$^{18}Ne(\alpha,p)^{21}Na$ via $^{18}Ne(^{6}Li,d)^{22}Mg^*$ alpha transfer

E1110

TRIUMF, EEC July 24, 2006

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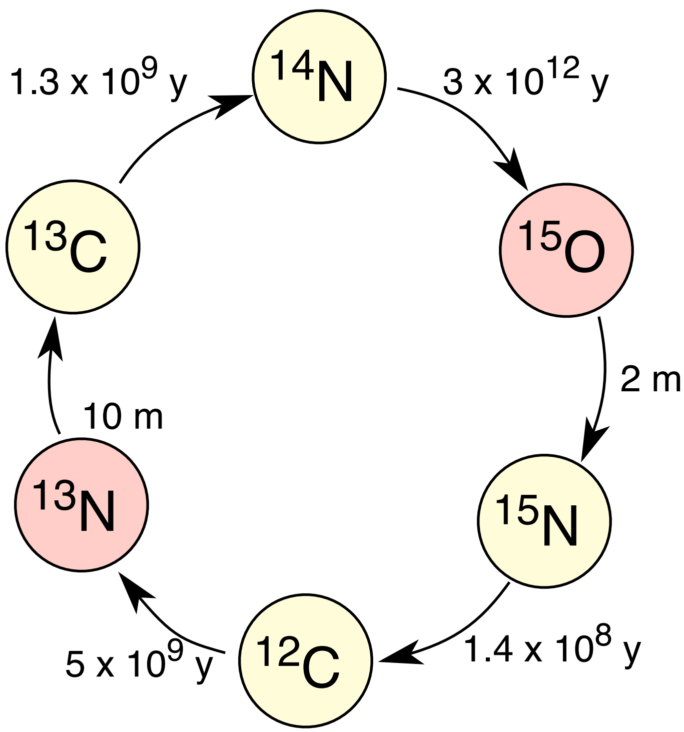
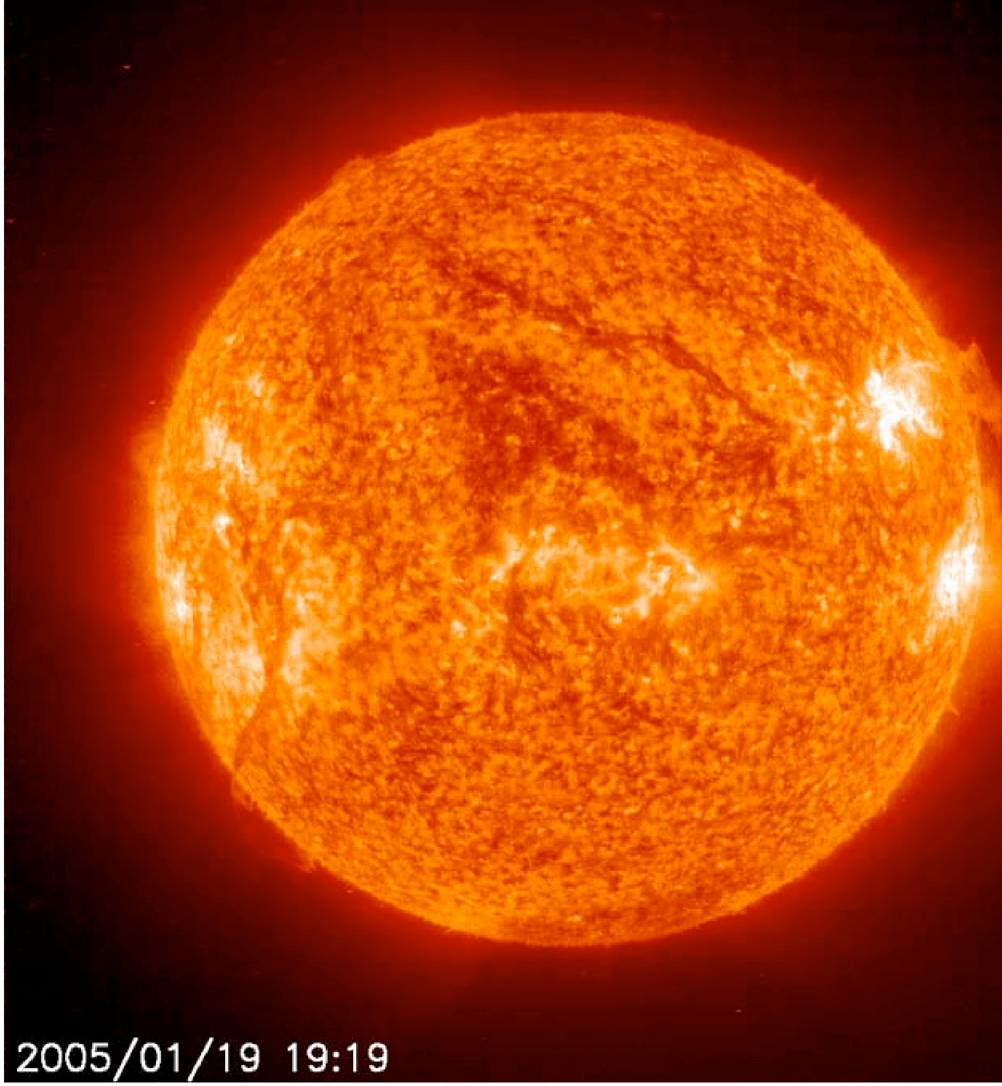
The hot CNO cycle and its breakout

