

The $^{22}\text{Ne}(\alpha, \text{n})^{25}\text{Mg}$ neutron source

The experimental state of the art and open problems

Claudio Ugalde

Collaborators

A. Karakas
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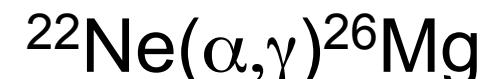
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CHICAGO

Neutron source in the weak component of the s process

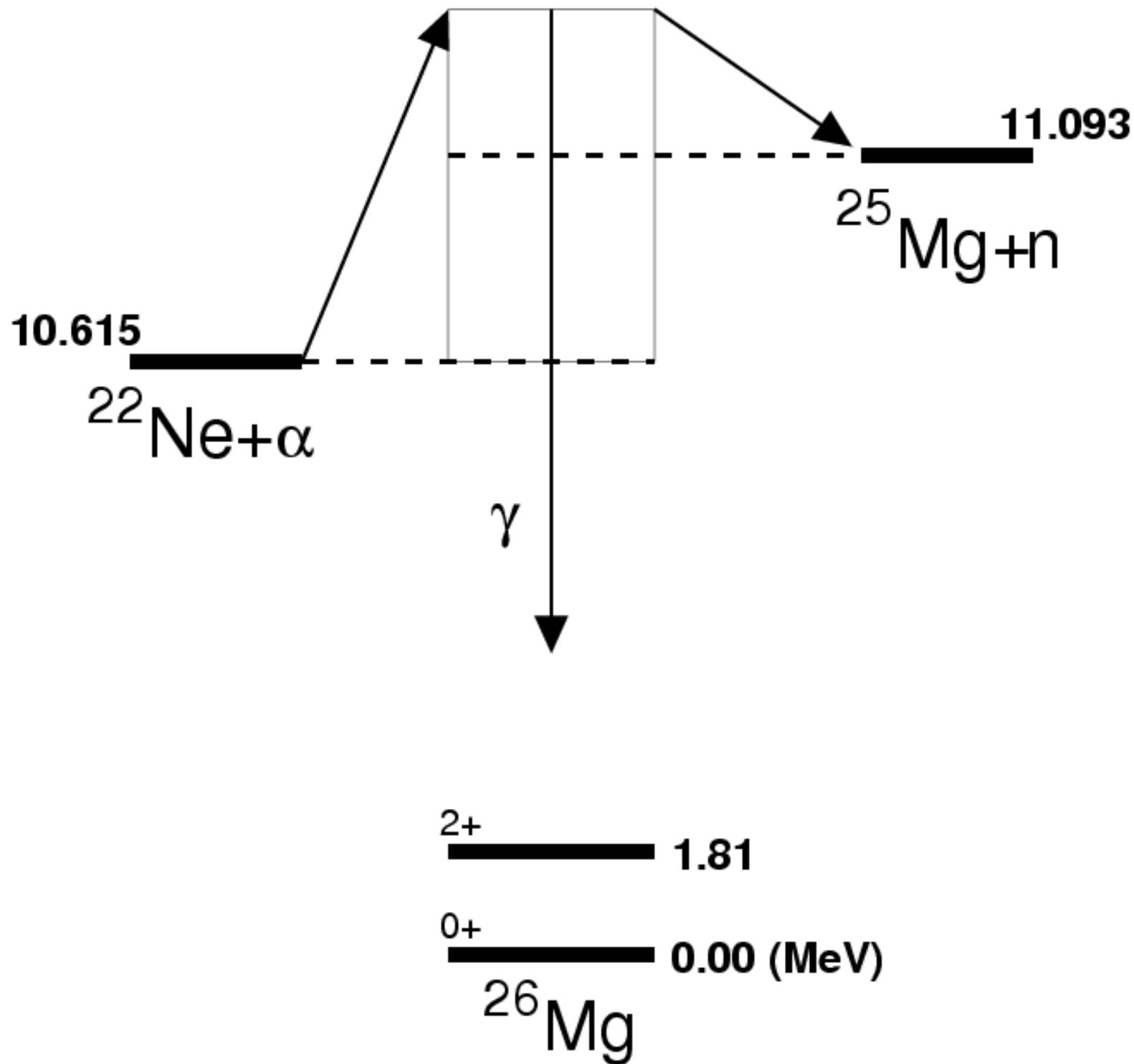
Peters 1958 (ApJ 154, 224)

“The s-process neutron source in massive stars is the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction”.

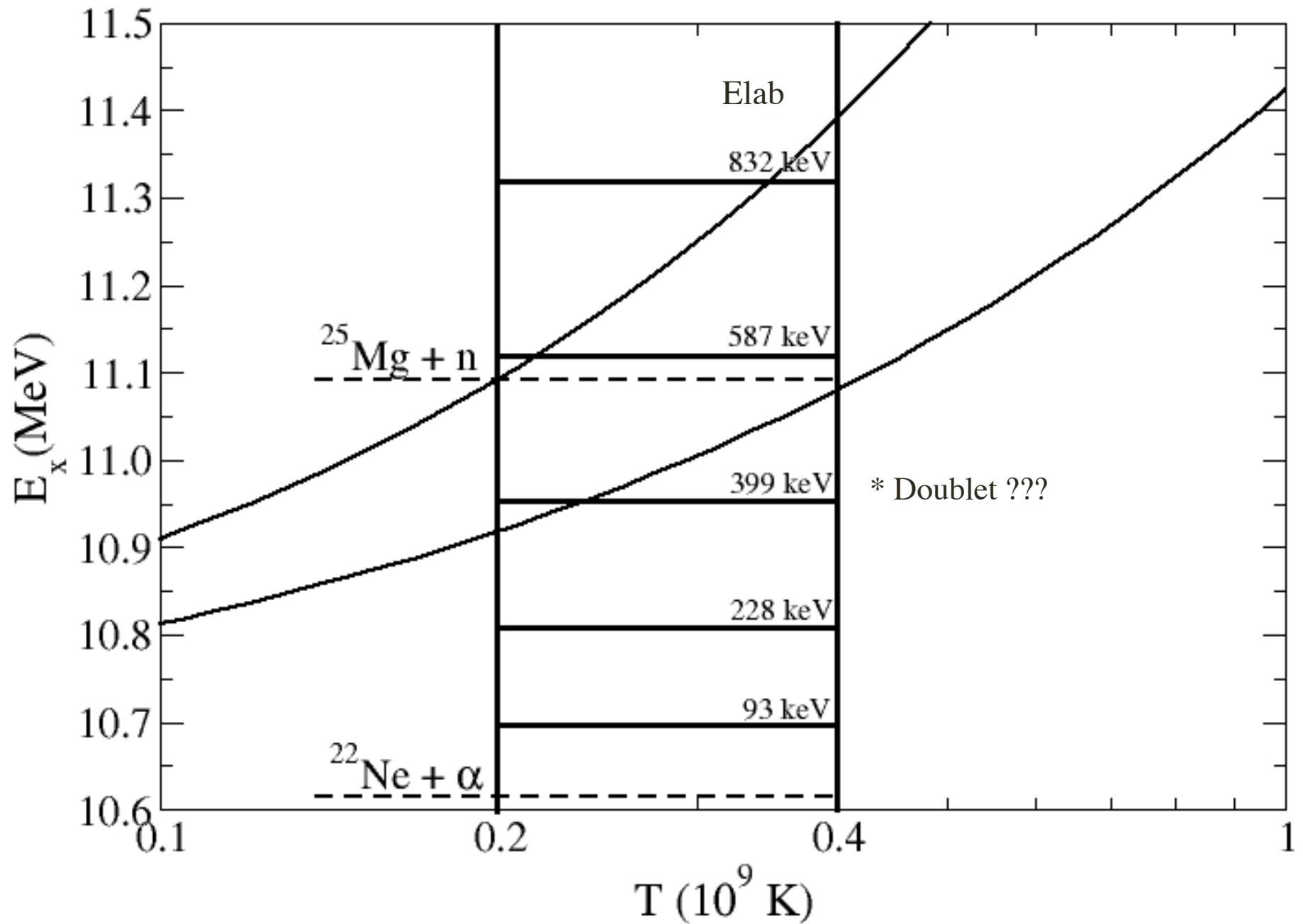
Starting with ^{14}N from the CNO cycle in the He shell:



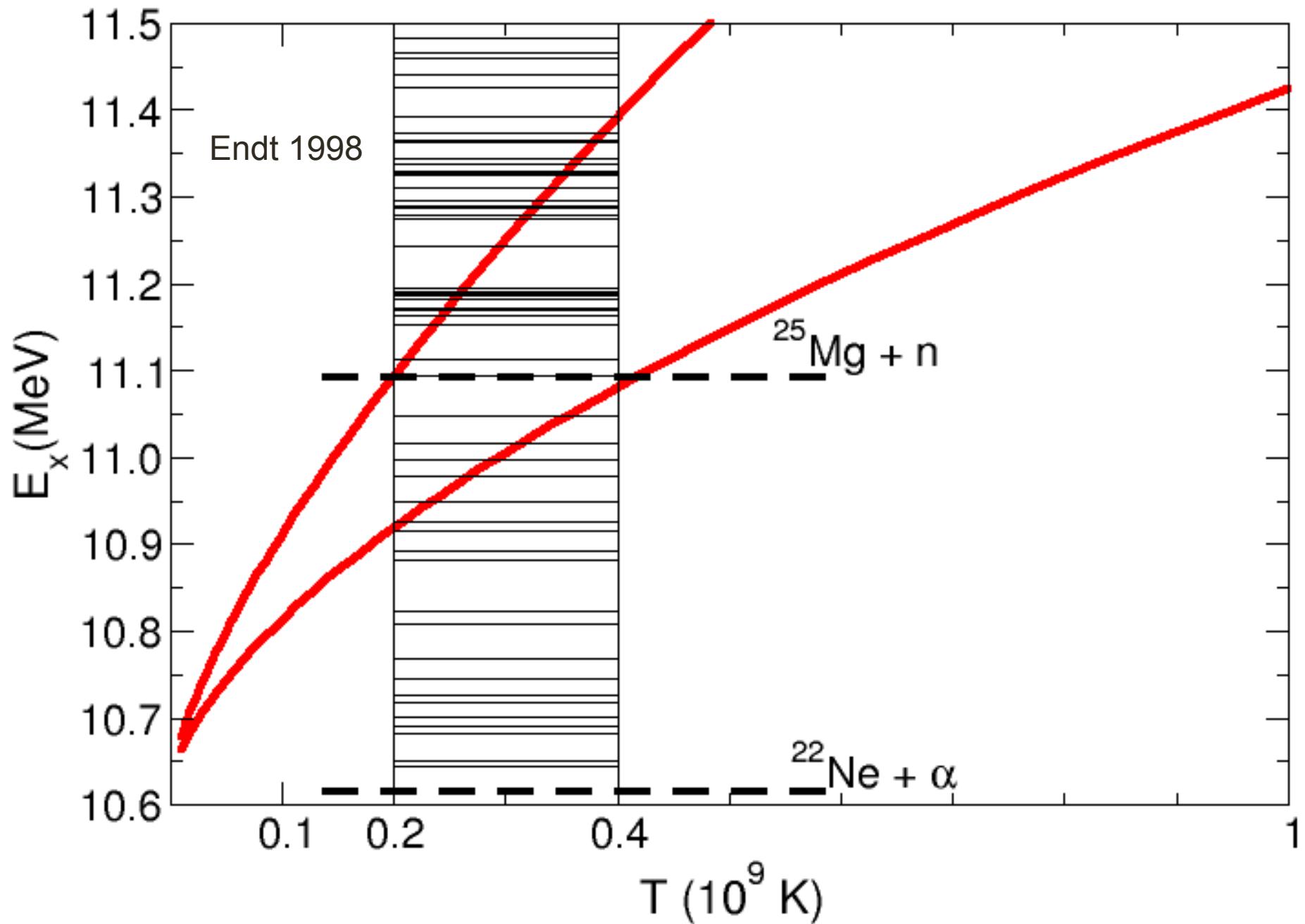
Red giant in hydra supercluster



In the reaction rate calculations ($^{22}\text{Ne}+\alpha$)



