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Precision measurements of ^{20}Na, ^{24}Al, ^{28}P, ^{32}Cl, and ^{36}K for the *rp* process

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NIC XI, Heidelberg, Germany
July 22nd, 2010

Collaboration

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Outline

- Motivation: explosive hydrogen burning
- Targets: ion implanted at CENPA
- Experiment: (^{3}He,*t*) with Munich Q3D
- Results: general (^{20}Na, ^{24}Al, ^{28}P, ^{32}Cl, ^{36}K)
- Results: ^{23}Mg(p,γ)^{24}Al
- Results: ^{35}Ar(p,γ)^{36}K
- Conclusions

Motivation

- Explosive hydrogen burning[a,b,c]
- (p,γ) reactions on the unstable even-Z, T_z = 1/2 nuclei ^{19}Ne, ^{23}Mg, ^{27}Si, ^{31}S, and ^{35}Ar dominated by resonant contributions
- Low Q values: statistical methods unreliable
- Need experimental information on resonances
- Direct RIB measurement not yet possible in most cases[d,e,f]
- Use (^{3}He,t) reaction on stable targets to determine properties of resonances indirectly
- $E_r = E_x - Q_{p\gamma}$

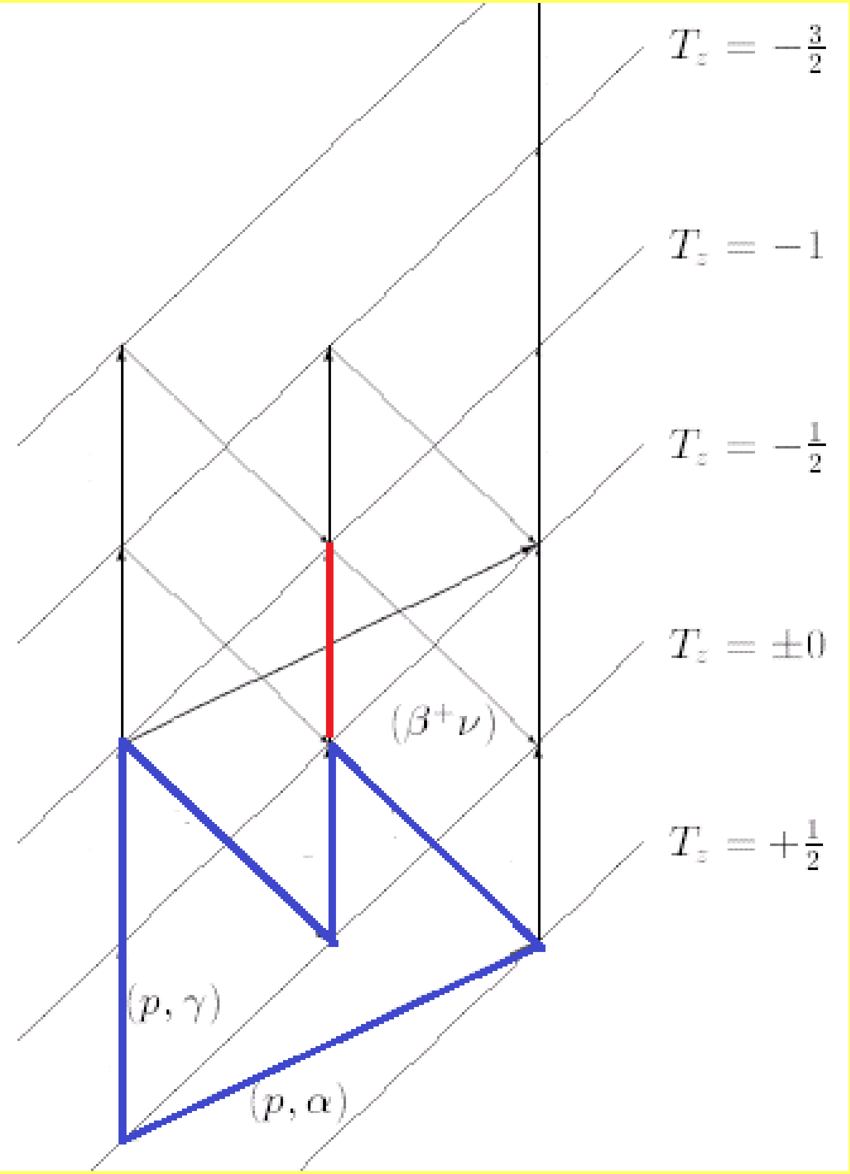

Figure adapted from:
Rembges *et al*. ApJ **484**, 412 (1997)

[a] Rembges *et al*. ApJ **484**, 412 (1997)
[b] Iliadis *et al*., ApJ **524**, 434 (1999)
[c] Herndl *et al*., PRC **58**, 1798 (1998)
[d] Vancraeynest *et al*., PRC, **57**, 2711 (1998)
[e] Erikson *et al*., PRC **81**, 045808 (2010)
[f] Couder *et al*., NIC_XI_189