The "cold" CNO cycle

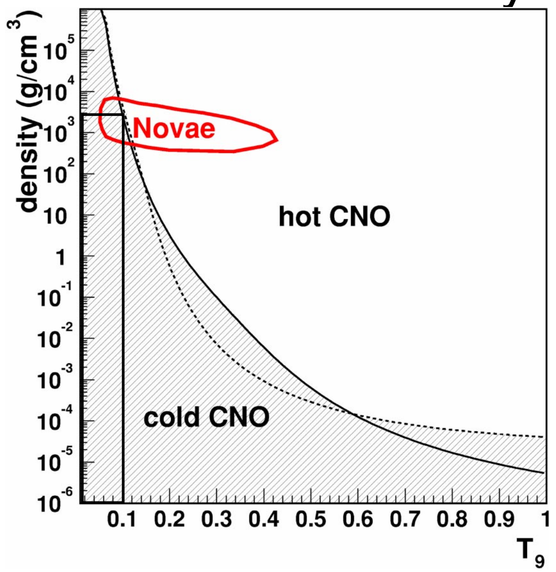


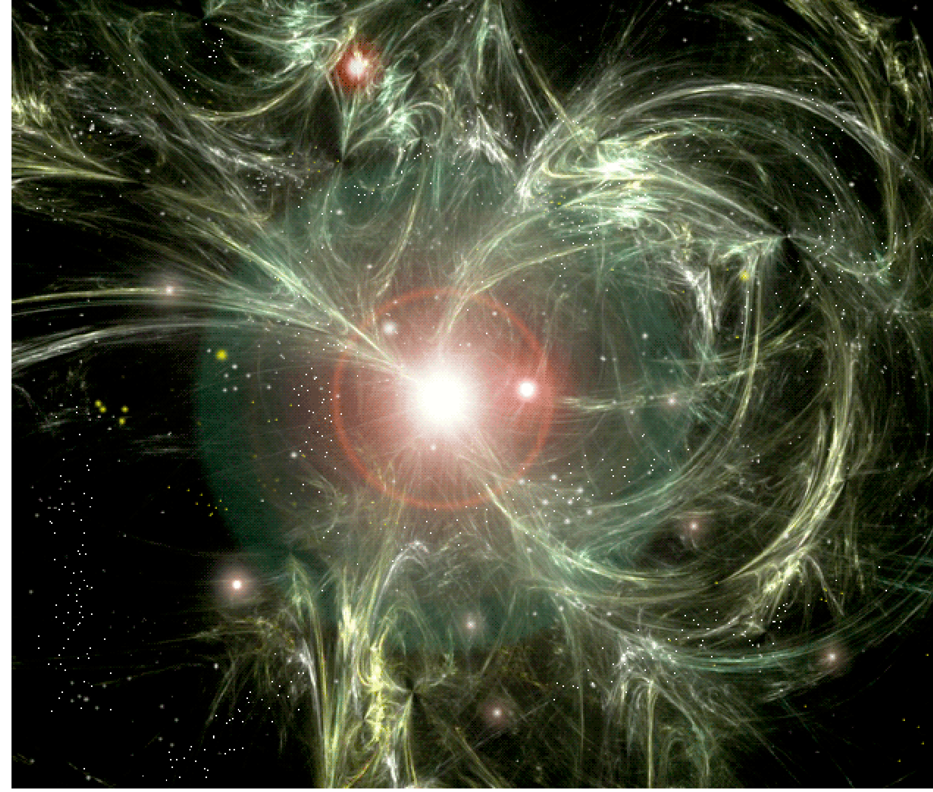


$T_9 = 0.01$

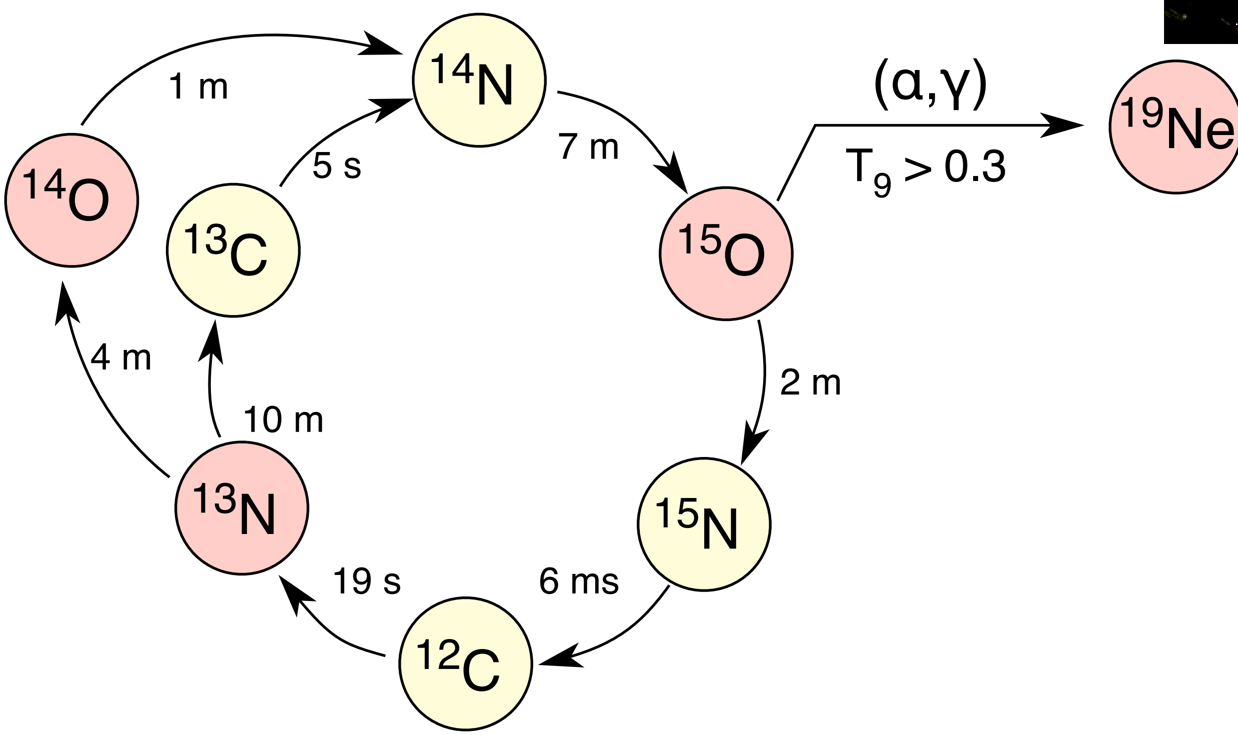
$\rho = 100\ g/cm^3$

The hot CNO cycle and its breakout