All states observed experimentally



Direct measurements $^{22}\text{Ne}(\alpha,\text{n})^{25}\text{Mg}$

Ashery 1969

Haas 1973

Wolke 1989

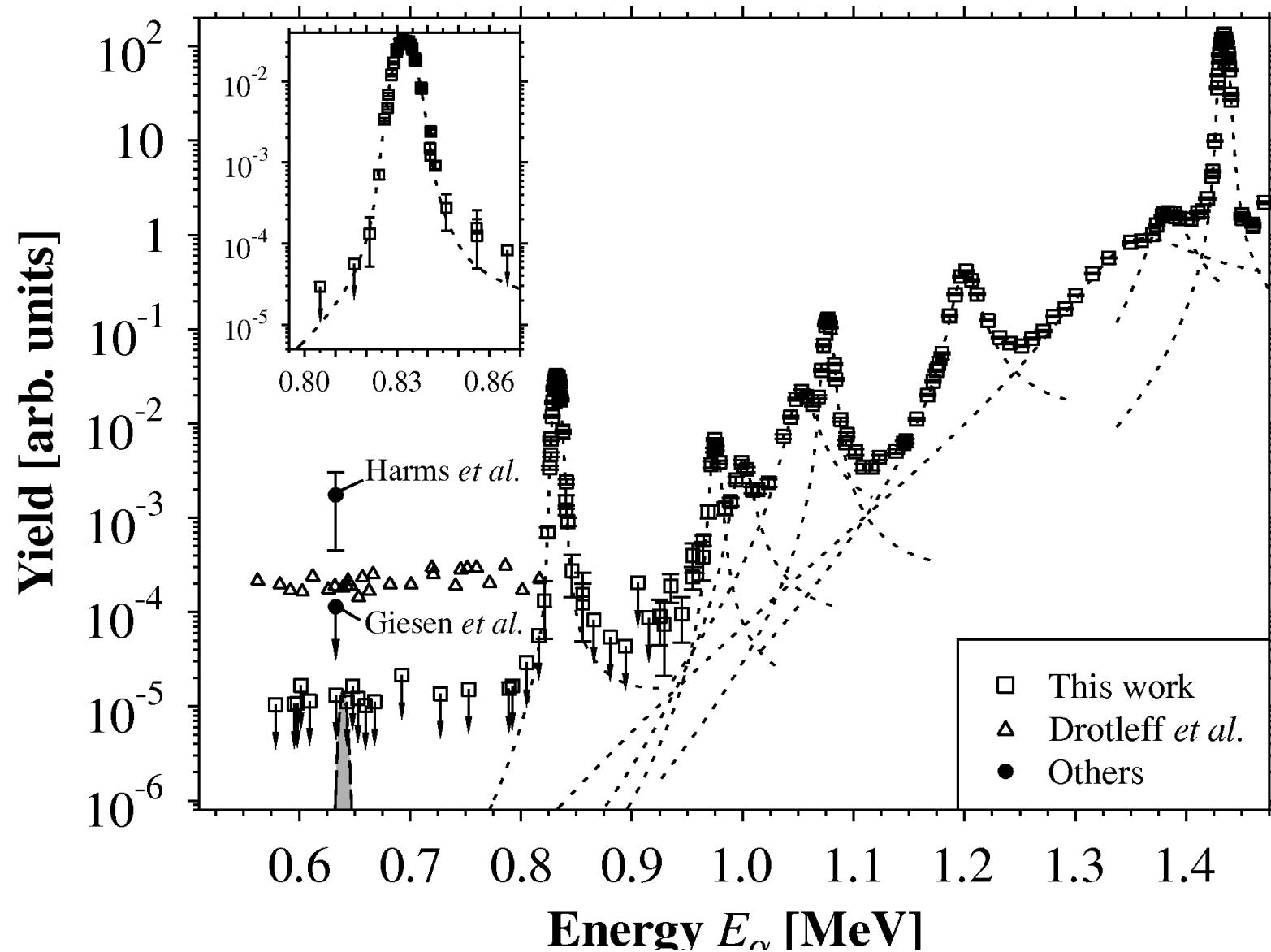
Harms 1991

Drotleff 1991, 1993

Giesen 1993

Jaeger 2001

Jaeger 2001



Indirect measurements

Newson 1969, $^{25}\text{Mg}(\text{n},\text{n}')$

Bendel 1968, $^{26}\text{Mg}(\text{e},\text{e})$

Berman 1969, $^{26}\text{Mg}(\gamma,\text{n})$

Moss 1976, $^{26}\text{Mg}(\text{p},\text{p})$

Weigmann 1976, $^{25}\text{Mg}(\text{n},\gamma)$

Glatz 1986, $^{23}\text{Na}(\alpha,\text{p}\gamma)$

Crawley 1989, $^{26}\text{Mg}(\text{p},\text{p}')$

$$\omega\gamma \sim \omega\Gamma\alpha$$

Walkiewicz 1992, $^{25}\text{Mg}(\text{n},\gamma)$

Giesen 1993, $^{22}\text{Ne}(^{6}\text{Li},\text{d})$

Ugalde 2007, $^{22}\text{Ne}(^{6}\text{Li},\text{d})$

Schwengner 2009, $^{26}\text{Mg}(\gamma,\gamma)$

Longland 2010, $^{26}\text{Mg}(\gamma,\gamma)$

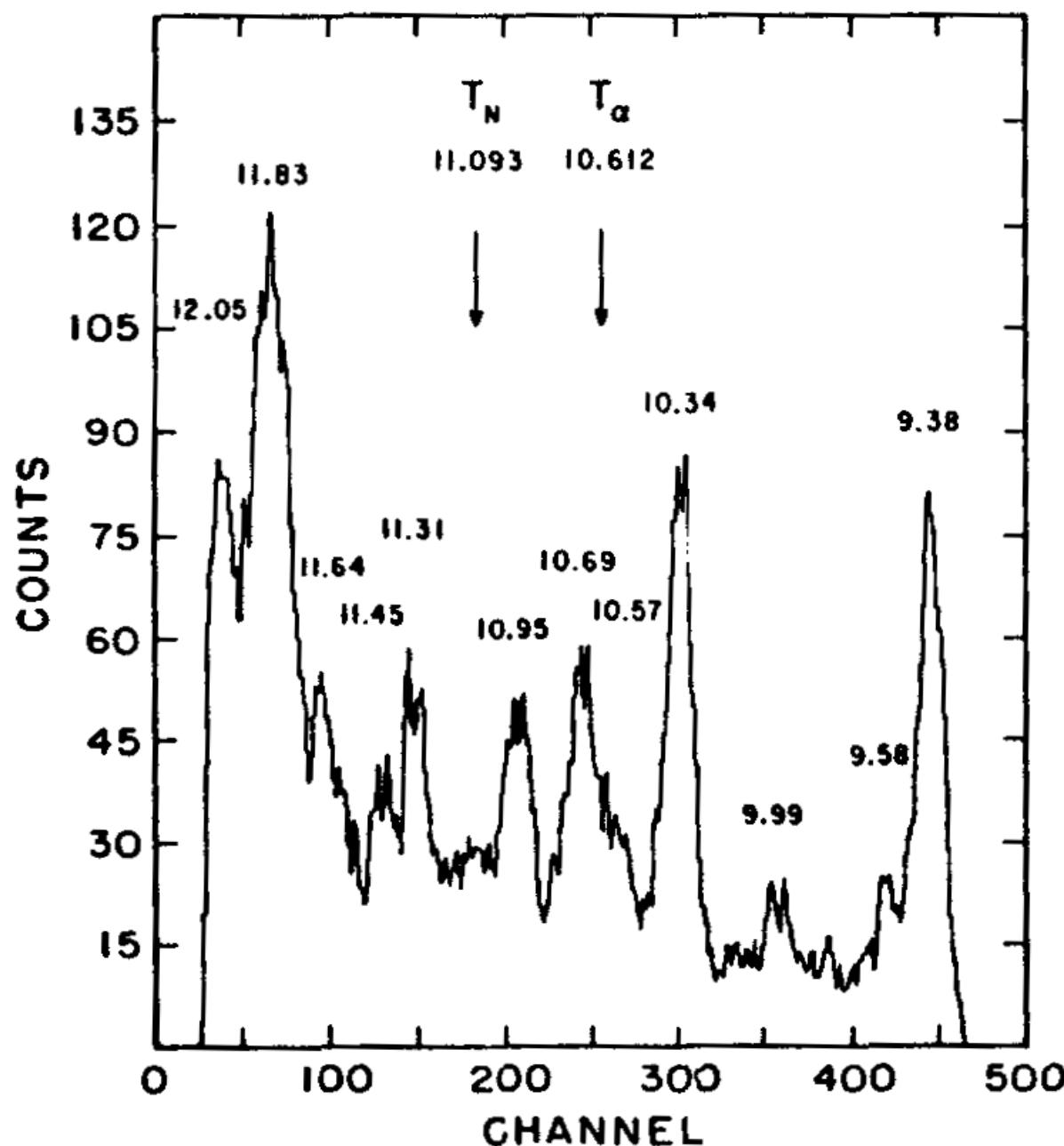
deBoer 2010, $^{26}\text{Mg}(\gamma,\gamma)$

Ota 2012, $^{6}\text{Li}(^{22}\text{Ne},\text{d})$

- a) Identify states in ^{26}Mg
- b) Measure their energy
- c) Measure spin and parity
- d) Measure α -particle width

$^{22}\text{Ne}(^6\text{Li},\text{d})^{26}\text{Mg}$

U. Giesen et al. / Resonances



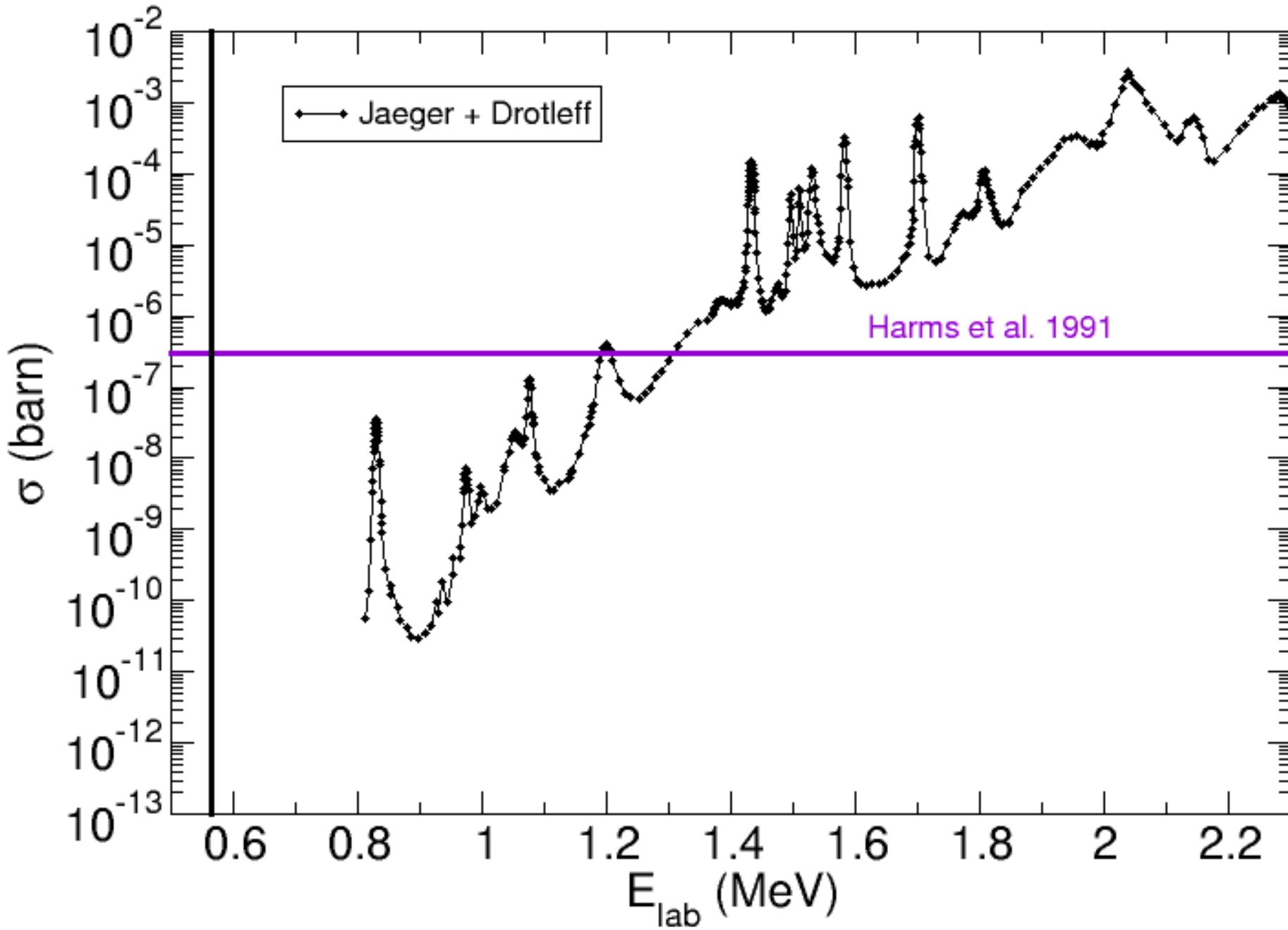
Other compilations, data reanalyses, etc.

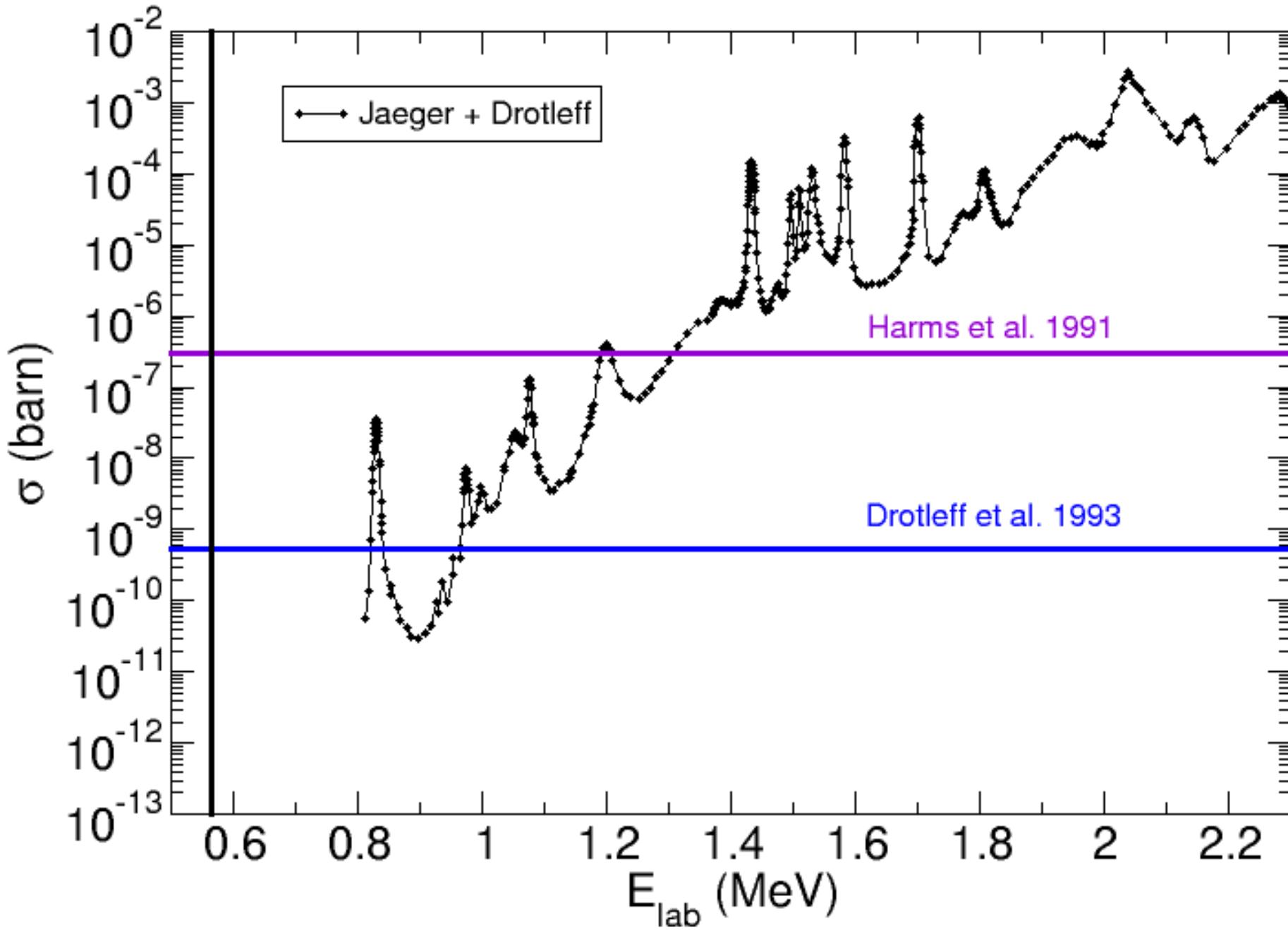
Käppeler, Wiescher, Giesen, Görres, Barafe, El Eid, Raiteri, Busso, Gallino, Limongi, and Chiefi. Ap. J. 437, 396 (1994)

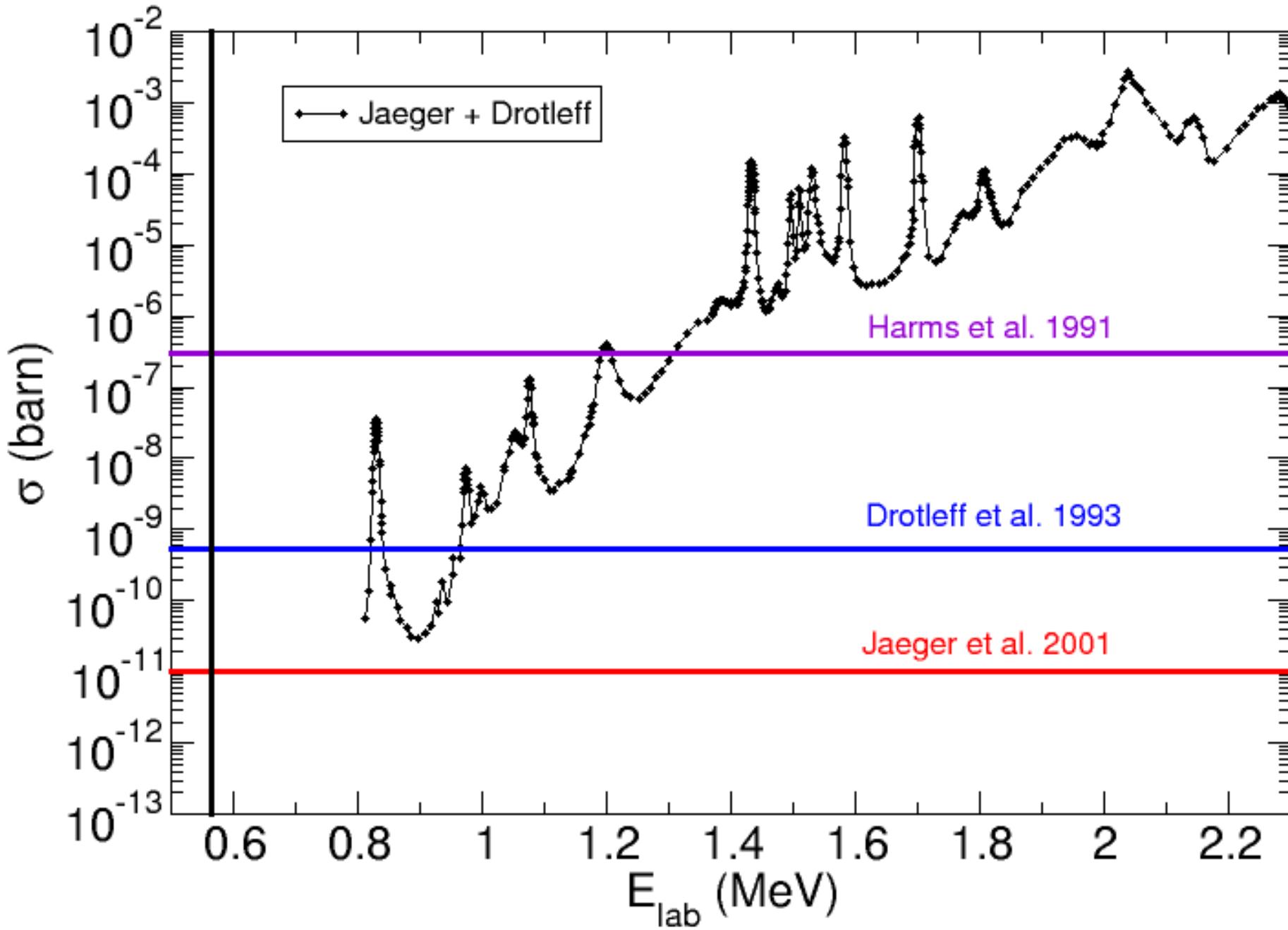
P. E. Koehler, Phys Rev C 66, 055805 (2002)