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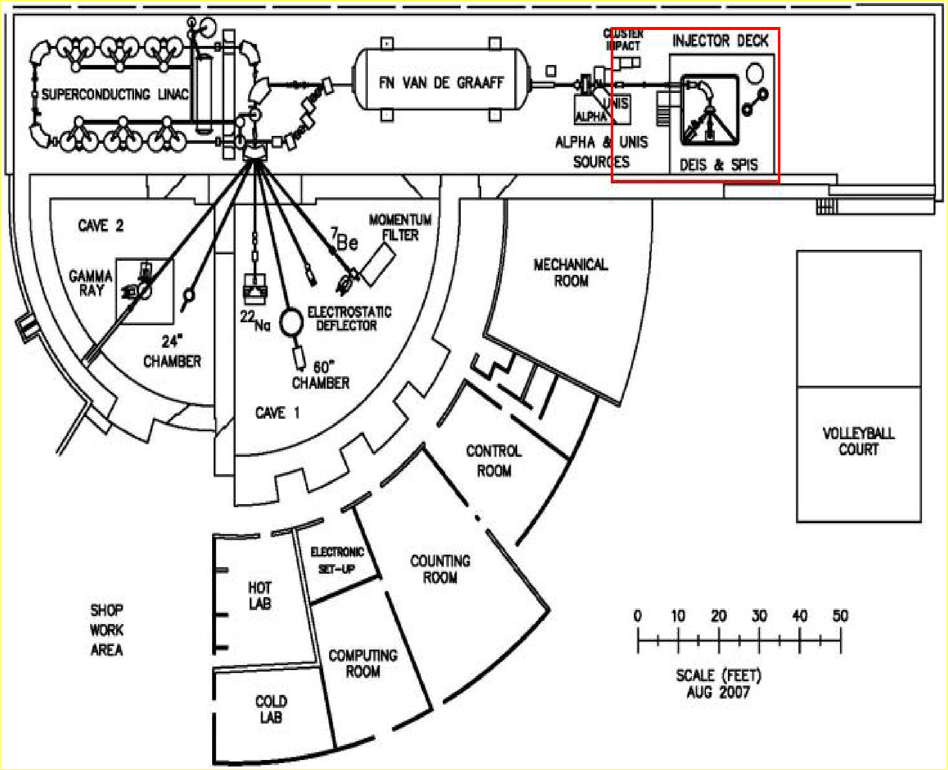
Targets: U. of Washington, CENPA

- Need thin targets of ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar
- Prefer similar, solid targets
- But chemical properties differ dramatically
- Solution: implant ions into five thin carbon foils of same thickness
- Same method for every target



Wrede *et al*. (in preparation for NIM B)

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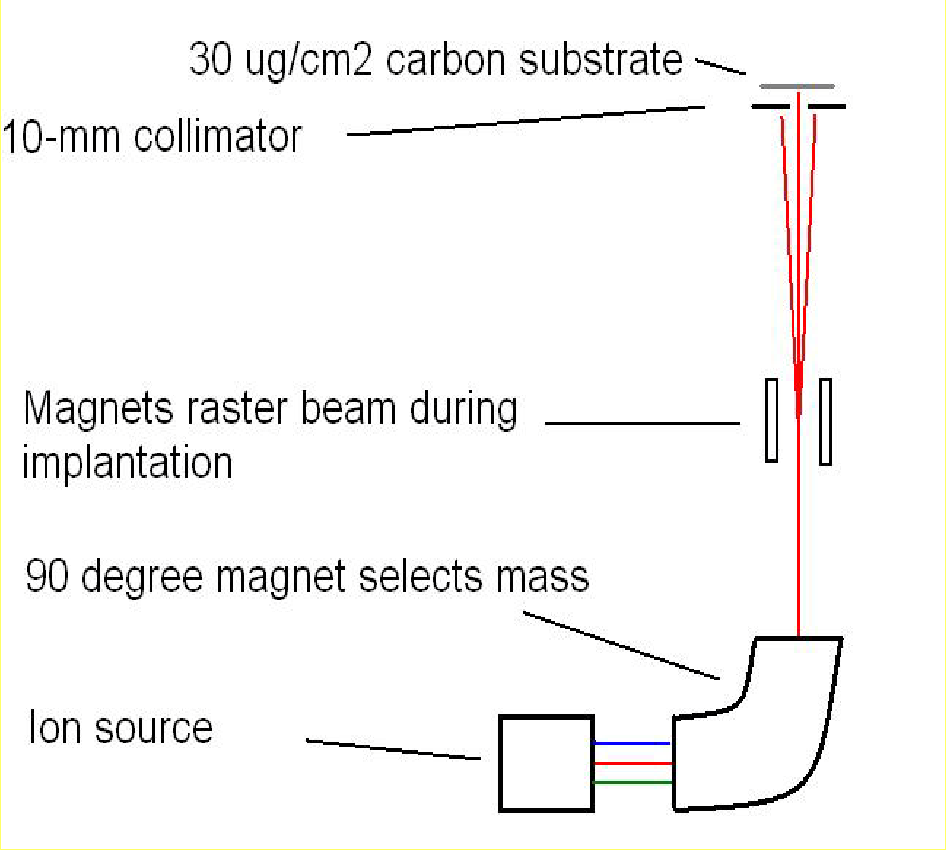