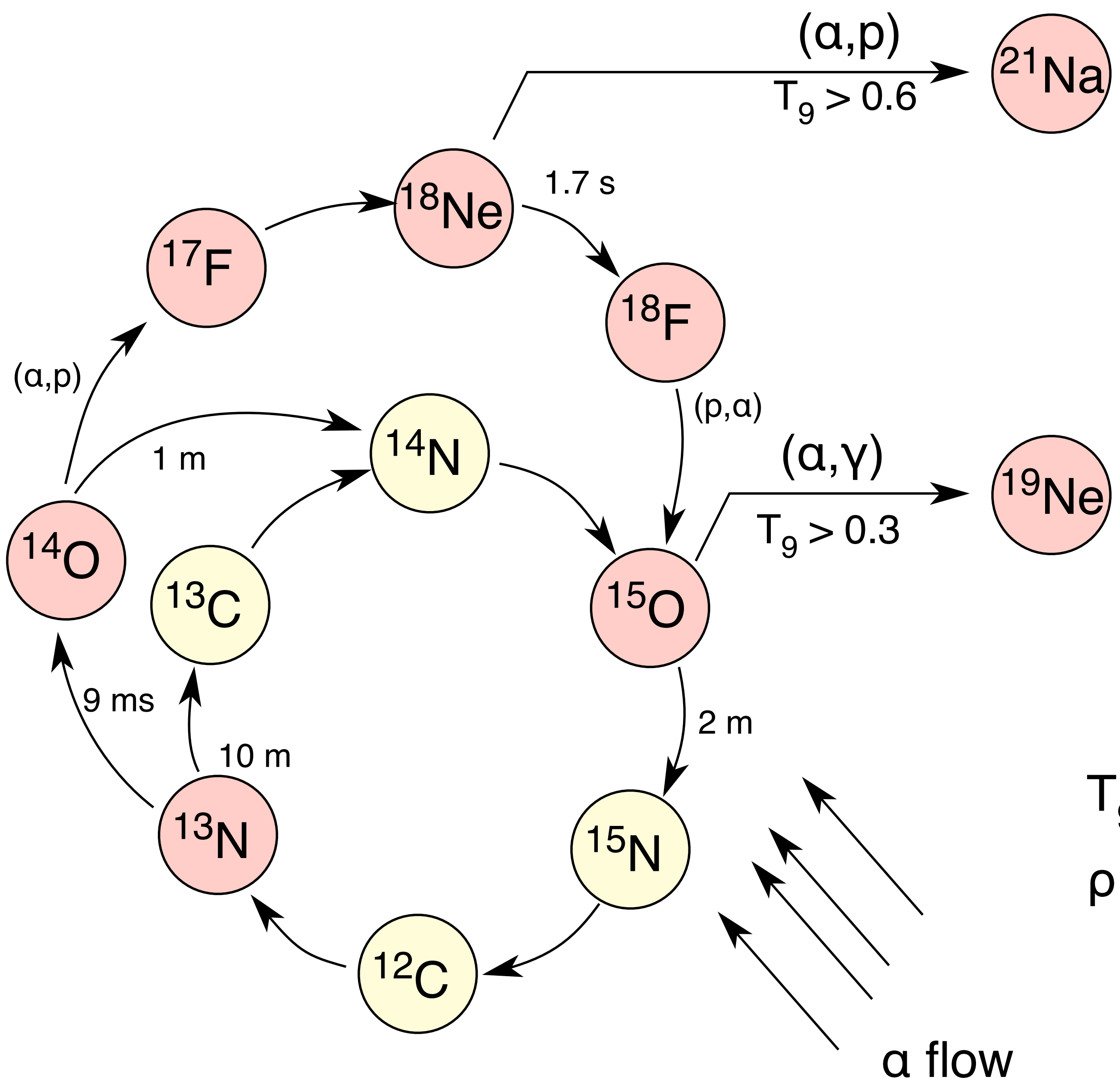
The "hot" CNO cycle

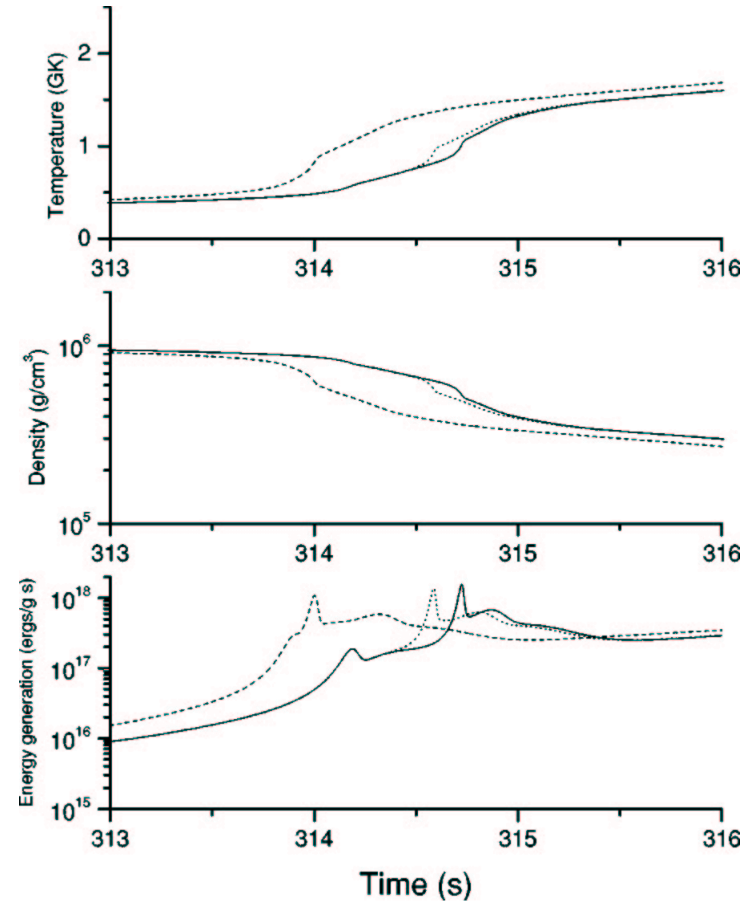


$T_9 = \mathbf{0.1} - 0.3$

$\rho = 3000\ \mathrm{g/cm^3}$

The hot CNO cycle and its breakout





