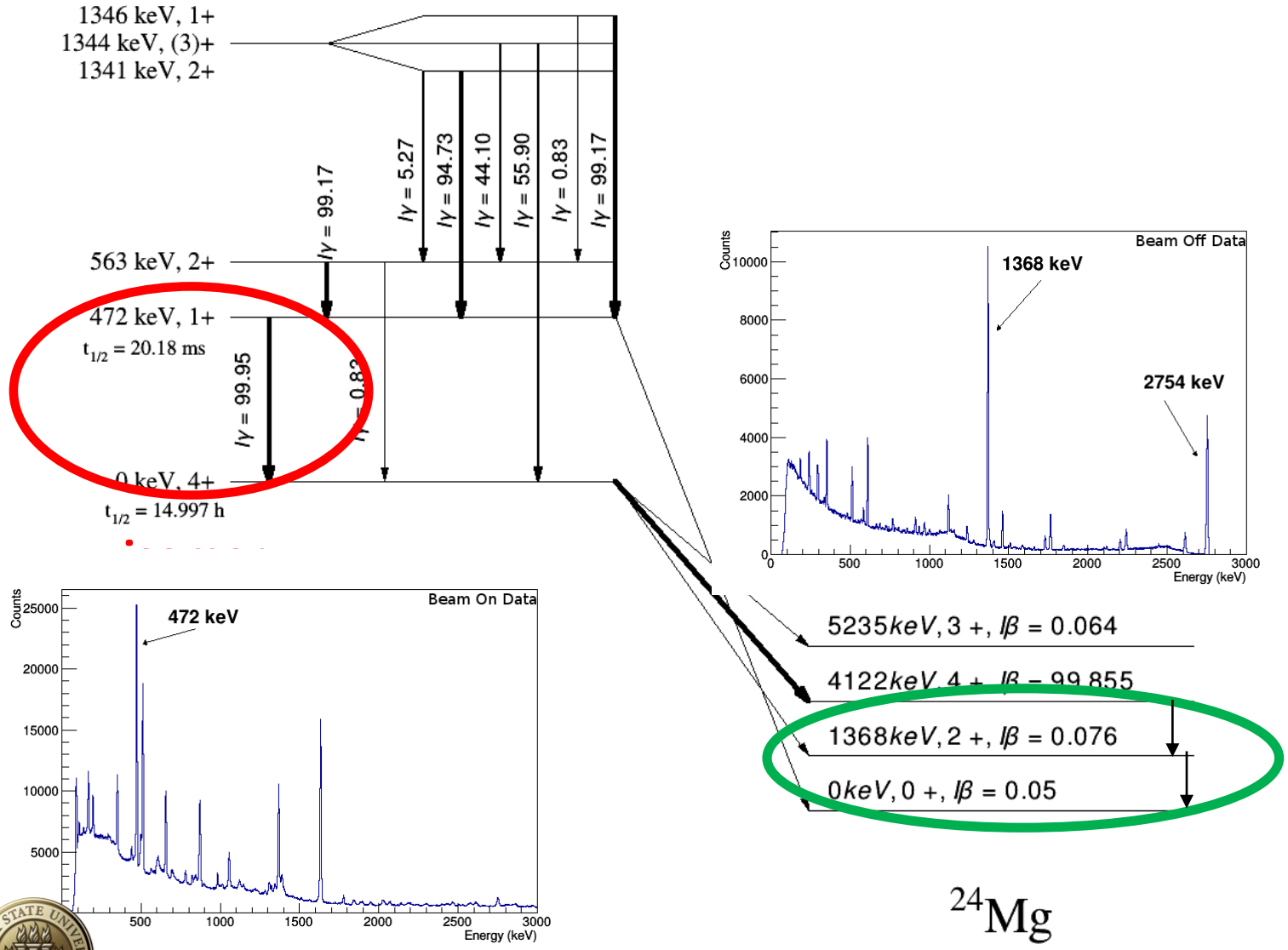


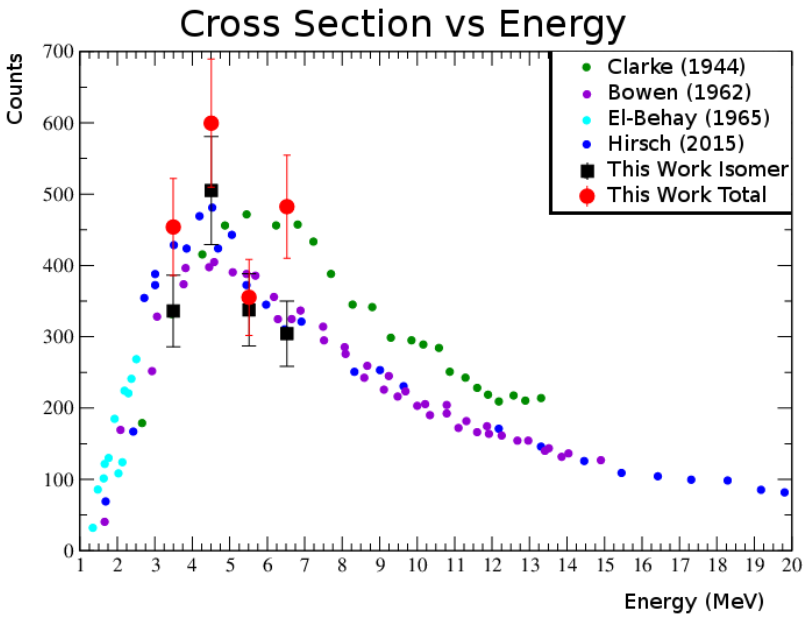
T.Y.Hirsh et al, NIM B 362:29–33, 2015

5. $^{24}Na^{m}$

Deuterium beam bombarding a NaCl target → $^{23}Na(d,p)^{24}Na$ @ FSU







Summary

- Isomer beams can give new insight to nuclear astrophysics (.. And nuclear structure)
- In-flight production is an ideal way to make isomer beams
- Production energy can be tuned
- Production cross sections need to be studied
- RAISOR can provide high quality beams
- Charge particle experiments can be done now … (d,p) – type reactions
- Higher intensities are needed to measure other reaction channels (n,γ)

Thank you