Karakas, Lugardo, Wiescher, Görres, and Ugalde, Ap. J. 643, 471 (2006)

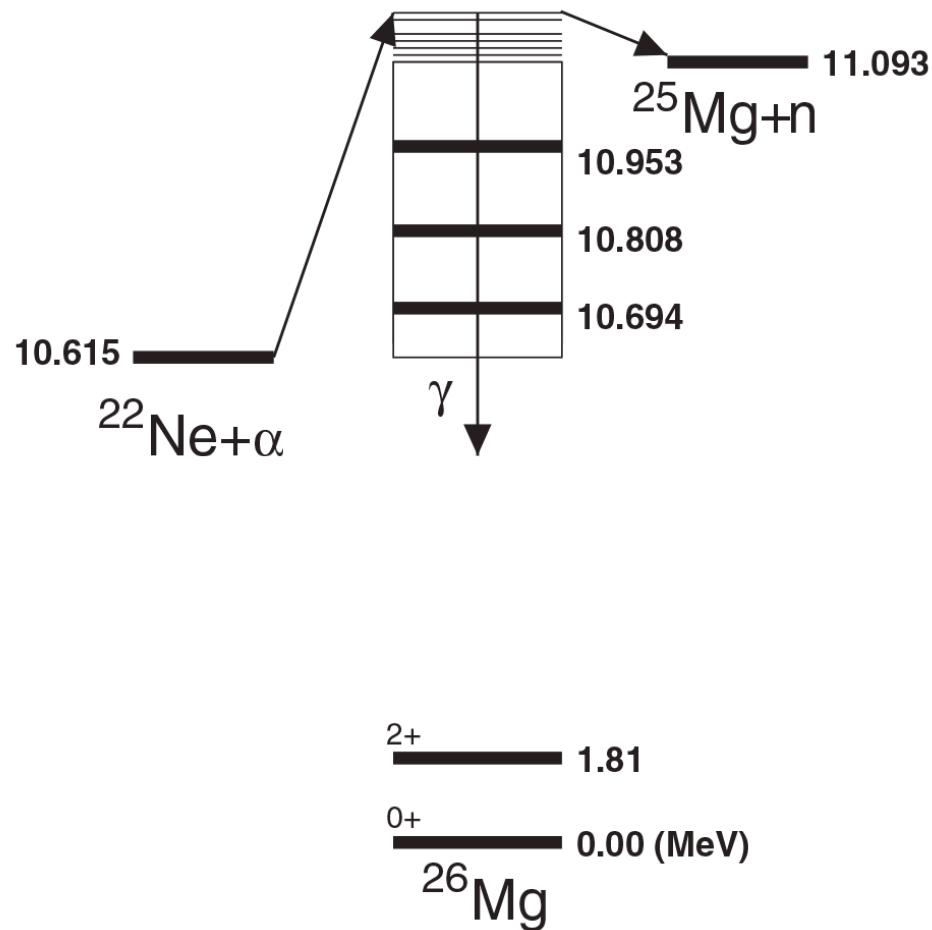
Longland, Iliadis, and Karakas, Phys Rev C 85, 065809 (2012)







Below neutron threshold



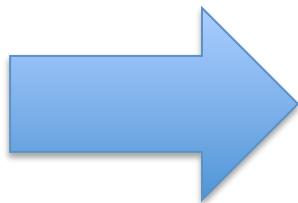
All spectroscopic factors are very uncertain

The 10.95 MeV resonance

Most likely a doublet: 10.943 MeV and 10.949 MeV

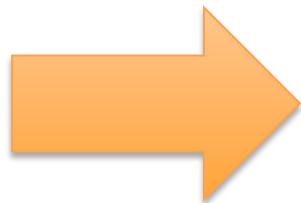
All known properties **from indirect measurements**

10.943 MeV has a high spin ($J\pi=5-, 6+, \text{ or } 7-$)



May contribute weakly to
the reaction rate

10.949 MeV ($J\pi=1-$), spin recently measured



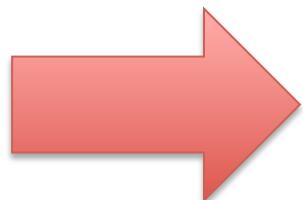
Might be important to the
rate

The 10.806 MeV resonance

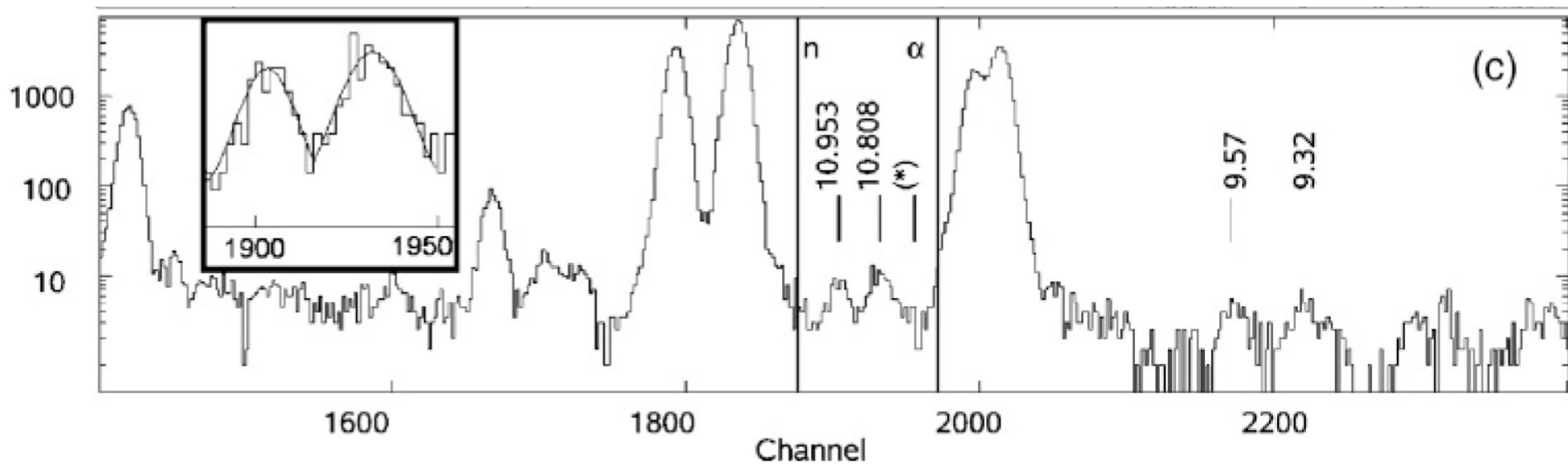
Assumed to exist in $^{22}\text{Ne} + \alpha$ from
 $^{22}\text{Ne}(^6\text{Li},d)^{26}\text{Mg}$ studies

Observed for the first time in $^{22}\text{Ne}(^6\text{Li},d)^{26}\text{Mg}$
by Ugalde 2007

Spin determined by Longland 2010 ($J\pi=1^-$)



Might be important to the
rate at temperatures <0.2
GK (maybe astrophysically
irrelevant)

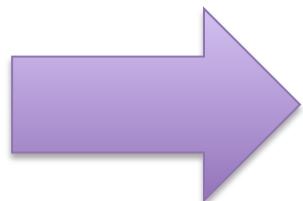


Ugalde 2007

The 10.693 MeV resonance

Observed several times in indirect studies,
e.g. $^{26}\text{Mg}(\text{p.p})$, $^{23}\text{Na}(\alpha, \text{p}\gamma)$, $^{22}\text{Ne}(^6\text{Li}, \text{d})$

Spin determined at ($J\pi=4+$)



Outside of the Gamow window. Irrelevant.

Above the neutron threshold

State at $E_{\text{lab}} = 831 \text{ keV}$ contributes only at higher temperatures ($>0.35 \text{ GK}$).

Observed directly and studied many times ($J\pi = 2^+$). **Better resolution needed** as γ and neutron channels may feed different states in previous studies.

Other resonances with $E_{\text{lab}} = 648\text{-}957 \text{ keV}$ have unknown α -particle widths. **LUNA-MV task.**

Beyond that, only very broad states' tail may contribute to astrophysical rate.

Last 5 years' achievements...
above the threshold

$E_x = 11.15$ MeV resonance
controversy resolved

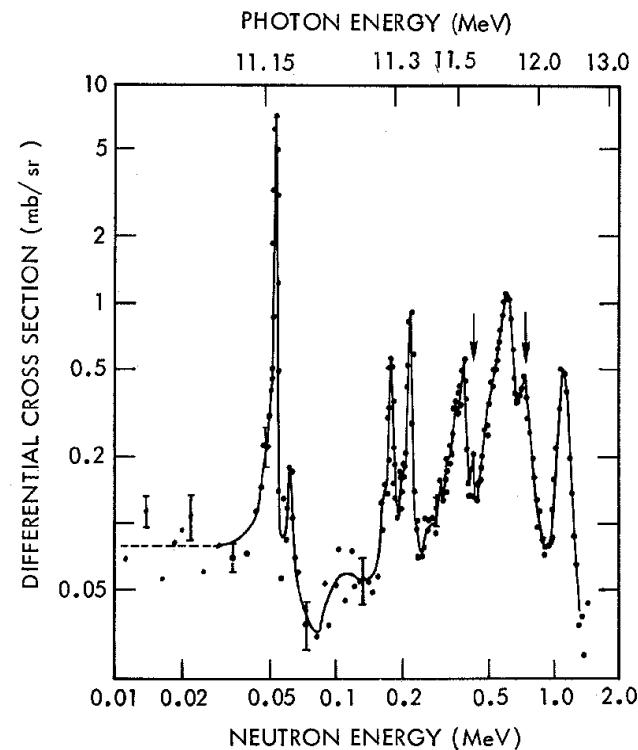
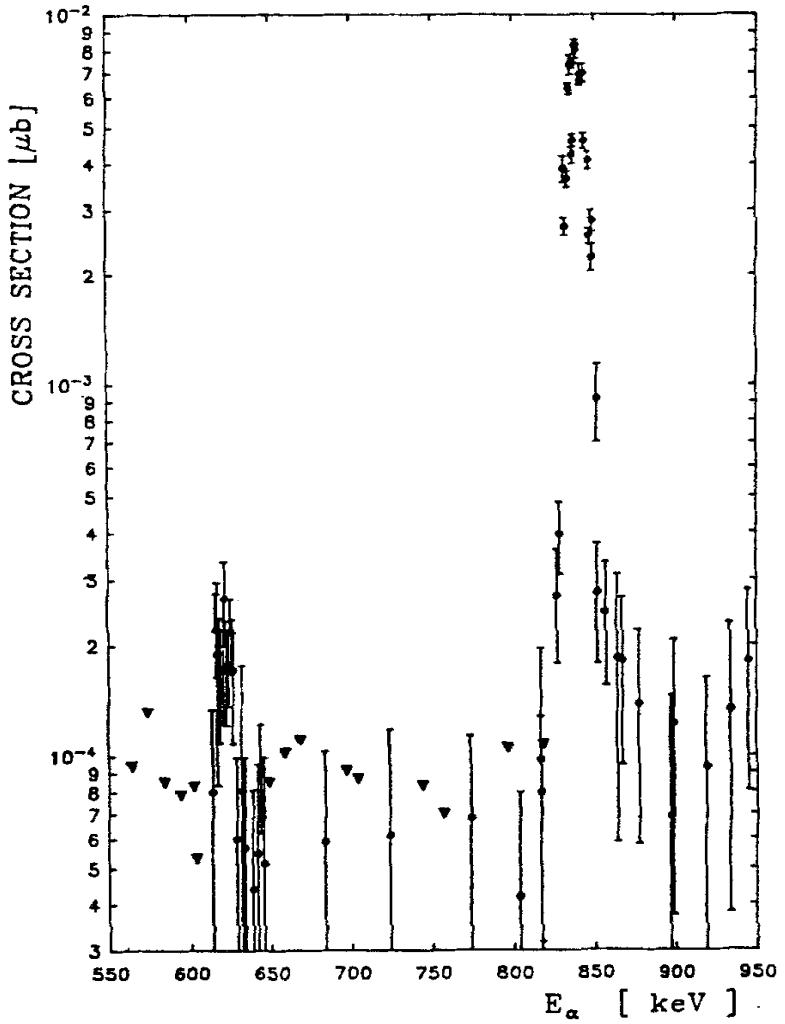
Learned how to make
 $^{22}\text{Ne}(^6\text{Li},\text{d})^{26}\text{Mg}$ experiments

More states than originally
thought might be contributing to
the rate

The 11.15 MeV resonance

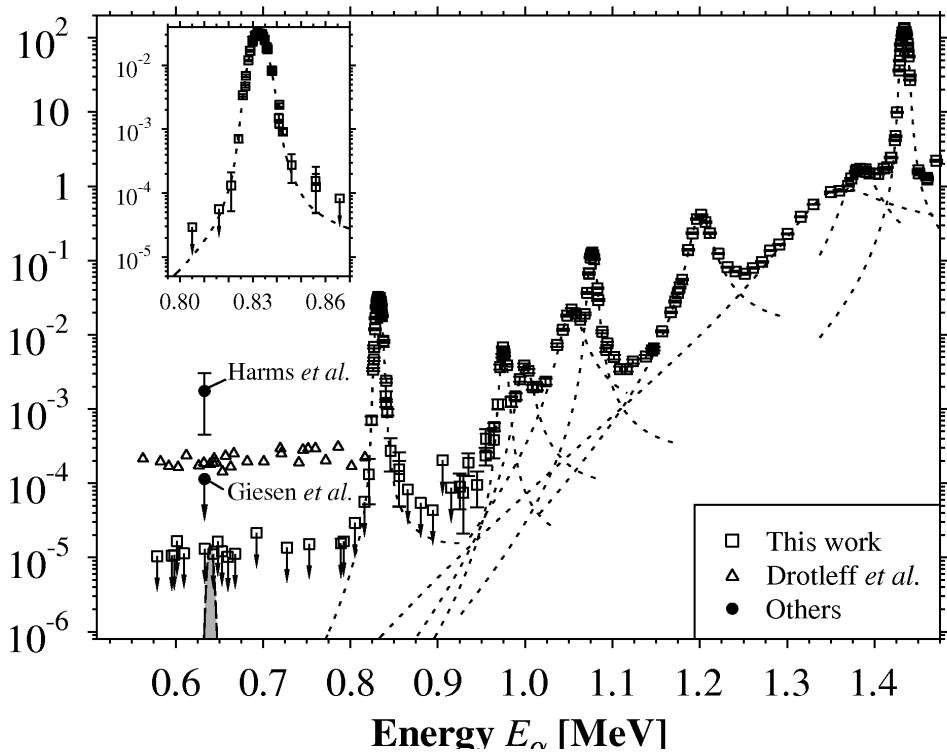
Berman '69

Drotleff '91

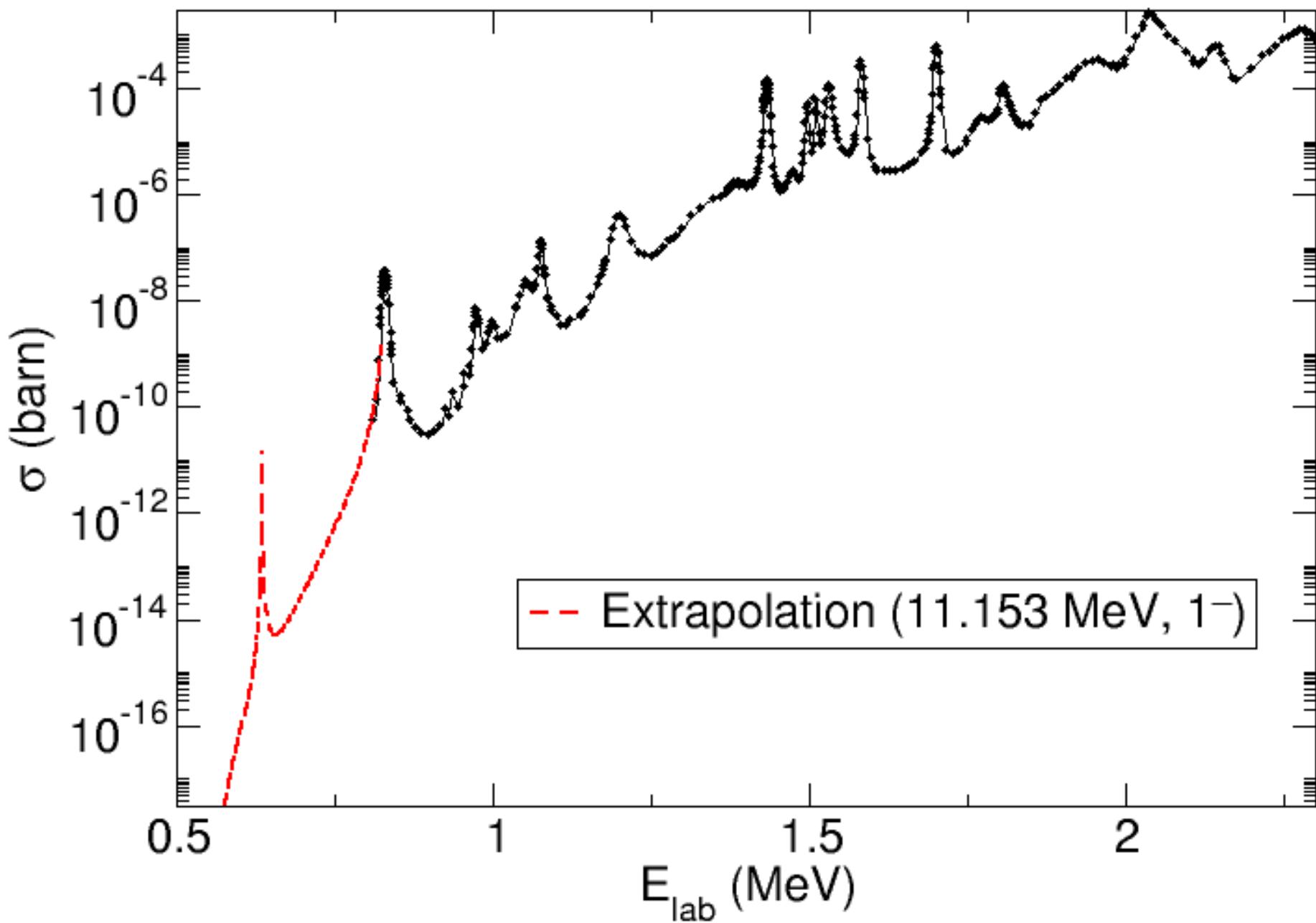


Jaeger '01

Yield [arb. units]



- This work
- △ Drotleff et al.
- Others



BUT...