$T_9 = \mathbf{0.3} - 0.6$

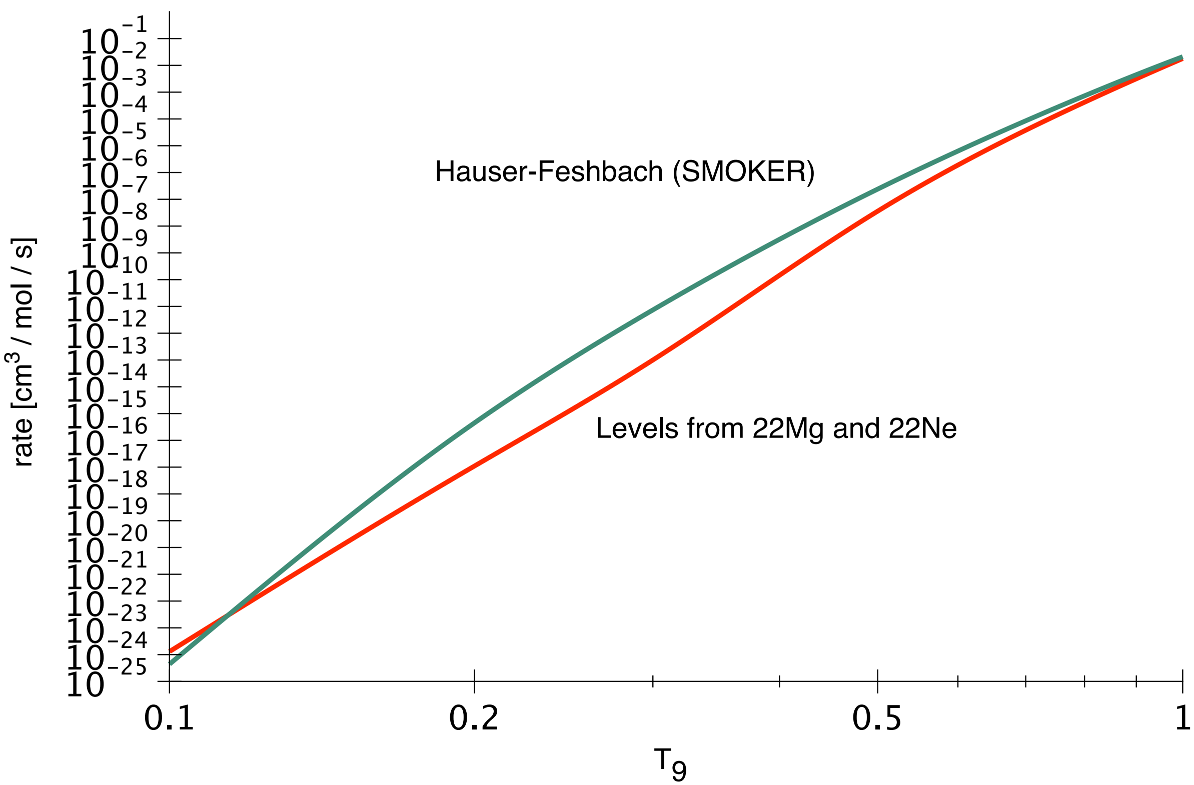
$\rho = 10^6\ g/cm^3$

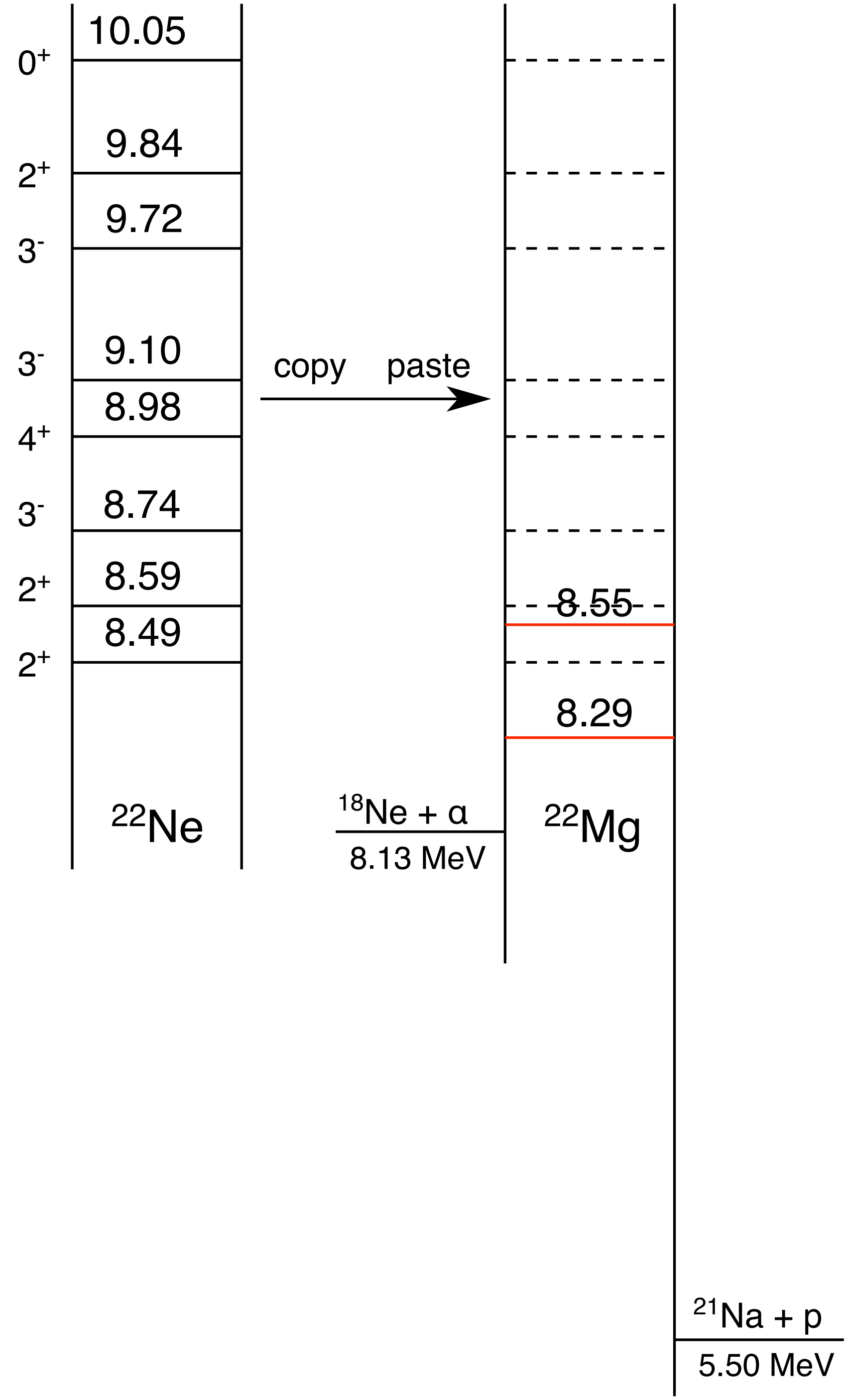
Hauser-Feshbach estimation

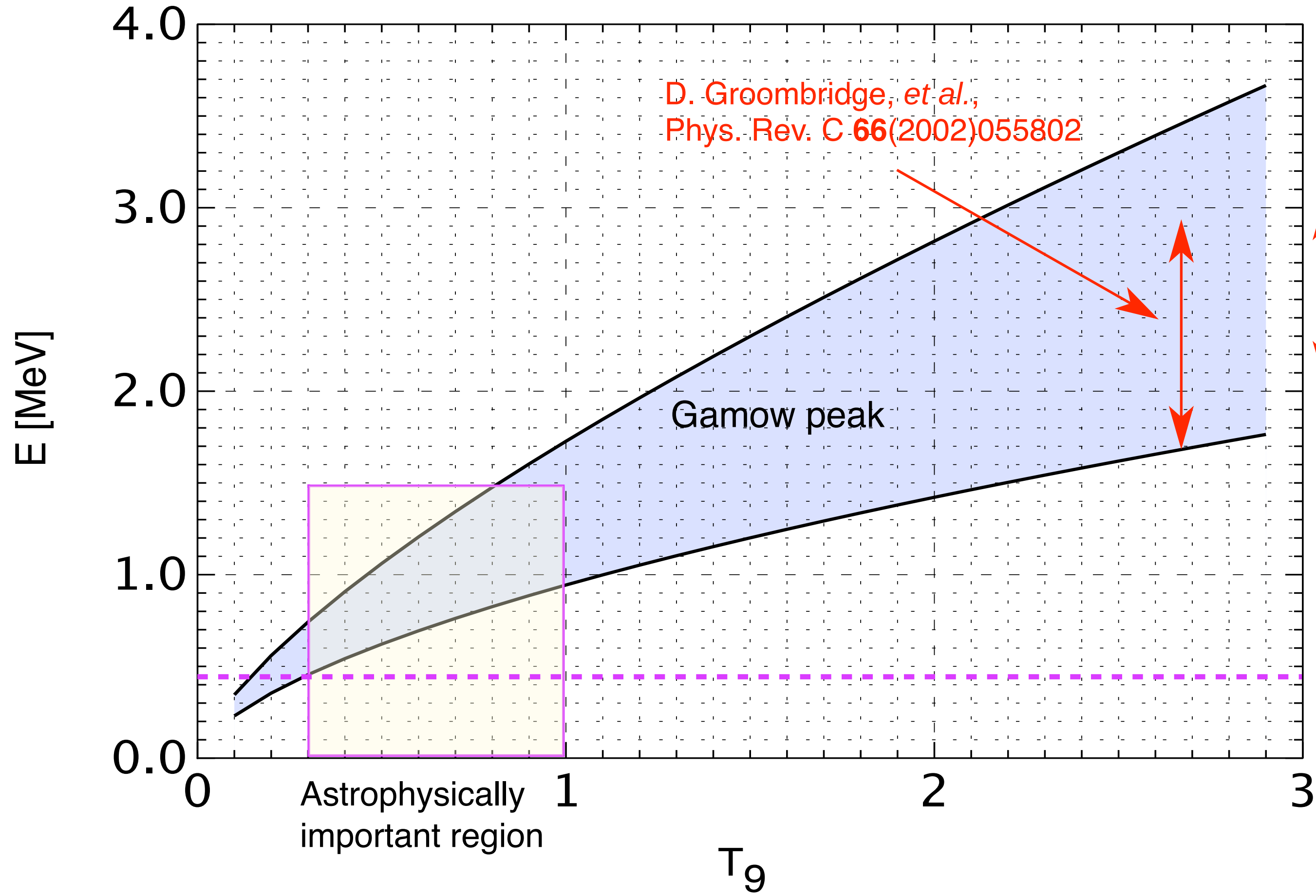
Görres et al., Phys. Rev. 51(1995)392