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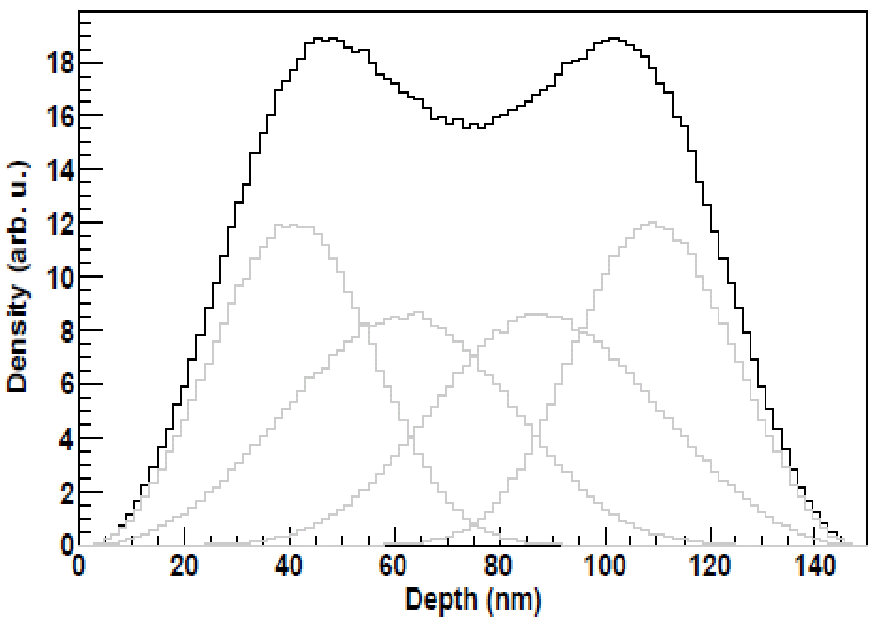
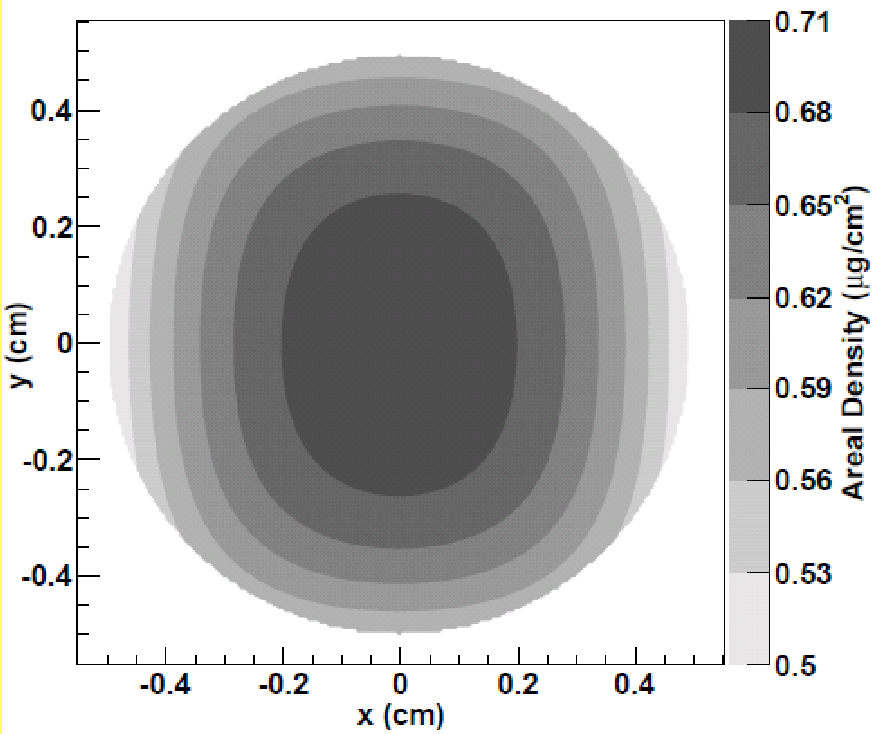
Target properties

- Carbon foil: 30 μg/cm^2
- Implanted: 3 to 6 μg/cm^2 of isotopically pure material
- four or six "layers" implanted (~1 μg/cm^2 each)
- Takes ~1 week/target
- E.g., $^{24}MgH^-$ @ 37.5 keV and 25 keV, ~100 nA
- Symmetric depth distribution
- Uniform transverse distribution in region where 1 x 3 mm beam hits





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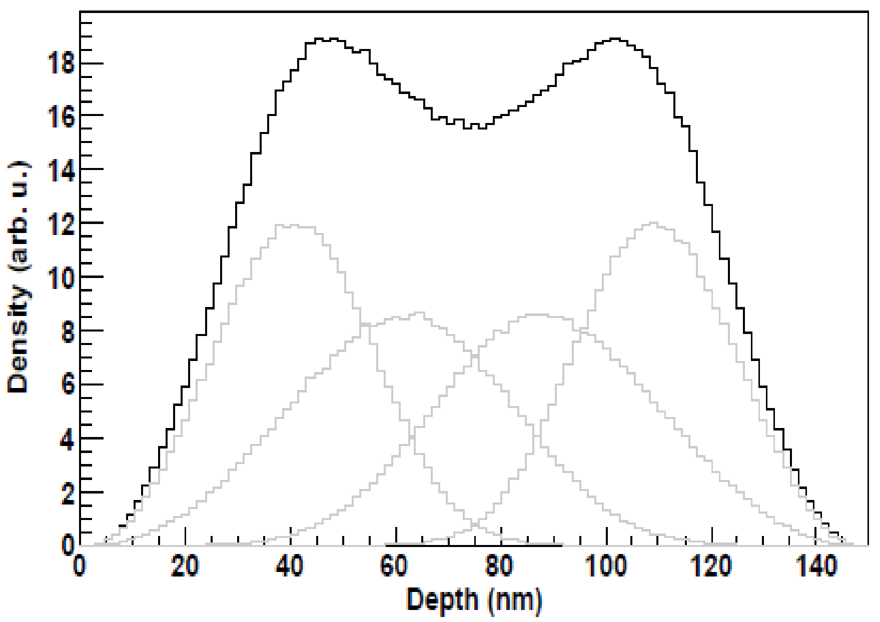