THIRD SERIES, VOLUME 39, NUMBER 2

FEBRUARY 1989

Isovector and isoscalar spin-flip excitations in even-even *s-d* shell nuclei excited by inelastic proton scattering

G. M. Crawley,^(a) C. Djalali,^{(a),(b)} N. Marty,^(b) M. Morlet,^(b) A. Willis,^(b) N. Anantaraman,^(a)
B. A. Brown,^(a) and A. Galonsky^(a)

^(a)National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy,
Michigan State University, East Lansing, Michigan 48824

^(b)Institut de Physique Nucléaire, Orsay 91406, France

(Received 14 July 1988)

Forward-angle cross sections for 1^+ states have been measured in $^{24,26}\text{Mg}$, ^{28}Si , and ^{32}S by 201 MeV proton inelastic scattering. Comparisons are made with (γ, γ') , (e, e') , and (p, n) results. The measured strength is compared with microscopic distorted-wave Born approximation calculations using large-scale shell-model wave functions. Ratios of experimental to theoretical 1^+ strengths are given. Almost no quenching is observed.

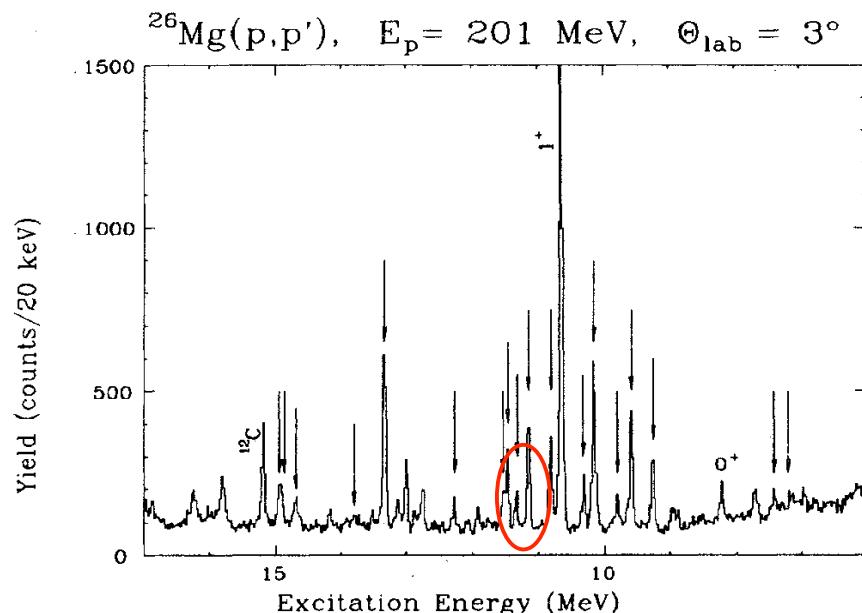


FIG. 5. Inelastic (p, p') spectrum measured at 3° on ^{26}Mg . 1^+ states are labeled by arrows. The peak at 15.2 MeV is due to ^{12}C contamination.

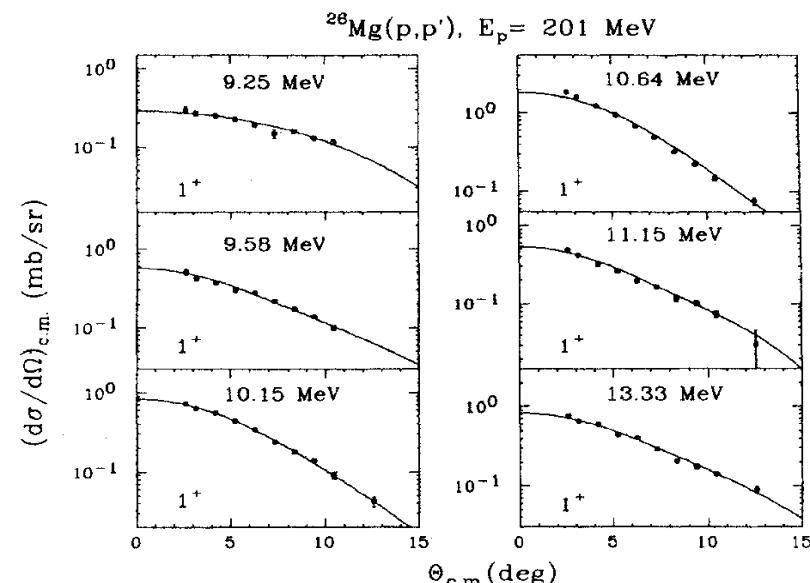
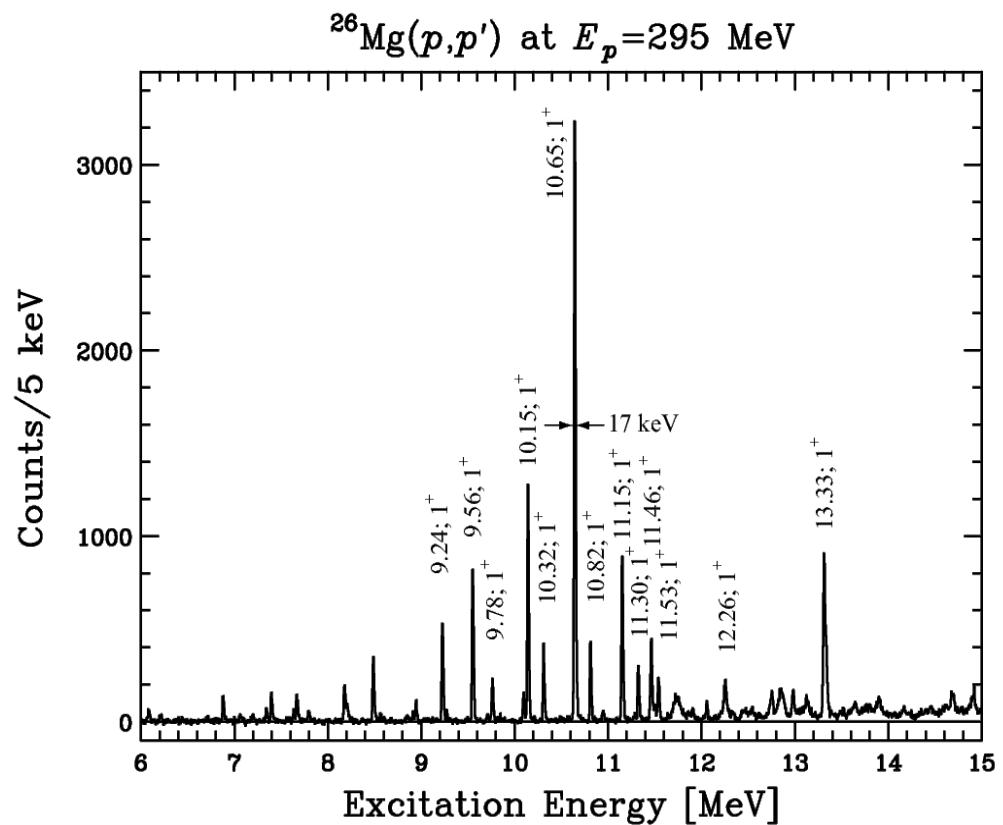
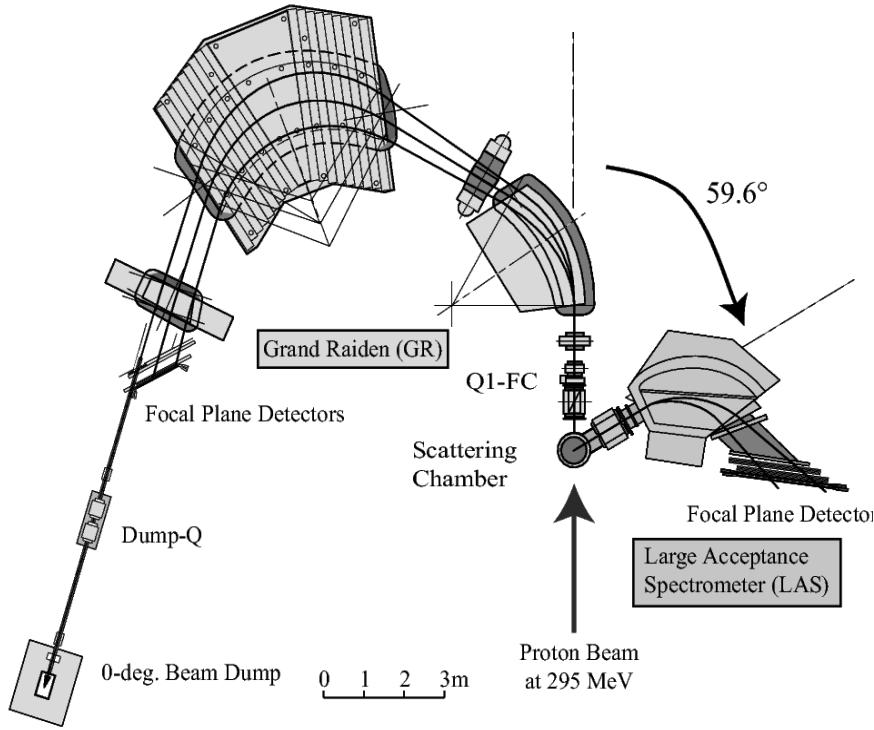


FIG. 6. Measured (p, p') angular distributions for some 1^+ states in ^{26}Mg compared in shape with microscopic DWIA calculations.

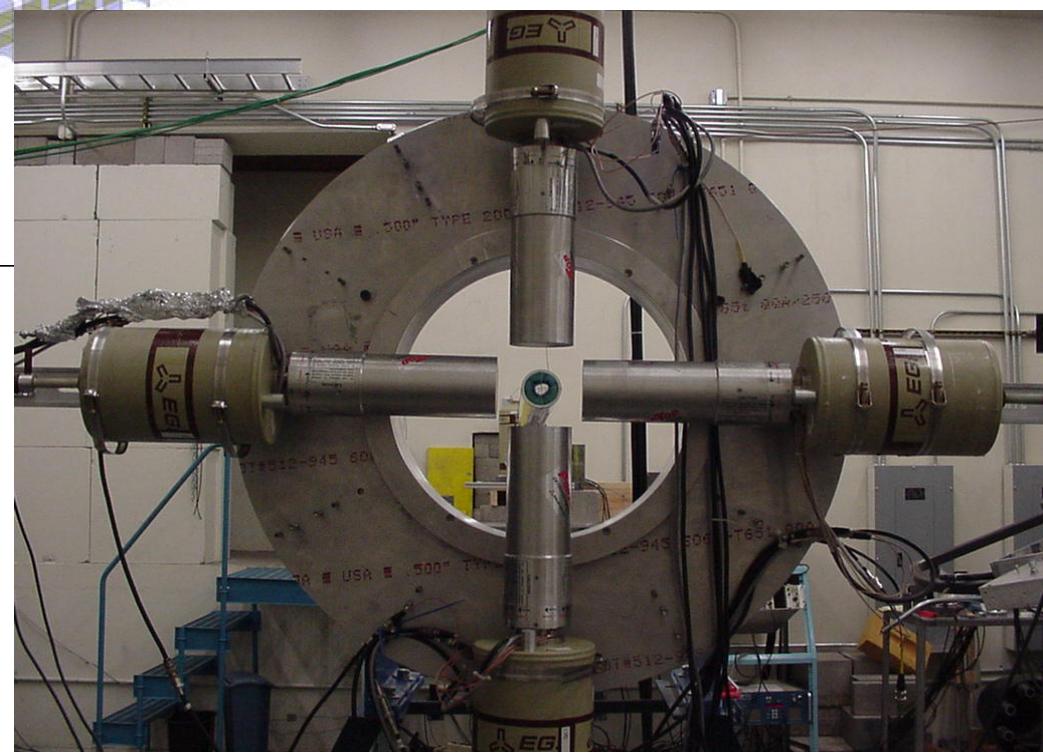
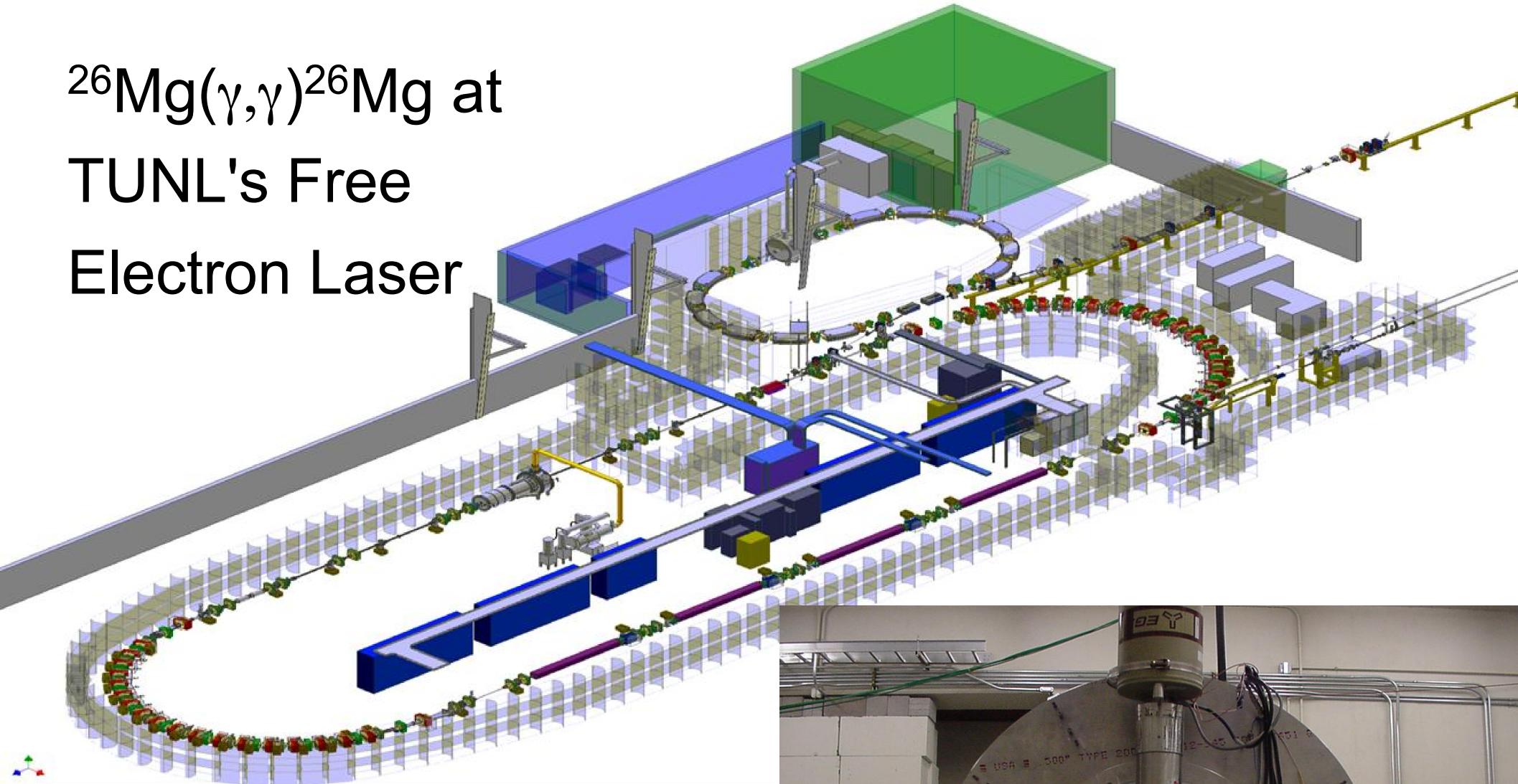
Study of $M1$ excitations by high-resolution proton inelastic scattering experiment at forward angles