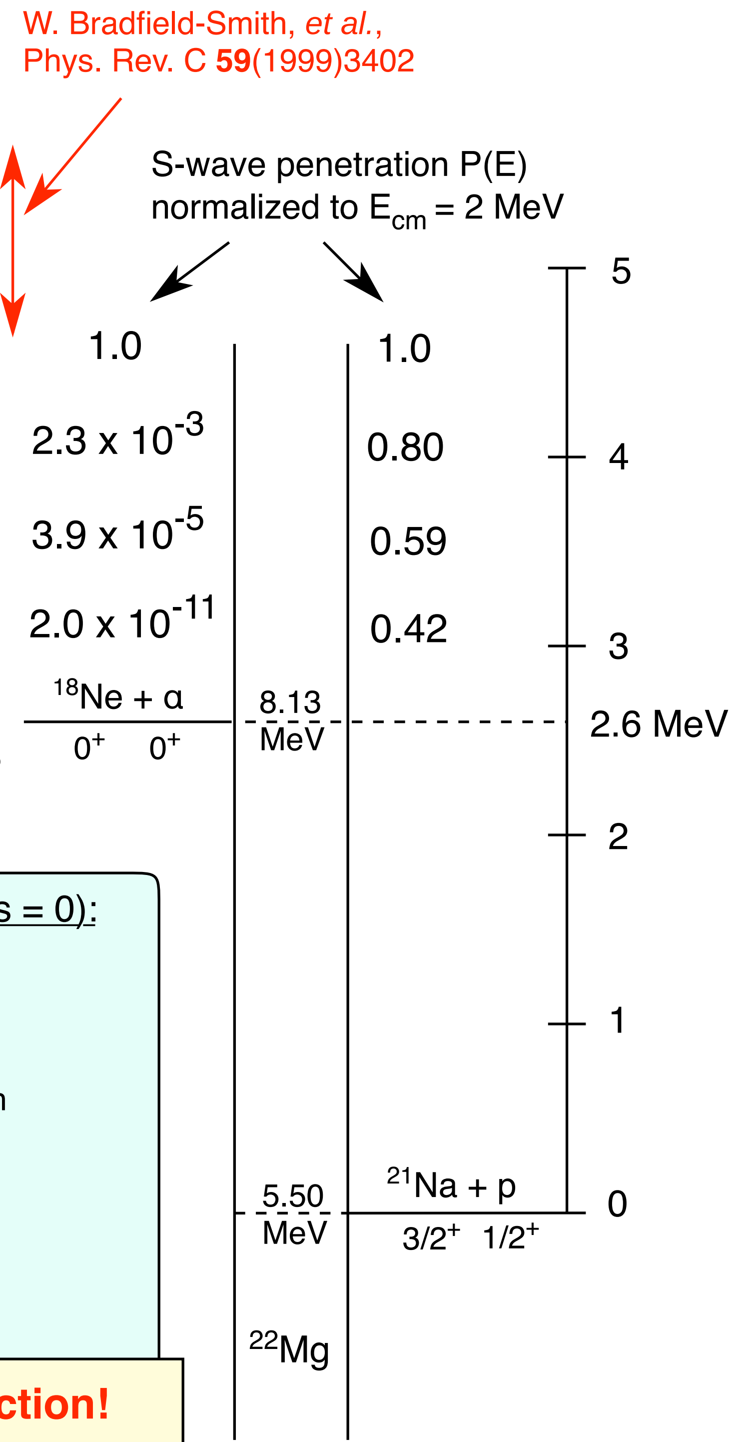
$D < \Gamma < \Delta E_G$ D = level spacing

$D = 0.2$ MeV
$\Gamma = 0.1 - 0.2$ MeV
$\Delta E_G = 0.4 - 0.8$ MeV









Partial width:

$$\Gamma_\lambda = P_\lambda \times k_\lambda R_\lambda \times \gamma_\lambda^2, \quad \lambda = \alpha, \mathrm{p}$$

Resonance integrated cross-section:

$$\int \sigma(E)dE = \frac{2\pi^2}{k_\alpha^2}\omega\gamma$$

Resonance strength (spins = 0):