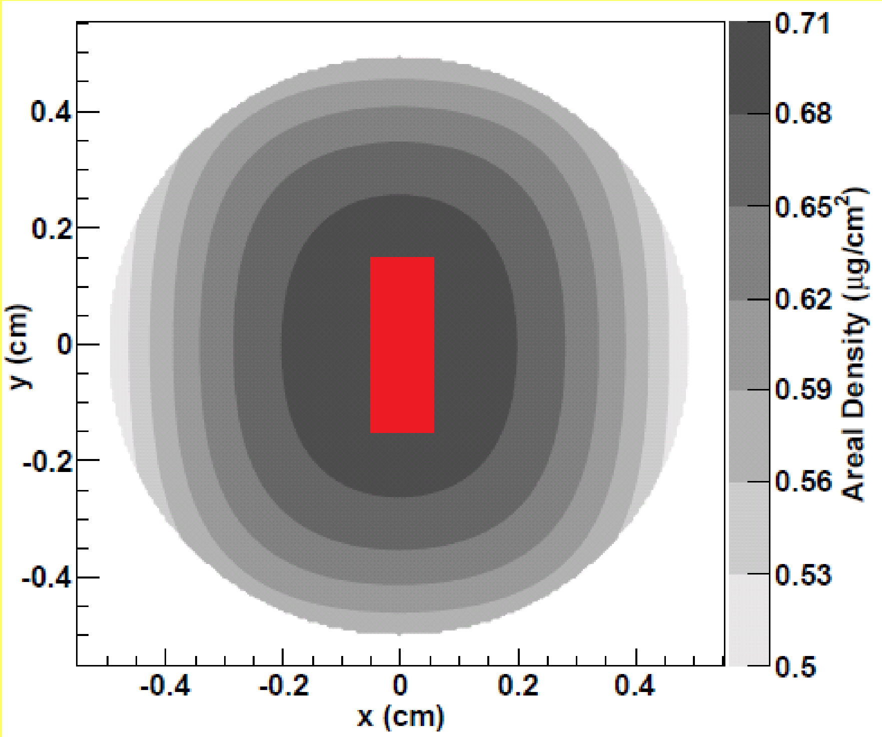

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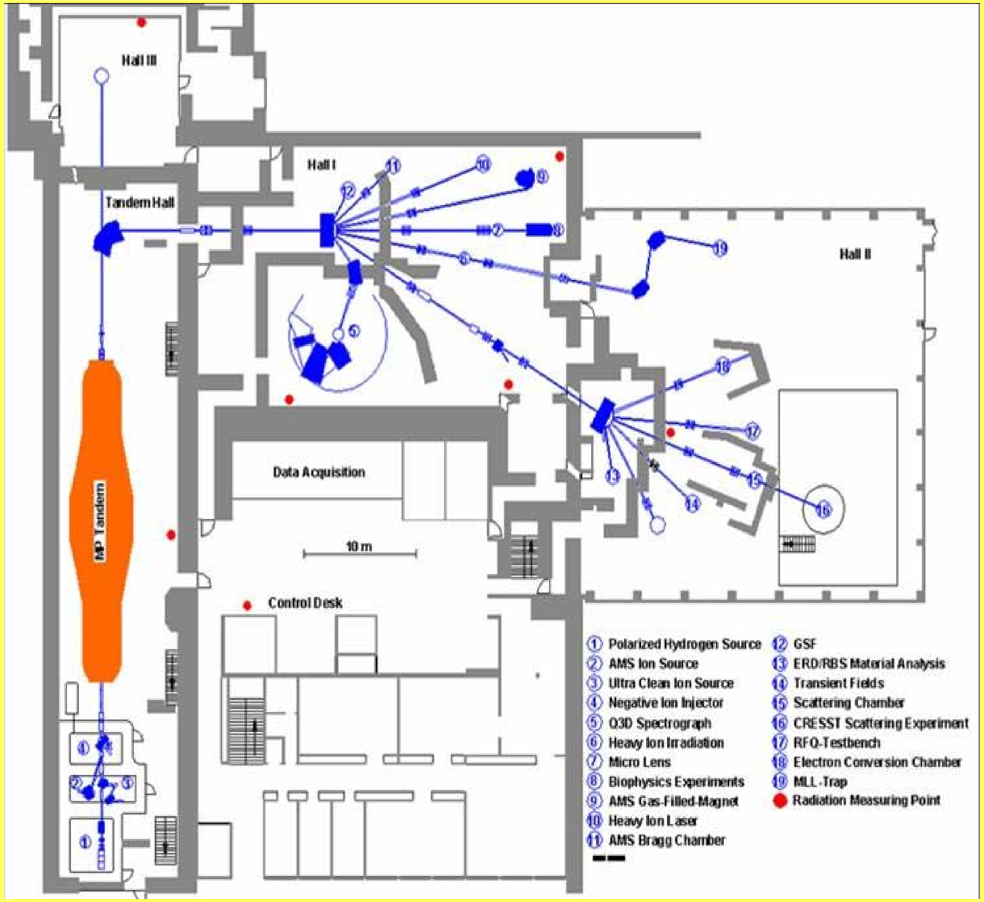
Experiment: (^{3}He,*t*) with Munich Q3D

- 6 days, November 2009
- 32 MeV, 400 *e*nA $^{3}He^{2+}$ beam
- Measurements at two angles: 10° and 20°
- Cycle ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, and ^{36}Ar targets
- Detect triton positions at focal plane
- Determine triton momenta from focal-plane position
- Momentum calibration using ^{36}Ar(^{3}He,*t*)^{36}K*
- Determine masses and excitation energies from momenta