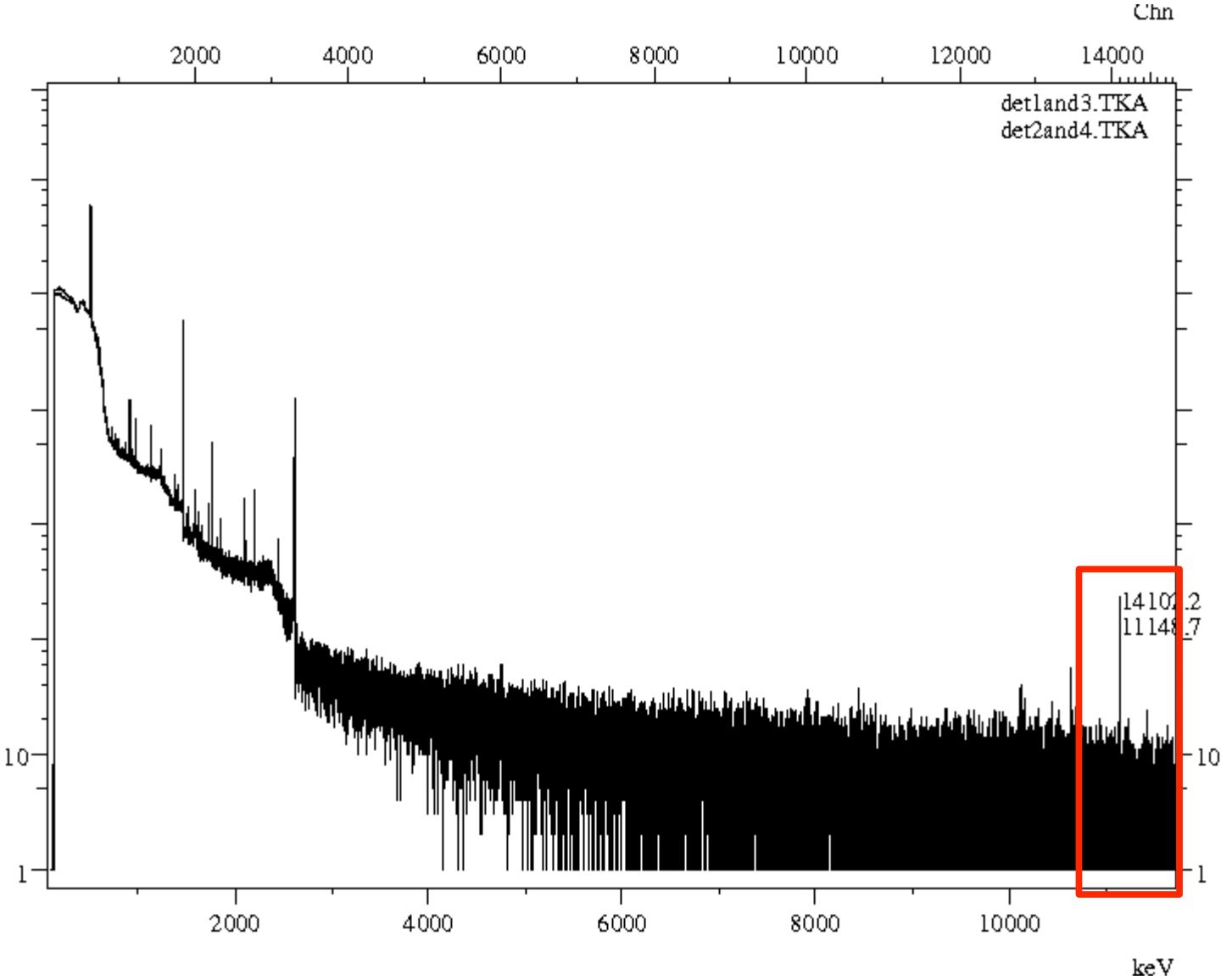
A. Tamii^a, T. Adachi^a, J. Carter^b, M. Dozono^c, H. Fujita^{b,d}, Y. Fujita^e, K. Hatanaka^a, H. Hashimoto^a, T. Kaneda^a, M. Itoh^f, T. Kawabata^g, H. Matsubara^a, K. Nakanishi^g, P. von Neumann-Cosel^h, H. Okamura^a, A. Perezⁱ, I. Poltoratska^h, V. Ponomarev^h, L. Popescu^j, A. Richter^h, B. Rubioⁱ, H. Sakaguchi^k, Y. Sakemi^a, Y. Sasamoto^g, Y. Shimbara^l, Y. Shimizu^a, F.D. Smit^d, Y. Tameshige^a, M. Yosoi^a, J. Zenihiro^k, and K. Zimmer^h

A. Tamii et al. / Nuclear Physics A 788 (2007) 53c–60c



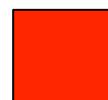
$^{26}\text{Mg}(\gamma, \gamma)^{26}\text{Mg}$ at TUNL's Free Electron Laser



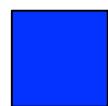


All 4 detectors together

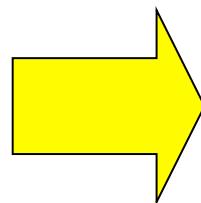
Longland 2010



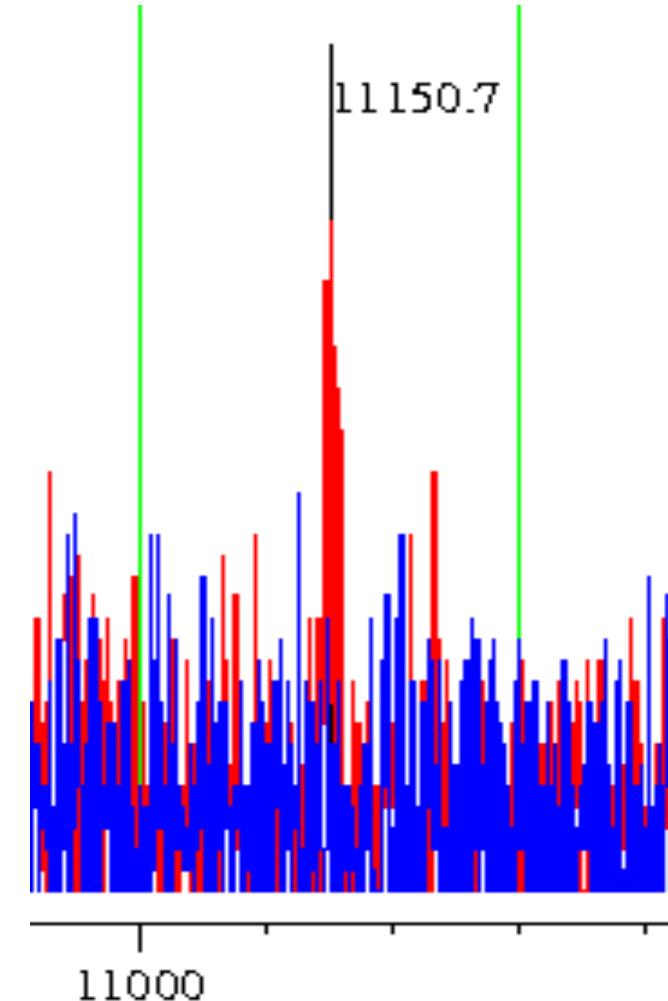
Out-of-plane detectors



In-plane detectors



M1 transition



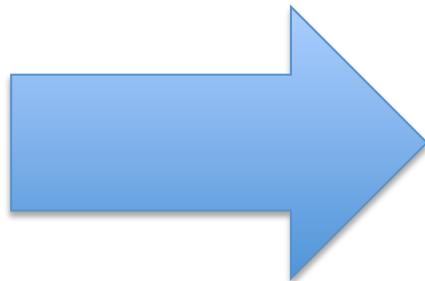
THE UNIVERSITY
of NORTH CAROLINA
at CHAPEL HILL



The 11.15 MeV resonance

$J\pi = 1+$

$^{22}\text{Ne} + \alpha$ reactions only populate natural parity states

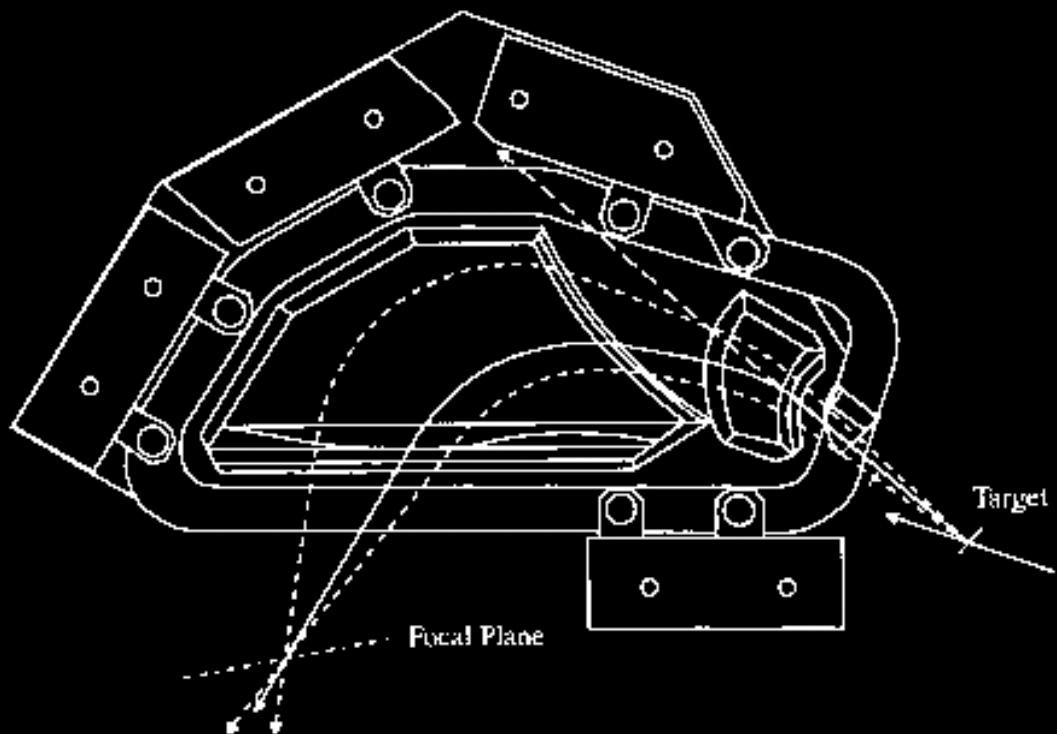
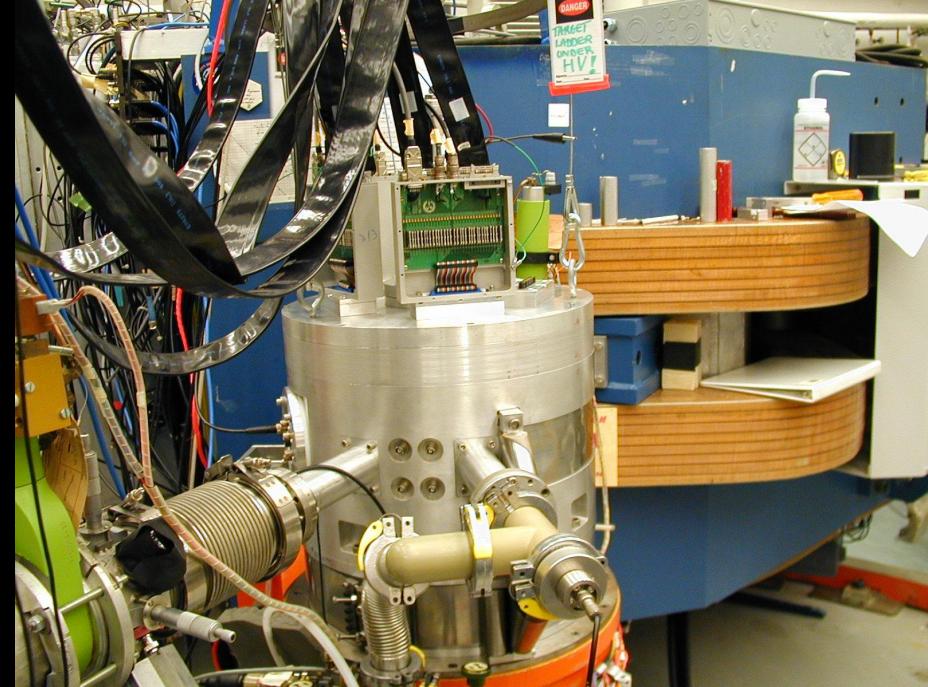


Is irrelevant to
the reaction rate

Recent searches for other resonances that may contribute to the reaction rate.