$$\omega\gamma = (2J+1)\frac{\Gamma_\alpha \Gamma_p}{\Gamma}$$

Huge proton width, tiny α width

$$\Gamma_\alpha \ll \Gamma_p \approx \Gamma$$

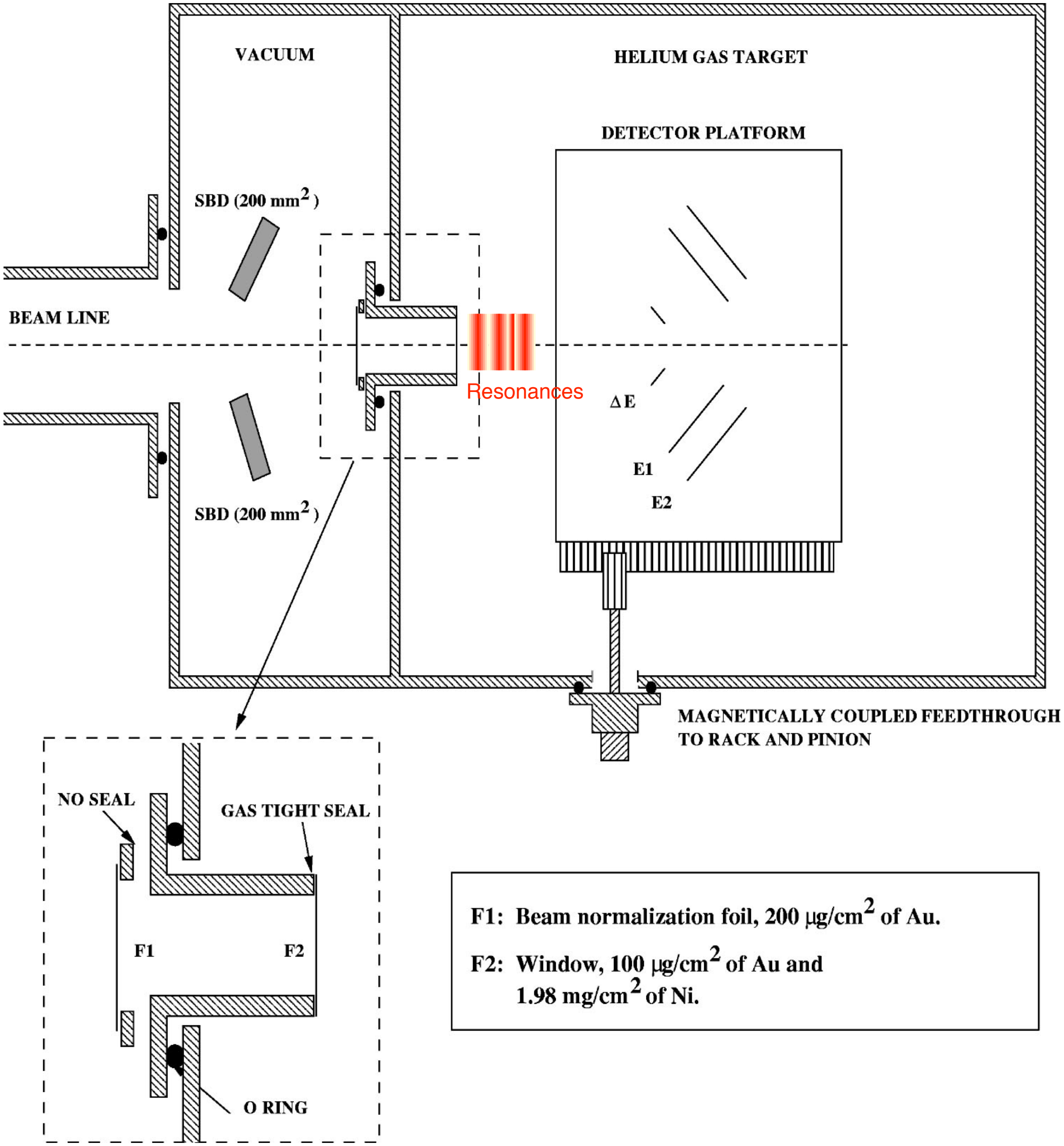
$$\downarrow$$

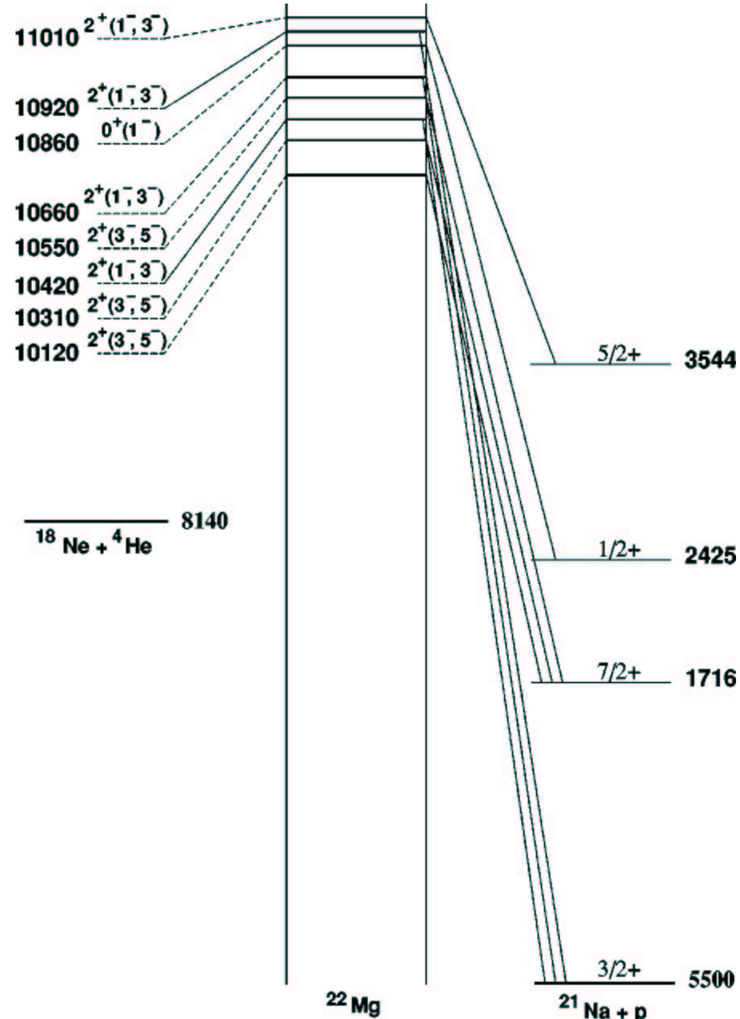
$$\omega\gamma \approx (2J+1)\,\Gamma_\alpha$$

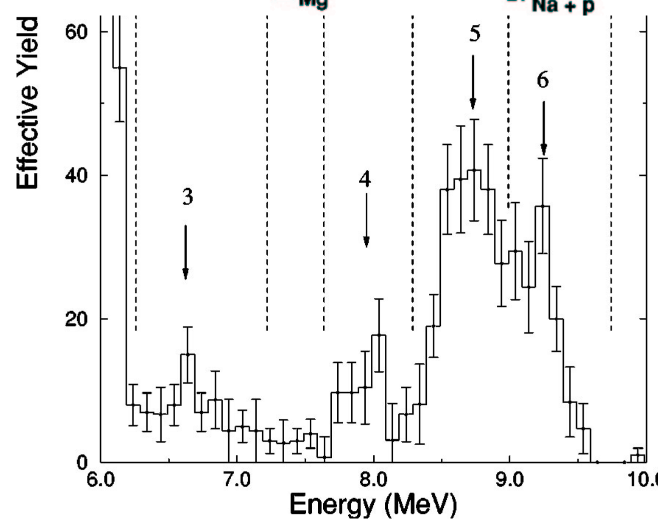
α width dominates the cross-section!