Wrede *et al*., PRC **81**, 255503 (2010)

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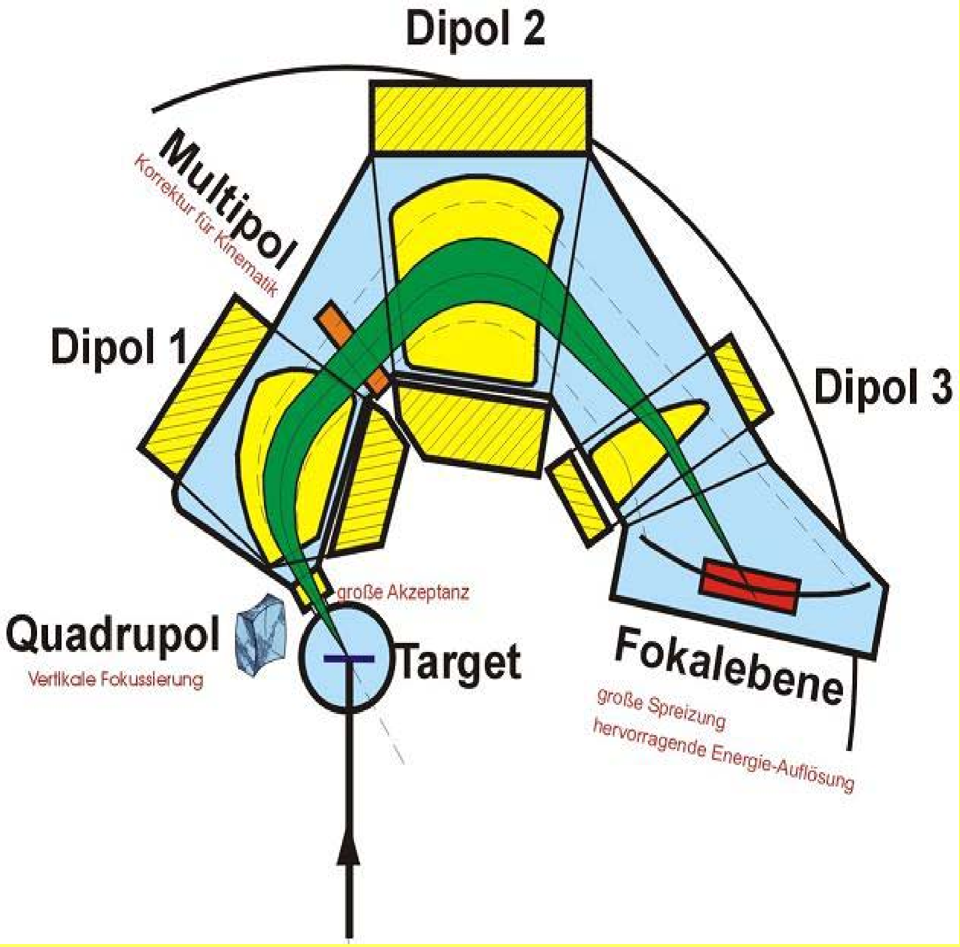
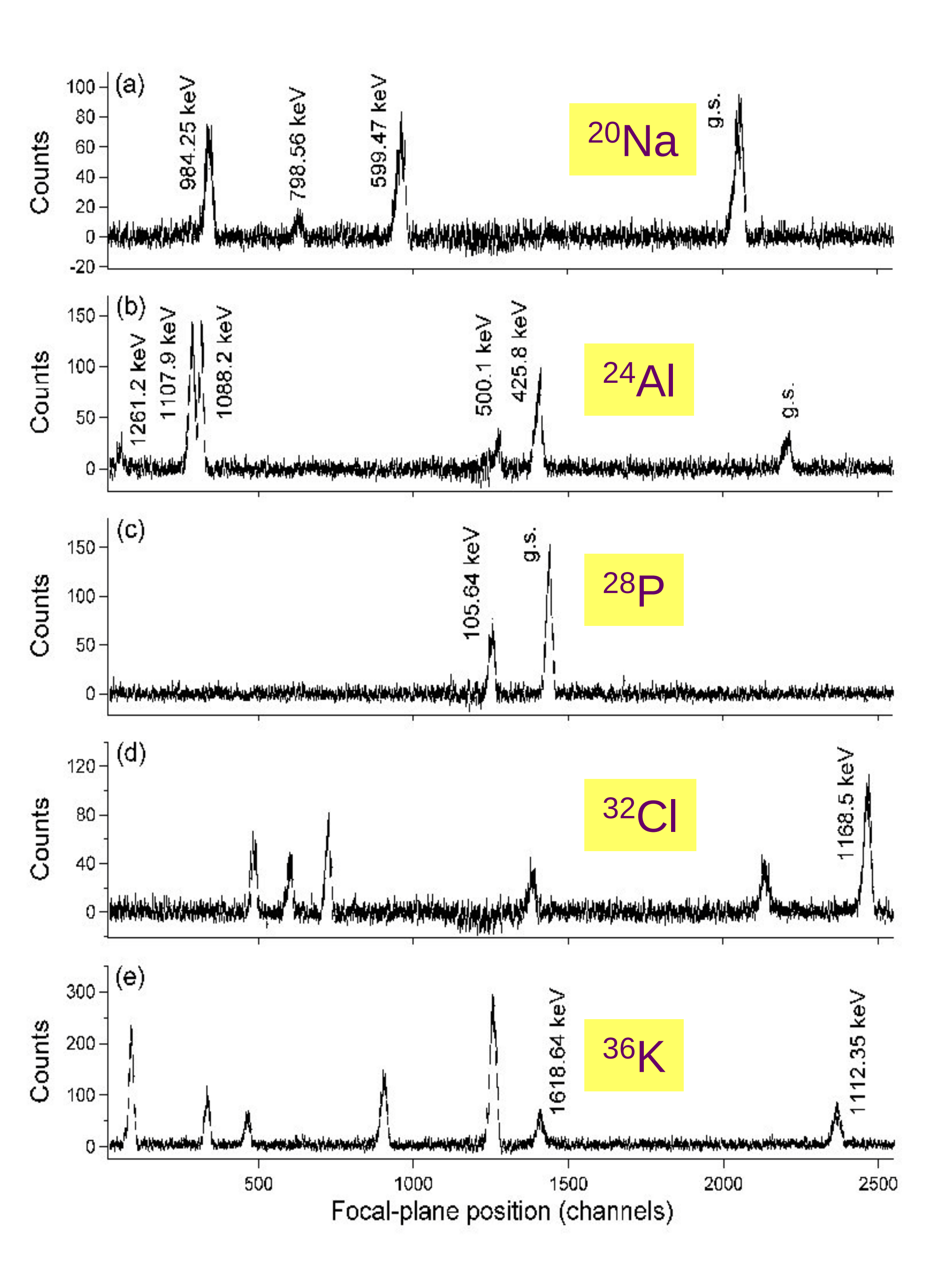