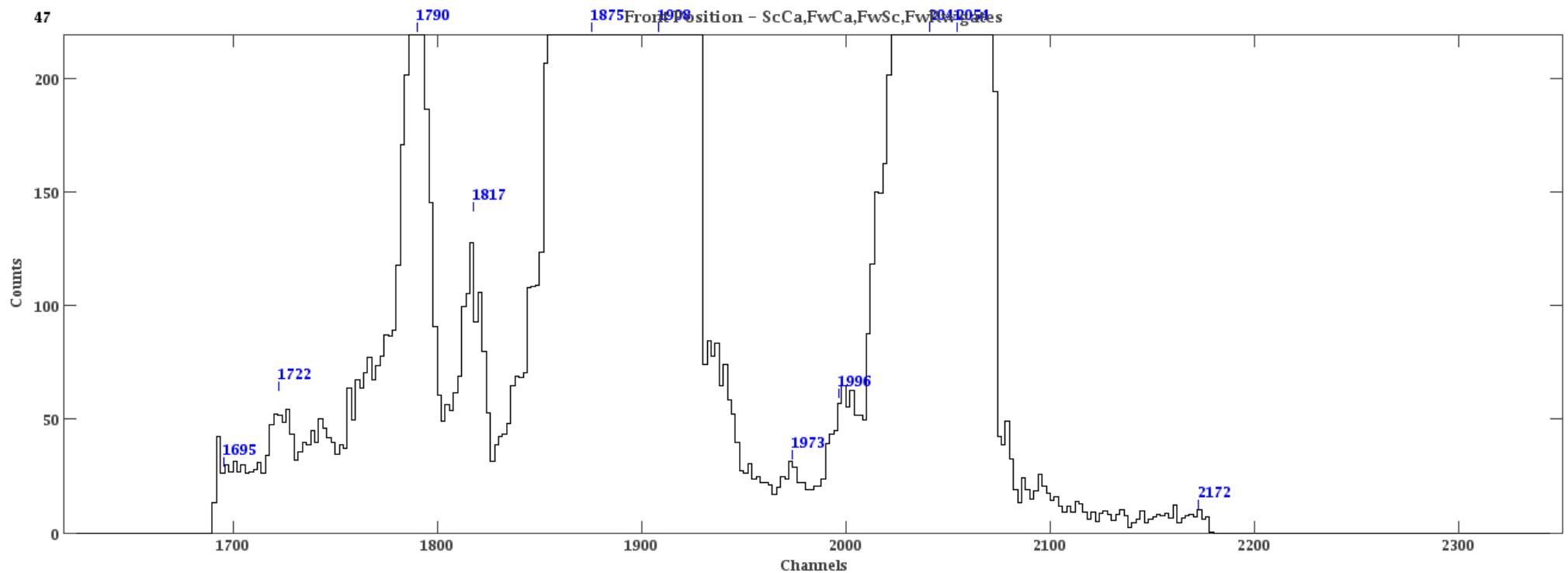
PRELIMINARY

Enge split-pole spectrometer at Yale



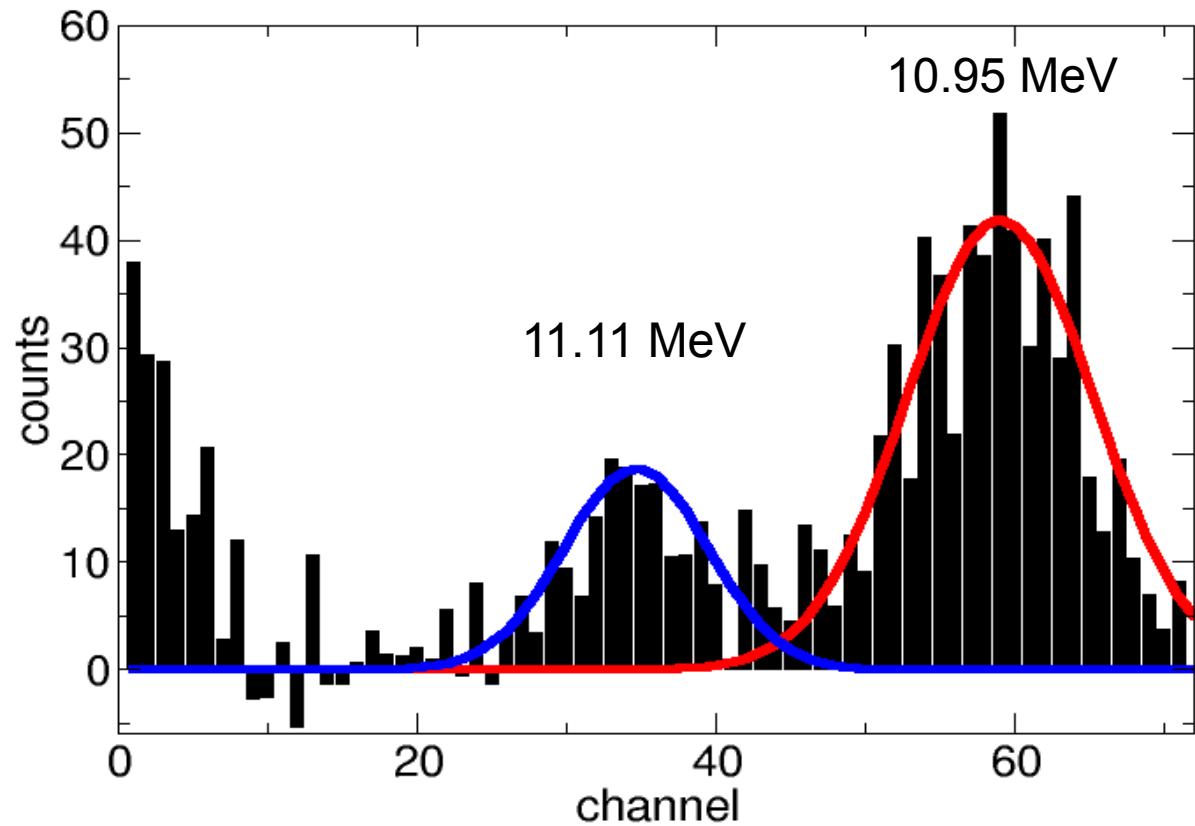
${}^6\text{Li}$ beam, @ 37.5 MeV
 $B_{\text{Enge}} = 14.4 \text{ kG}$
 $\theta_{\text{Enge}} = 4^\circ \text{ and } 8^\circ$
 $\Omega_{\text{Enge}} = 1.5 \text{ msr}$
 $\Delta E \sim 60 \text{ keV}$

$\Delta E(\text{Giesen}) \sim 120 \text{ keV}$



Claudio Ugalde, Art Champagne, Jason Clark, Catherine Deibel,
Christian Iliadis, Richard Longland, Peter Parker, Christopher Wrede,
Cynthia Wood





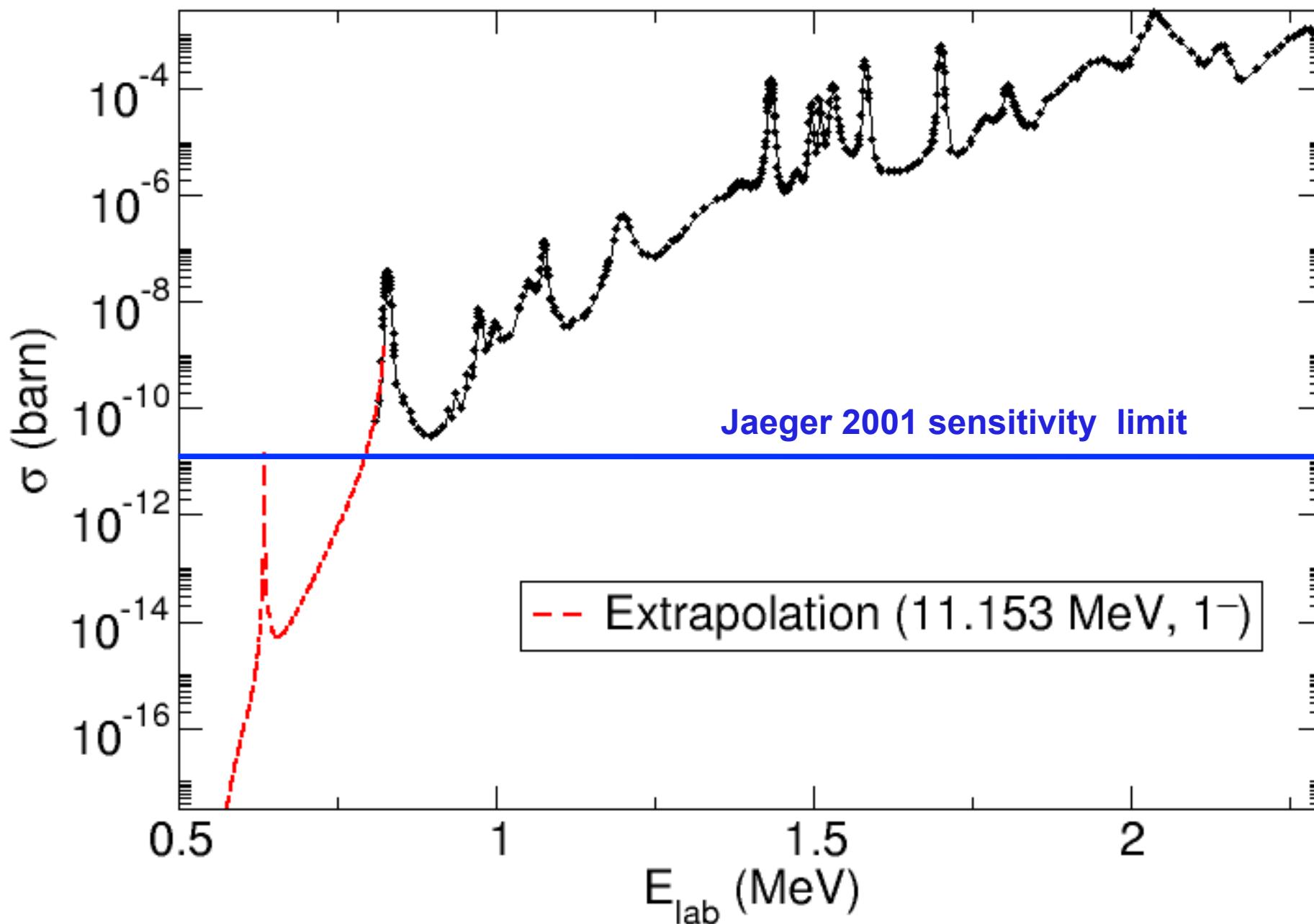
$E_x = 11.11 \text{ MeV}, J^\pi = 2+$

$E_x = 10.95 \text{ MeV}, J^\pi = (5-, 6+, 7-)$

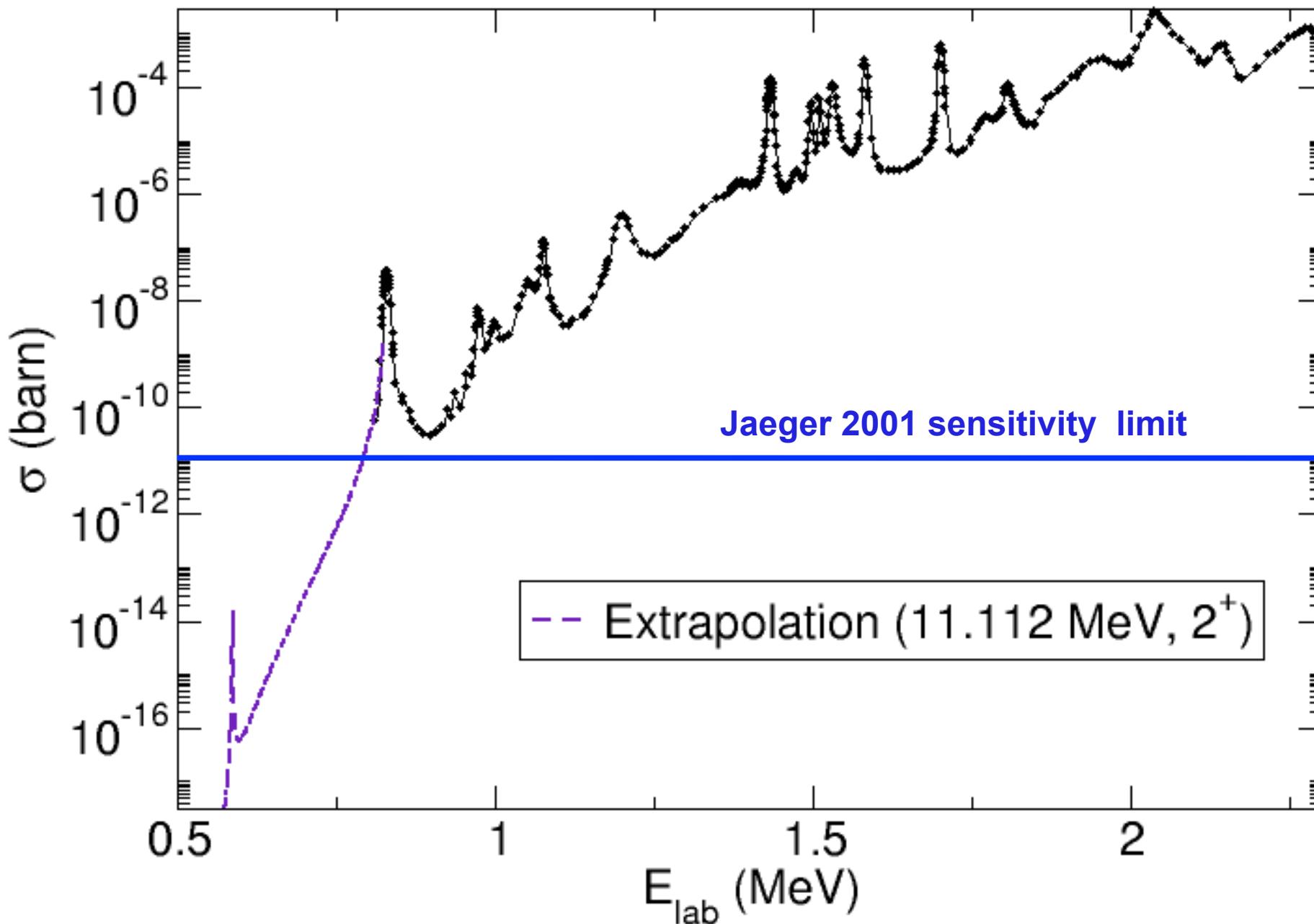
Not enough statistics to be conclusive!!



BEFORE...



TODAY... (best case scenario)



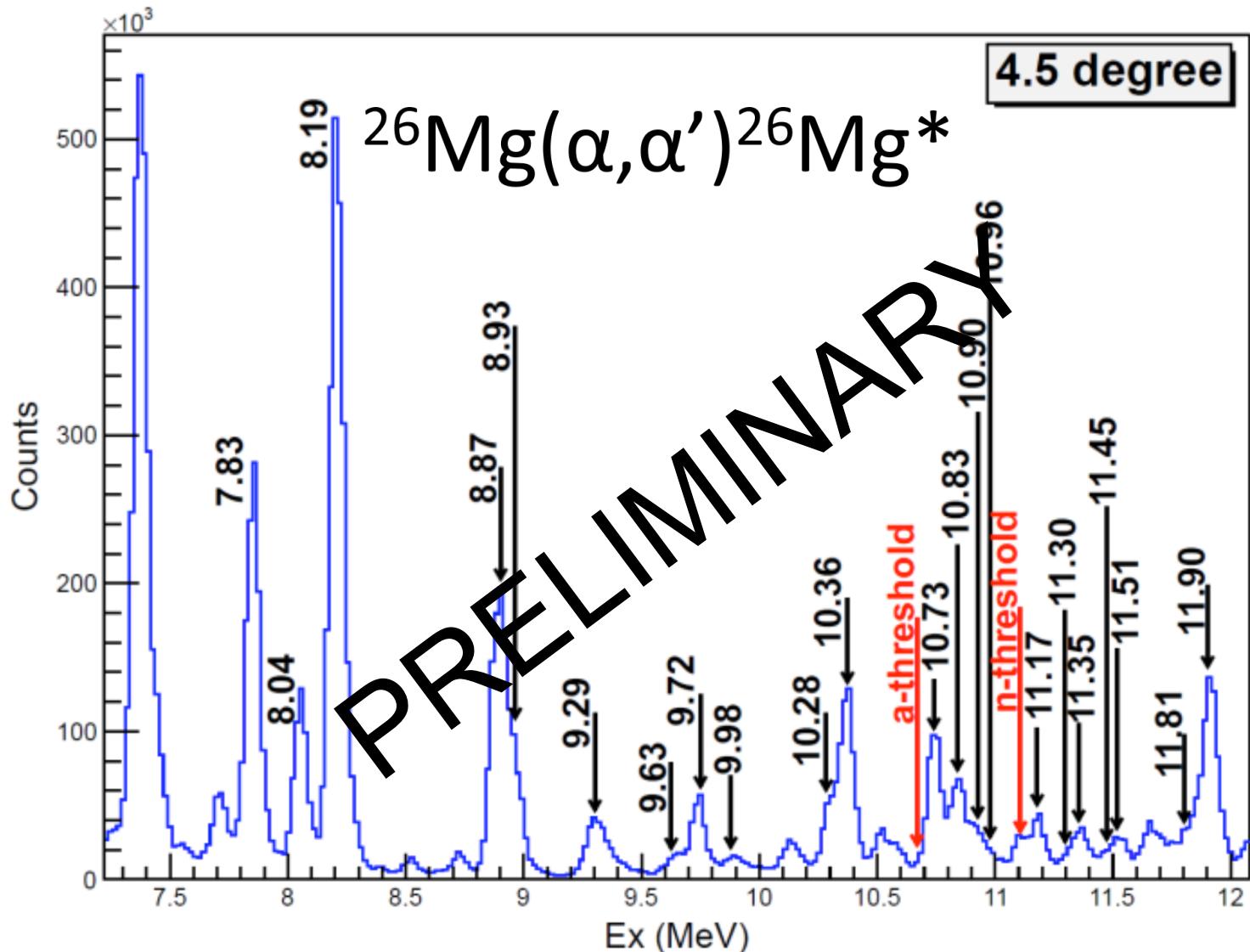


Wiescher et al.

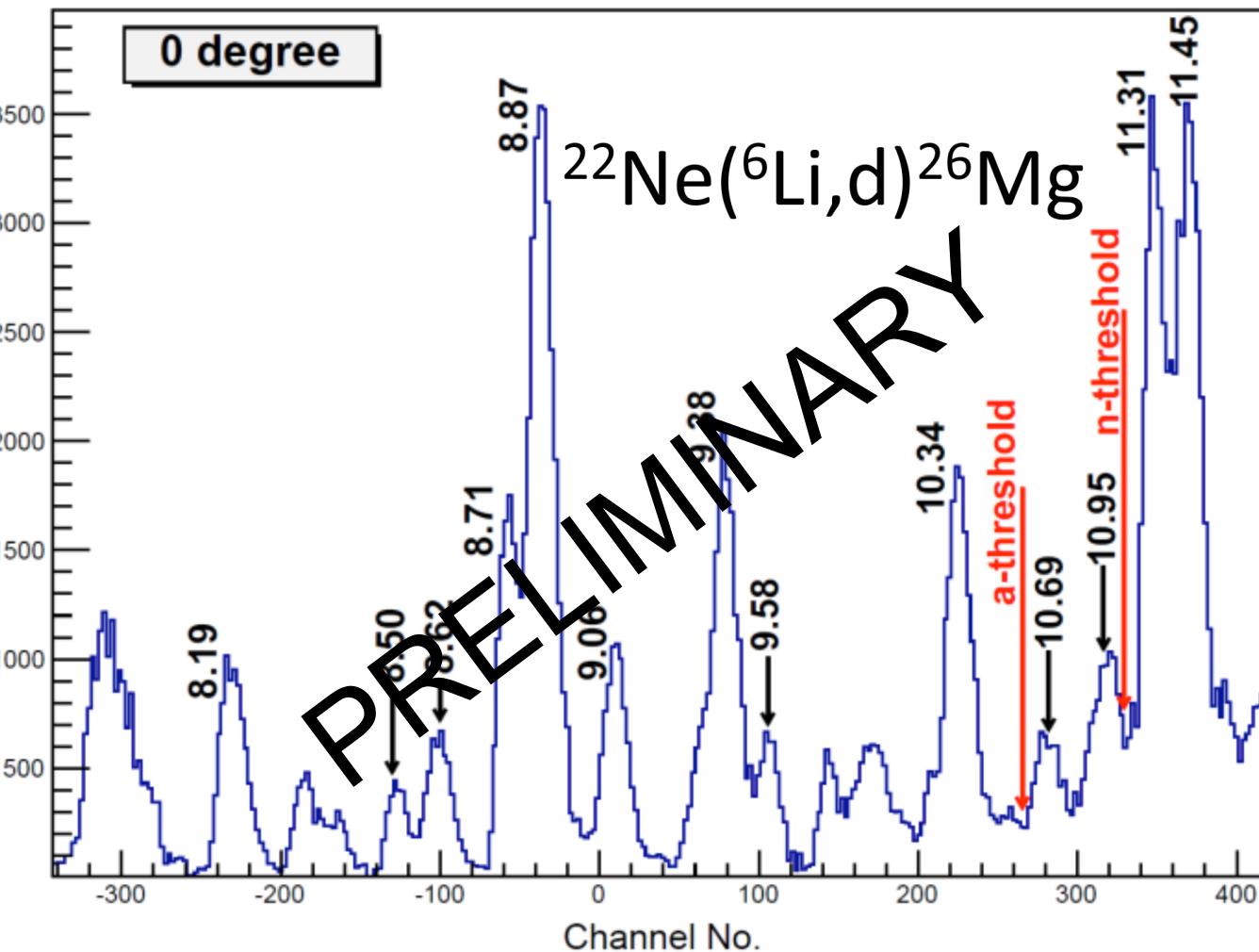


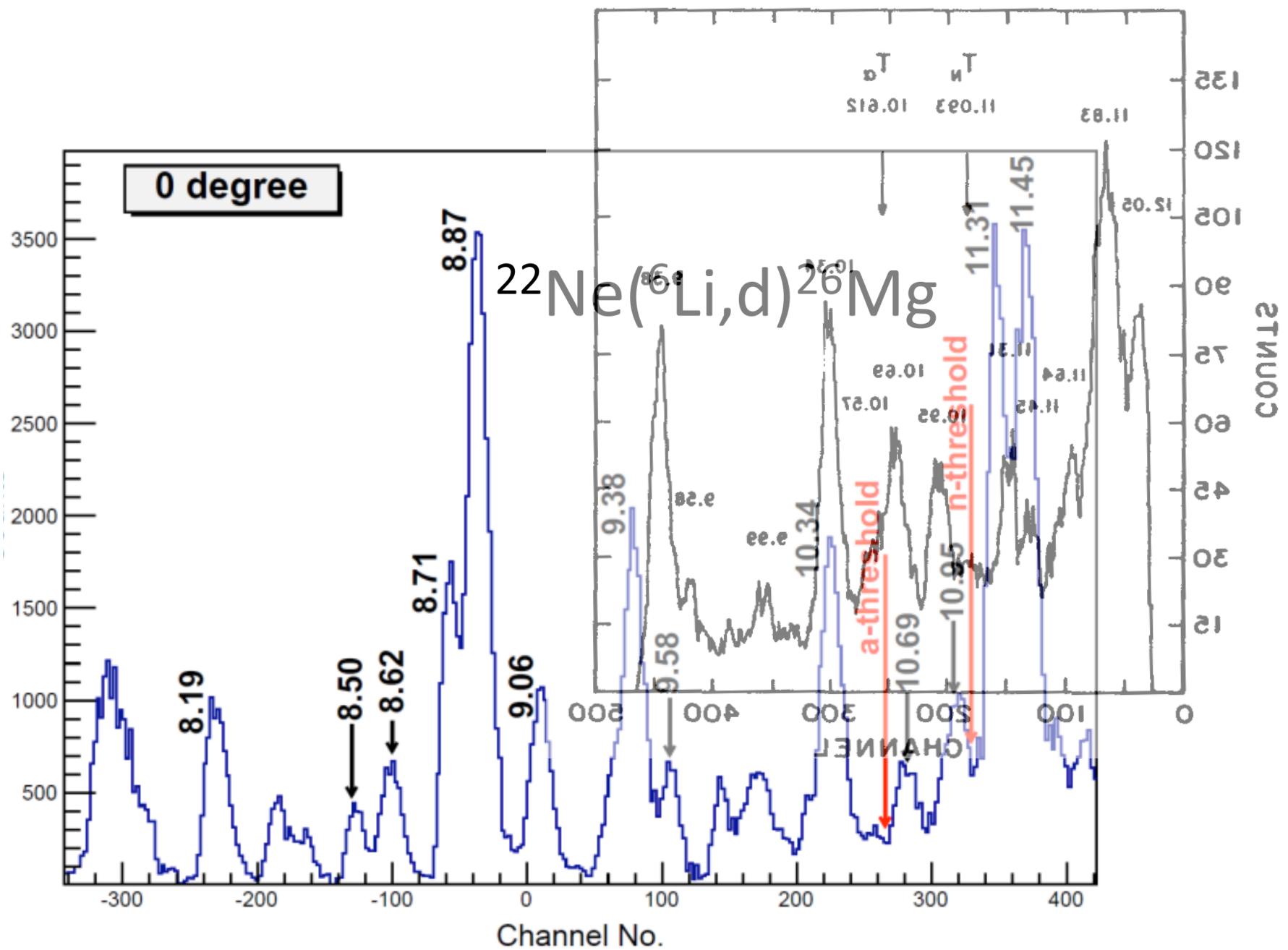
Grand Raiden

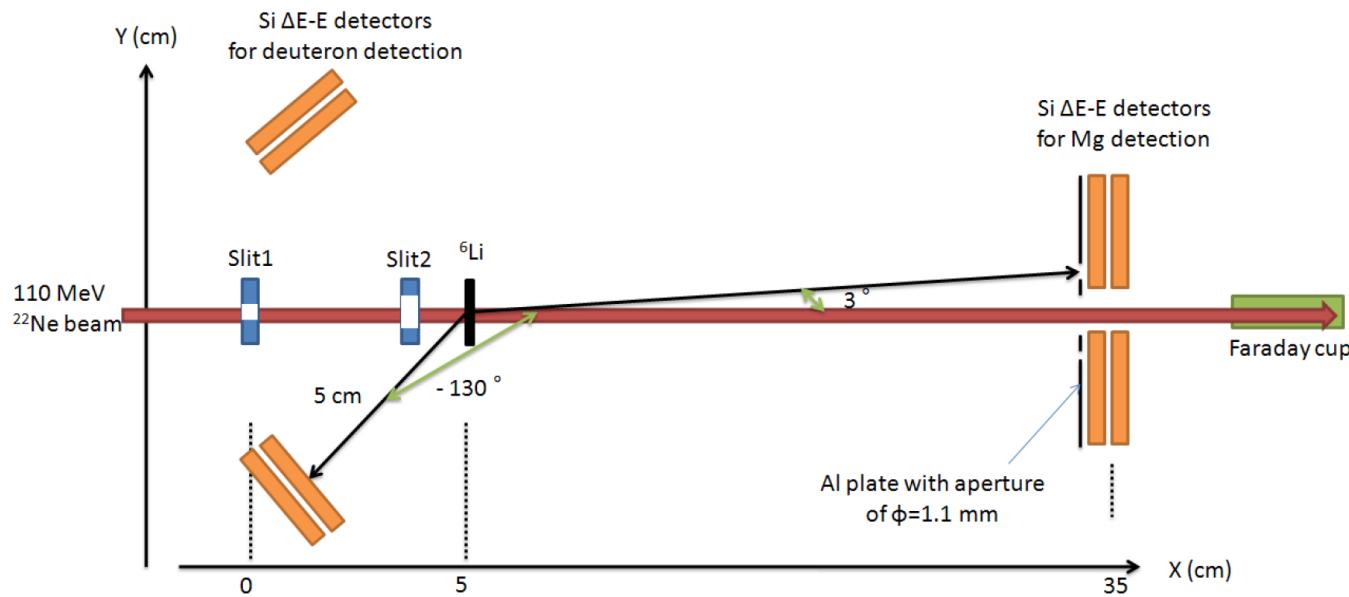




Wiescher et al. 2012



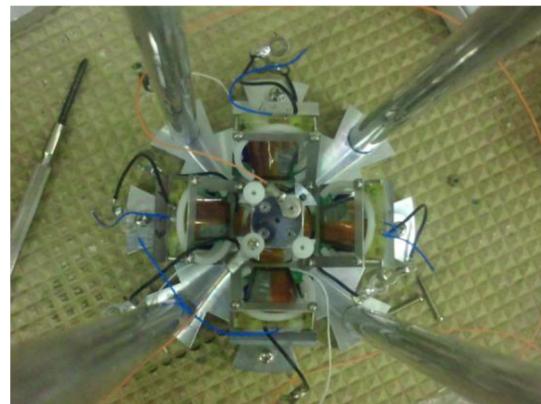




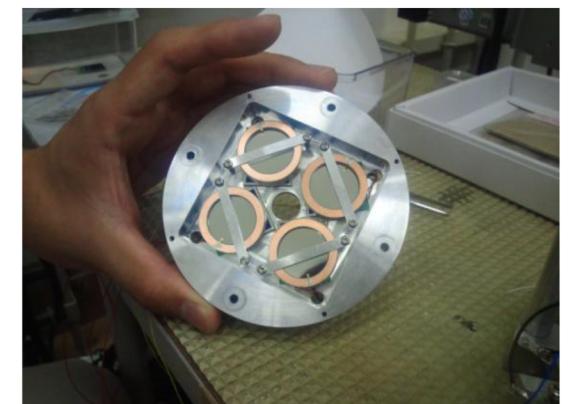
Ota 2012



Observed both reaction products in coincidence.
Count rates too small.
Different Mg isotopes could not be separated



For deuterons



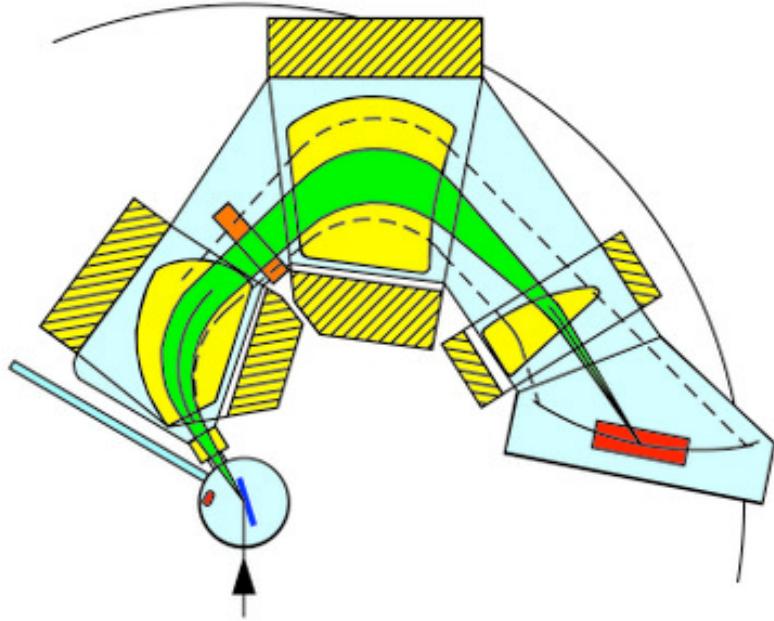
For Mg

October 2012



Longland, Parikh, Ugalde, et al.

Q3D magnetic spectrograph

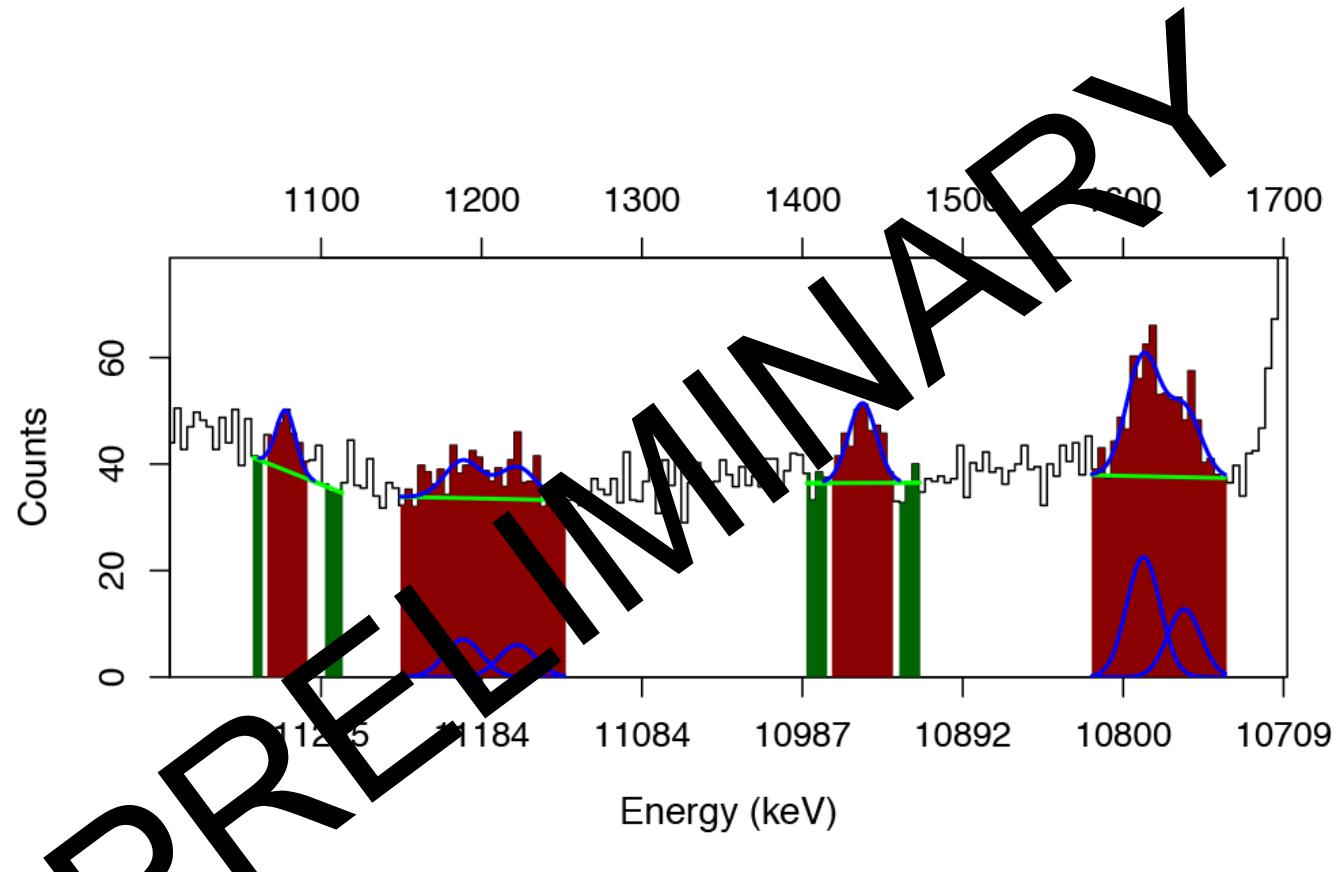


Targets implanted on natural C, ^{13}C , ^{26}Si , and old ^{12}C enriched.
Resolution for ^{26}Mg states: $\sim 25 \text{ keV}!!!$

Analysis in progress...