Wrede *et al*., PRC **81**, 255503 (2010)

Results: general

- Masses of ^{20}Na, ^{24}Al, ^{28}P, and ^{32}Cl to precisions of 1.1 or 1.2 keV/c^2
- Excitation energies in ^{32}Cl and ^{36}K to precisions of < 1 keV
- Improved resonance energies for ^{19}Ne(p,γ)^{20}Na, ^{23}Mg(p,γ)^{24}Al, ^{27}Si(p,γ)^{28}P, ^{31}S(p,γ)^{32}Cl, and ^{35}Ar(p,γ)^{36}K reactions
- Focus on ^{24}Al and ^{36}K…



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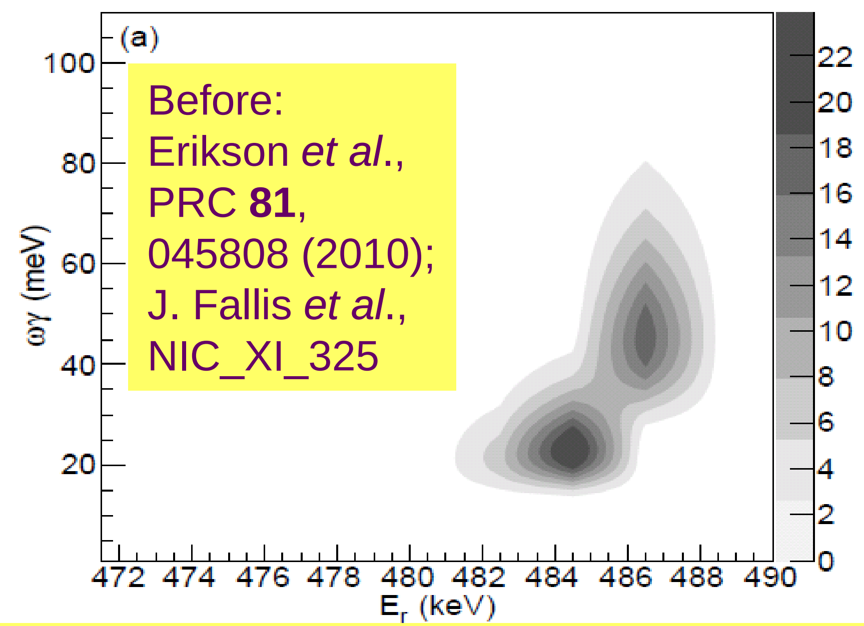
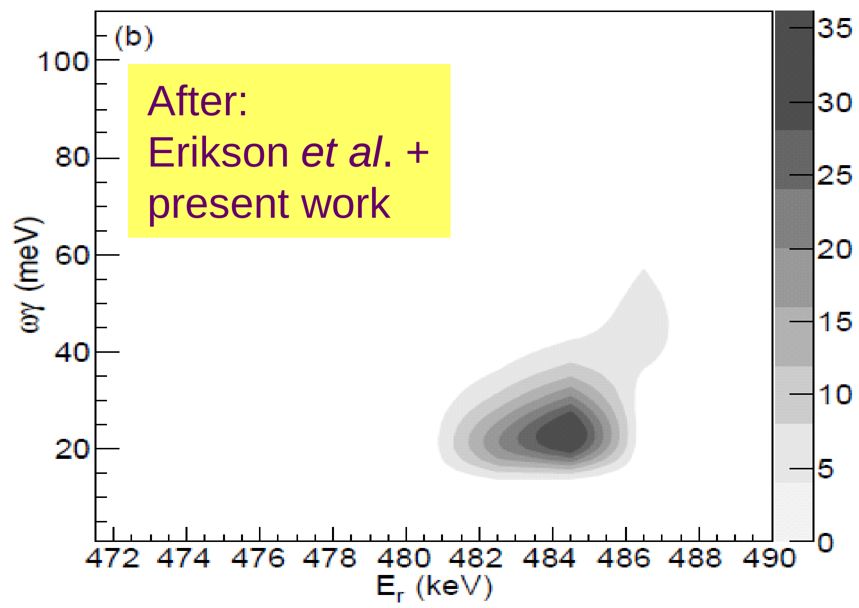
Results: $^{23}Mg(p,\gamma)^{24}Al$