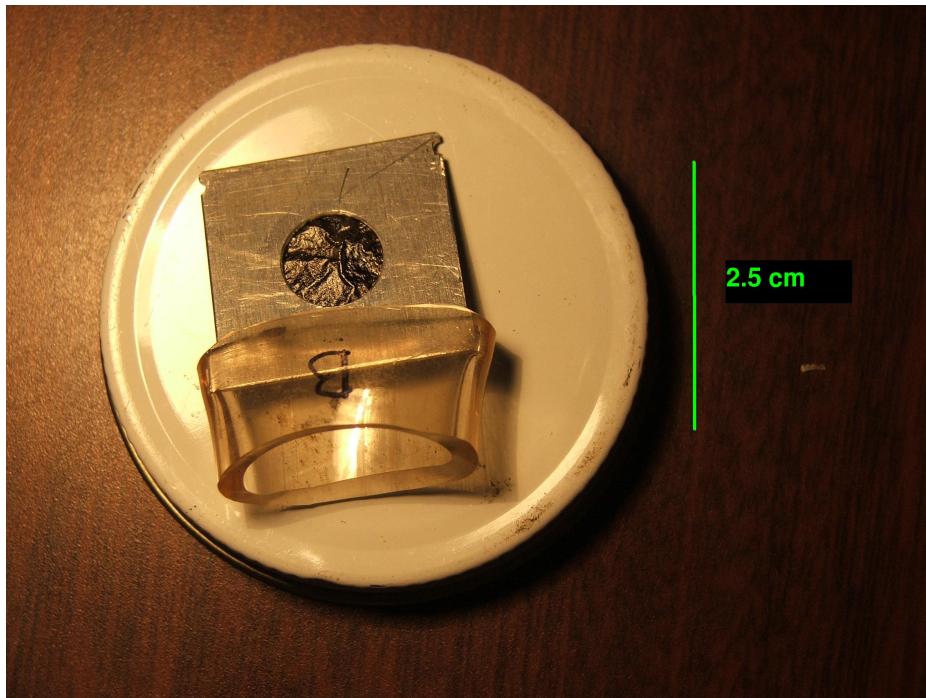
$^{22}\text{Ne}(^6\text{Li},\text{d})^{26}\text{Mg}$

Longland, Parikh, Ugalde, et al.



The trick...

^{22}Ne targets



$40\mu\text{g}/\text{cm}^2$ ^{12}C -enriched foils

Implanted on both sides, two energies each

Dose $\sim 20 \text{ mC}$ per target

Targets are very, very fragile.
Substrates can withstand up to
 400 nA of ^{22}Ne beam

Suggestion:

Do not use gas targets with foil windows. Your resolution will be inappropriate.

$^{22}\text{Ne} + \alpha$: to-do next 5 years

Direct measurements? EXTREMELY challenging below 800 keV. Need to start trying a combination of:

- a) DEEP underground labs (LUNA MV),
- b) recoil separators(St George, Caserta)
- c) detectors with new technologies (see next talk)
- d) ultra dense windowless jet gas targets. This is probably the next big technological problem that needs to be addressed. (JENSA is not enough, BTW).

$^{22}\text{Ne} + \alpha$: to-do next 5 years. (Continued)

- $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$. Concentrate on the $E_{\text{lab}} = 831$ keV resonance.
- $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$. Resonances above the neutron threshold. Our best bet for this reaction by far is LUNA MV.
- R-matrix analysis. Tail contribution and interference into the Gamow peak region. Any cusp contribution to the cross section?
- Start thinking about measuring $^{22}\text{Ne}(\alpha, \alpha)^{22}\text{Ne}$

$^{22}\text{Ne} + ^6\text{Li}$: to-dos

Now that we learned how to do it...

- Get better statistics
- Get more angles
- Get more energies
- Get optical potentials

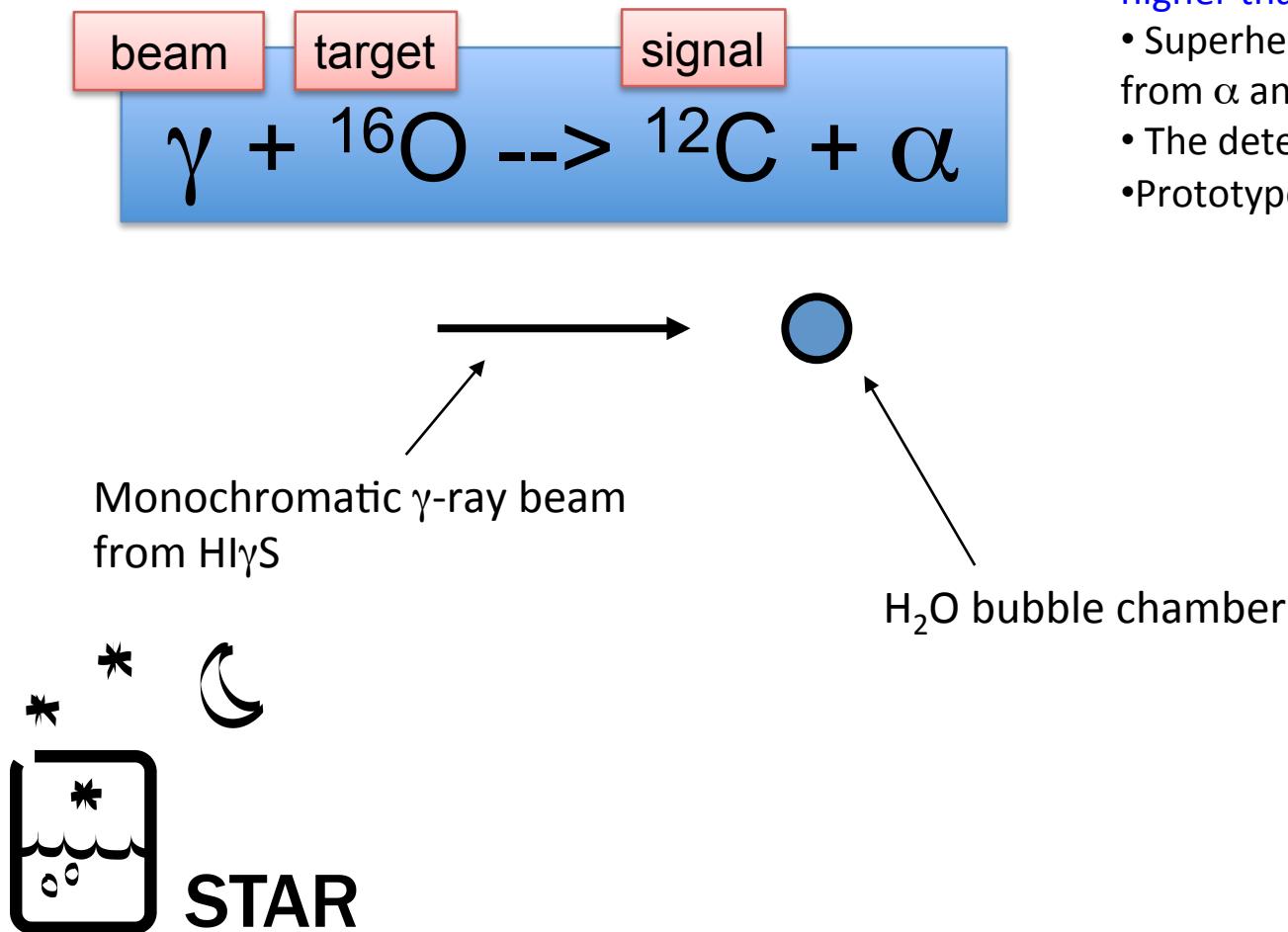
MOST IMPORTANT:

To what extent the transfer reaction mechanism assumptions are applicable to the calculation of α -particle widths ??? Systematic comparisons are needed. This is a monumental work.

Bubble chamber

C. Ugalde^{1,7}, B. DiGiovine¹, D. Henderson¹, R. J. Holt¹, K.E. Rehm¹, A. Robinson⁷, A. Sonnenschein⁴, A. Tonchev^{2,5}, R. Raut^{2,5}, G. Rusev^{2,5}, A. Champagne^{2,3}, N. Sturchio⁶

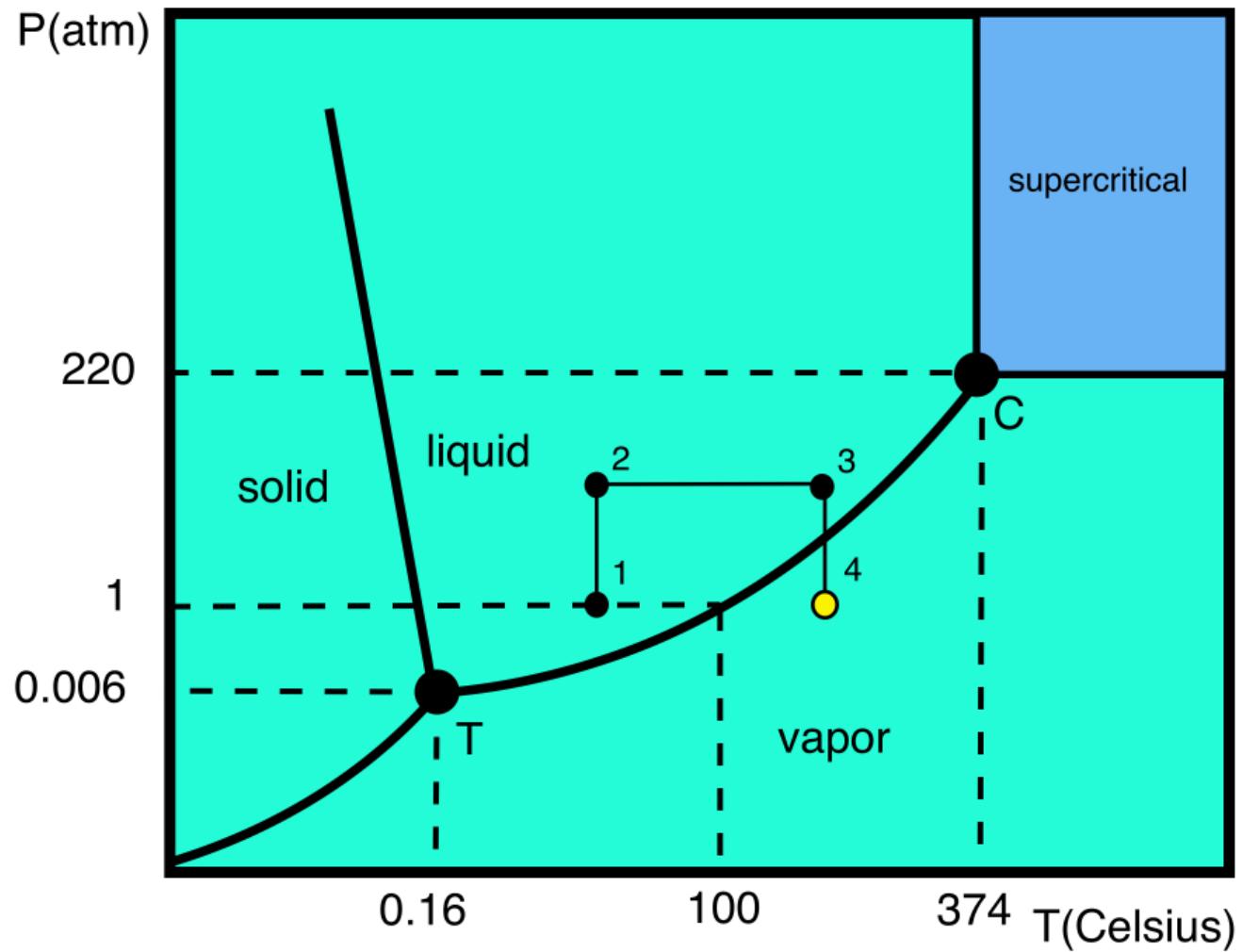
¹Argonne National Laboratory, ²Triangle Universities Nuclear Laboratory, ³University of North Carolina at Chapel Hill, ⁴Fermi National Accelerator Laboratory, ⁵Duke University, ⁶University of Illinois at Chicago, ⁷University of Chicago

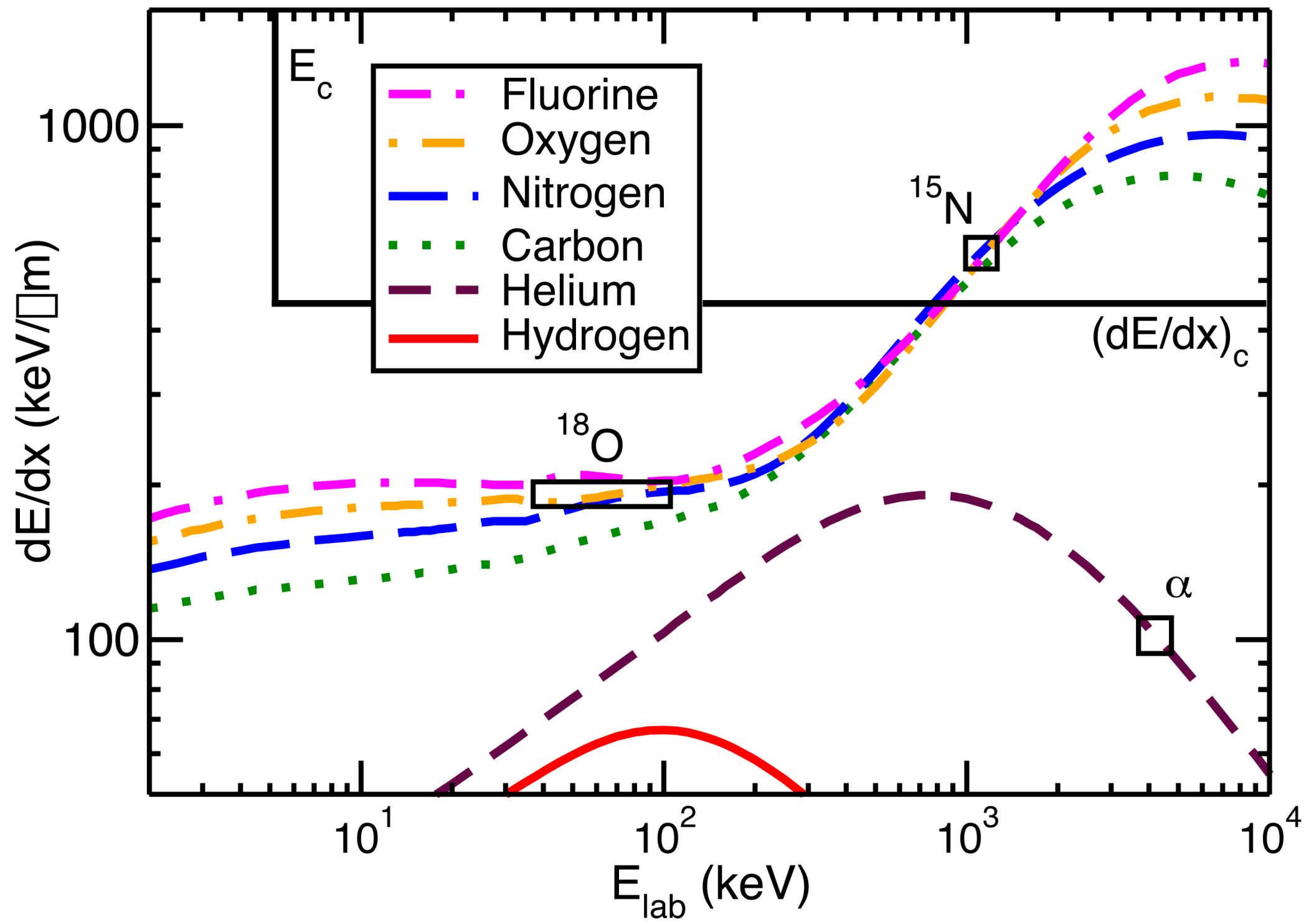


- The target density is 1000-10000x higher than gas targets.
- Superheated water will nucleate from α and ${}^{12}\text{C}$ recoils
- The detector is insensitive to γ -rays.
- Prototype tested at H γ S



Superheating of water





Ranges in water