- $E_r = E_x - Q_{p\gamma}$(old) = 473(3) keV[a]
- E_r (direct) = $485.7^{+1.3}_{-1.8}$ keV[b]
- Reducible uncertainty in $\omega\gamma$
- Measure ^{24}Al mass excess to be 9.5 keV (3.2σ) different from AME03
- $E_r = E_x - Q_{p\gamma}$(new) = 482.1(20) keV
- Constrains $\omega\gamma$ from 38^{+21}_{-15} meV to 27^{+15}_{-7} meV
- Excellent agreement with $\omega\gamma$ from shell model (25 meV)[c] *and* mirror level (27 meV)[d]





Wrede *et al.* (in preparation for PRC); thanks to C. Ruiz for probability density

[a] Lotay *et al.*, PRC **77**, 042802 (2008) & AME03
[b] Erikson *et al.*, PRC **81**, 045808 (2010)
[c] Herndl *et al.*, PRC **58**, 1798 (1998)
[d] Kubono *et al*. NPA **588**, 521 (1995)

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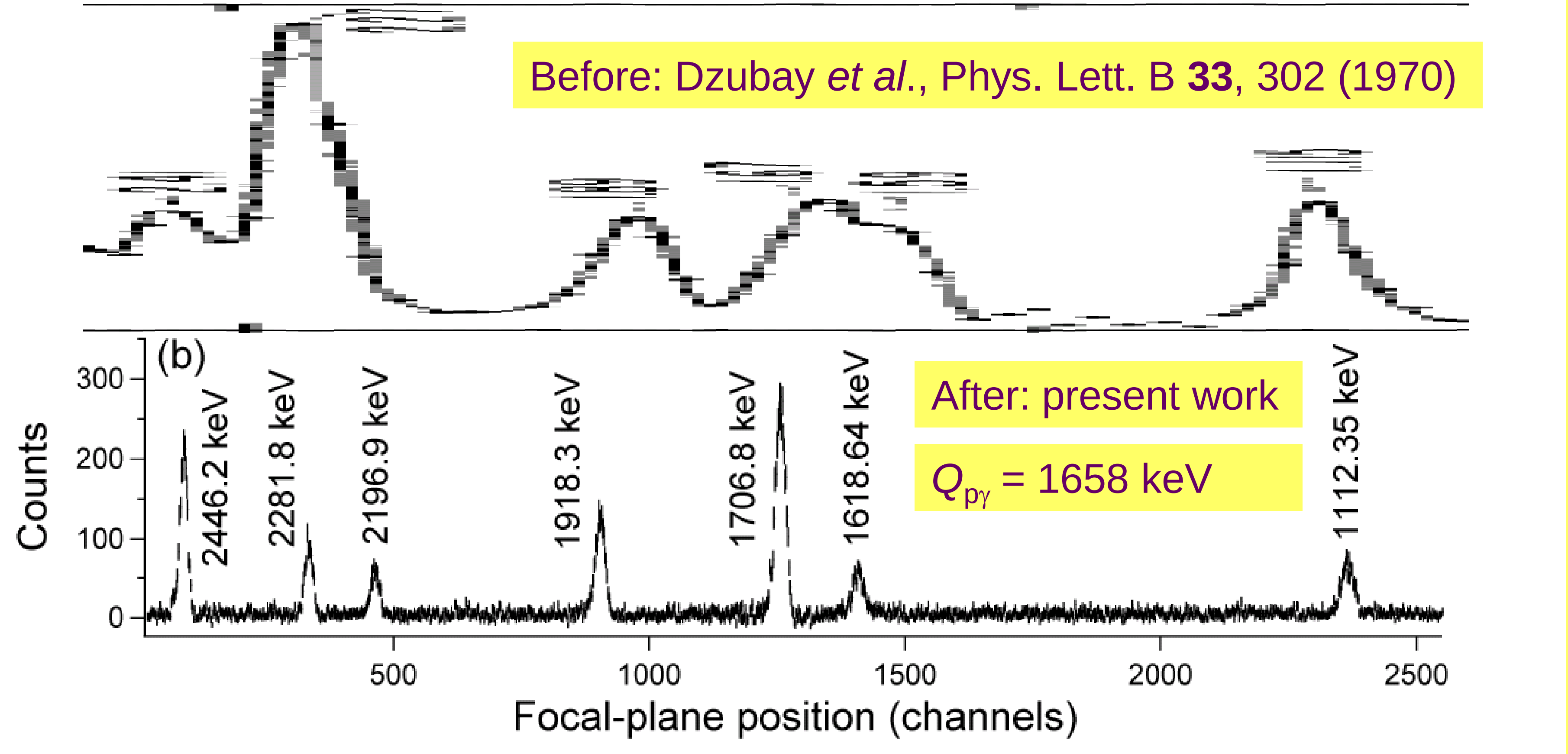
Results: $^{36}Ar(^{3}He,t)^{36}K$

- Improved resolution
- New level found in region of interest (E_x = 2197 keV, E_r = 538.5 keV)
- Uncertainties in excitation energies improved from 30 keV to < 1 keV



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Results: $A = 36$, $T = 1$ isobaric triplets

- Reexamined isobaric triplets due to new level and new energies
- Leads to rearrangement of optimal ^{36}K mirror levels
- $E_r(2_2^+)$: 224(21) ⟶ 259.9(9) keV
- $E_r(2_3^+)$: 744(31) ⟶ 623.4(7) keV
- Recalculate thermonuclear ^{35}Ar(p,γ)^{36}K reaction rate using new level, new energies, & new mirror assignments (i.e. spins and partial widths)
- Besides new data, method identical to Iliadis *et al*., ApJ **524**, 434 (1999)

Predict E_x (keV):

$E_x(^{36}\text{K}) = 2E^*_x(^{36}\text{Ar}) - E_x(^{36}\text{Cl})$
[Iliadis *et al*., ApJ **524**, 434 (1999)]

predicted E_x (^{36}K) present	measured E_x (^{36}K) present
1723	1707
1931	1918
2186	2197
2288	2282

$Q_{p\gamma}$ = 1658 keV

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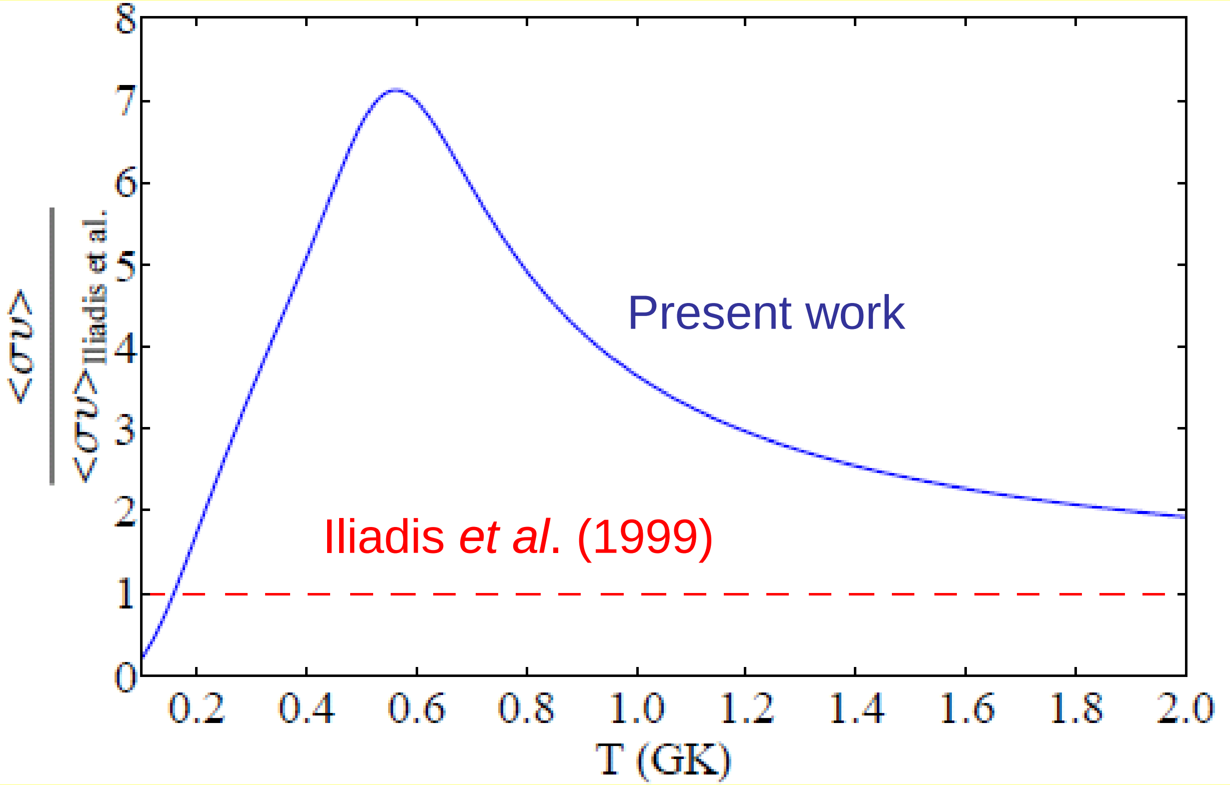
Results:
Change in $^{35}Ar(p,\gamma)^{36}K$ rate

[compared to Iliadis *et al*., ApJ **524**, 434 (1999)]



- Could have significant effect on energy generation in type I x-ray bursts [e.g. Parikh *et al*., ApJSS **178**, 110 (2008)]

Wrede *et al*., in preparation for PRC

Conclusions

- Measured masses of ^{20}Na, ^{24}Al, ^{28}P, ^{32}Cl to high precision
- Resolved discrepancy in energy of lowest-energy ^{23}Mg(p,γ)^{24}Al resonance, and constrained its strength
- Measured excitation energies in ^{32}Cl and ^{36}K to high precision
- Discovered new ^{35}Ar(p,γ)^{36}K resonance
- Rearranged A = 36, T = 1 triplets
- Substantial change in ^{35}Ar(p,γ)^{36}K rate: could affect energy generation in type I x-ray bursts
- Mass measurements also influence fundamental tests [e.g. scalar-current searches in ^{32}Ar β-ν_e correlation Adelberger *et al*. PRL **83**, 1299 (2009); Blaum *et al.* PRL **91**, 260801 (2003); Wrede *et al*. PRC **81** 255503 (2010)]

Other interesting results

- The ^{32}Cl mass measurement also influences fundamental tests via mass excess of lowest $T = 2$ level in ^{32}Cl

  -best test of quadratic IMME

  -scalar-current constraints from ^{32}Ar β-ν_e correlation shifted by 1σ

Adelberger *et al*. PRL **83**, 1299 (2009)
Blaum *et al.* PRL **91**, 260801 (2003)
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Thank You!

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