Direct measurements

W. Bradfield-Smith, *et al.*, Phys. Rev. C **59**(1999)3402
D. Groombridge, *et al.*, Phys. Rev. C **66**(2002)055802







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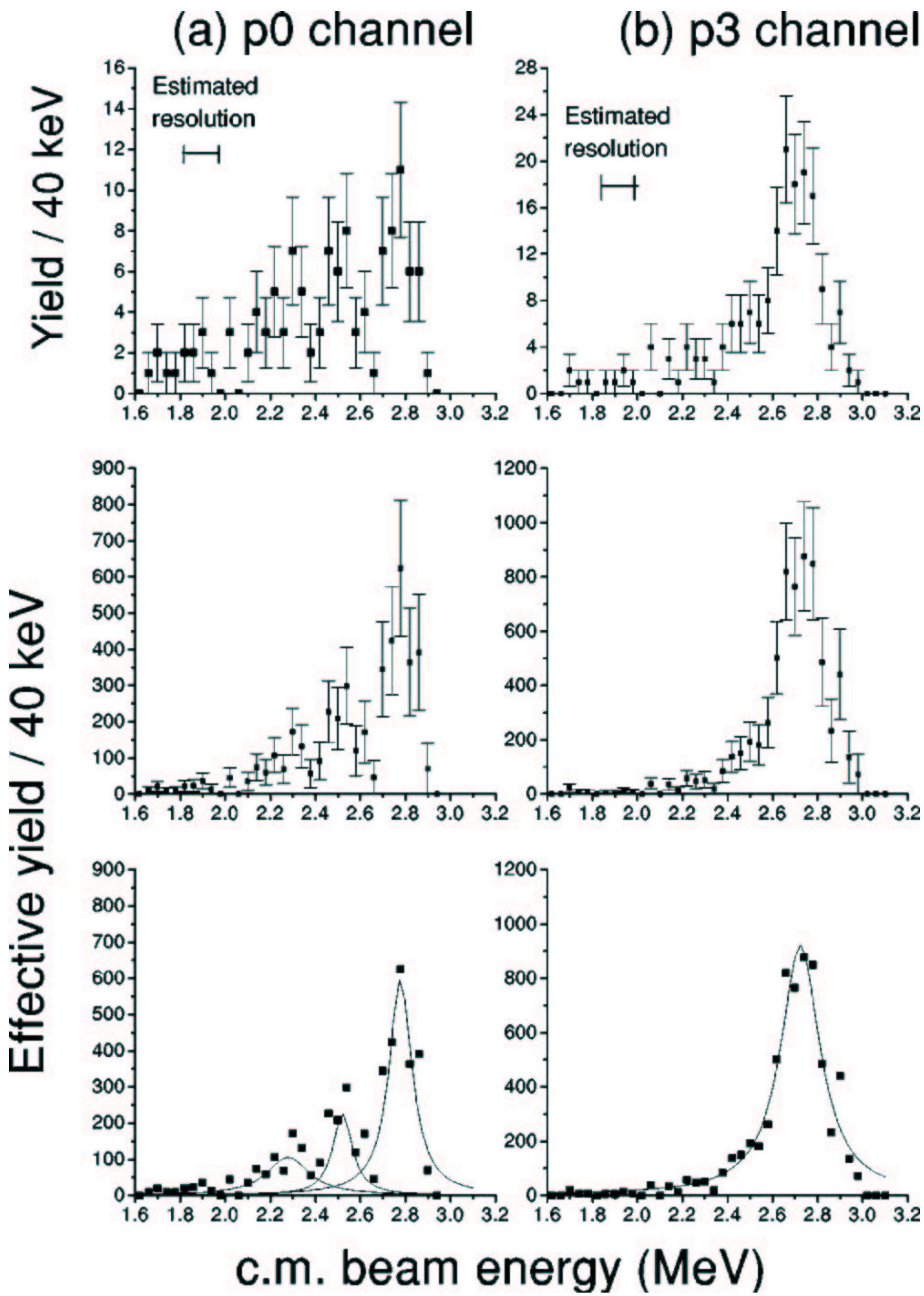

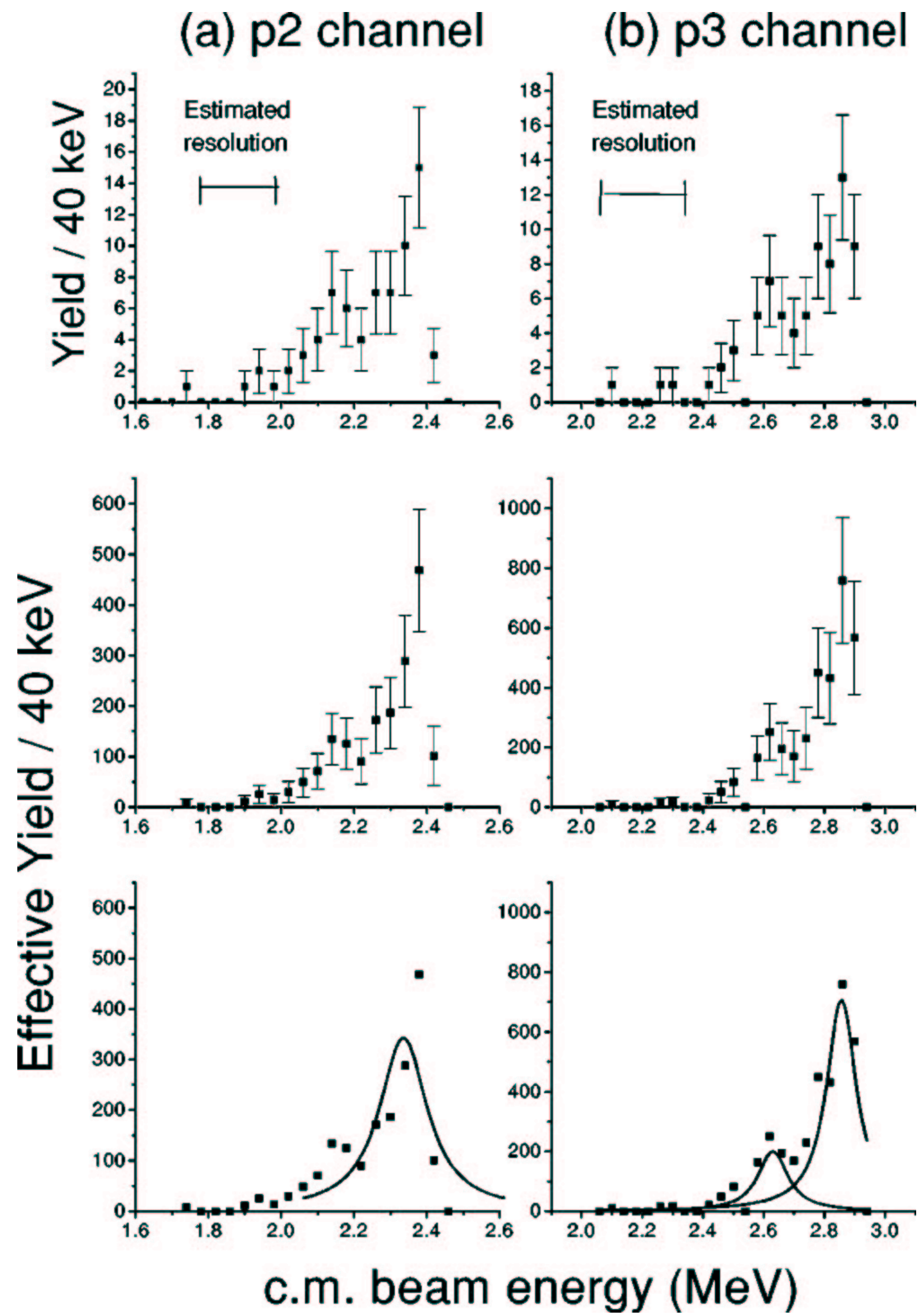

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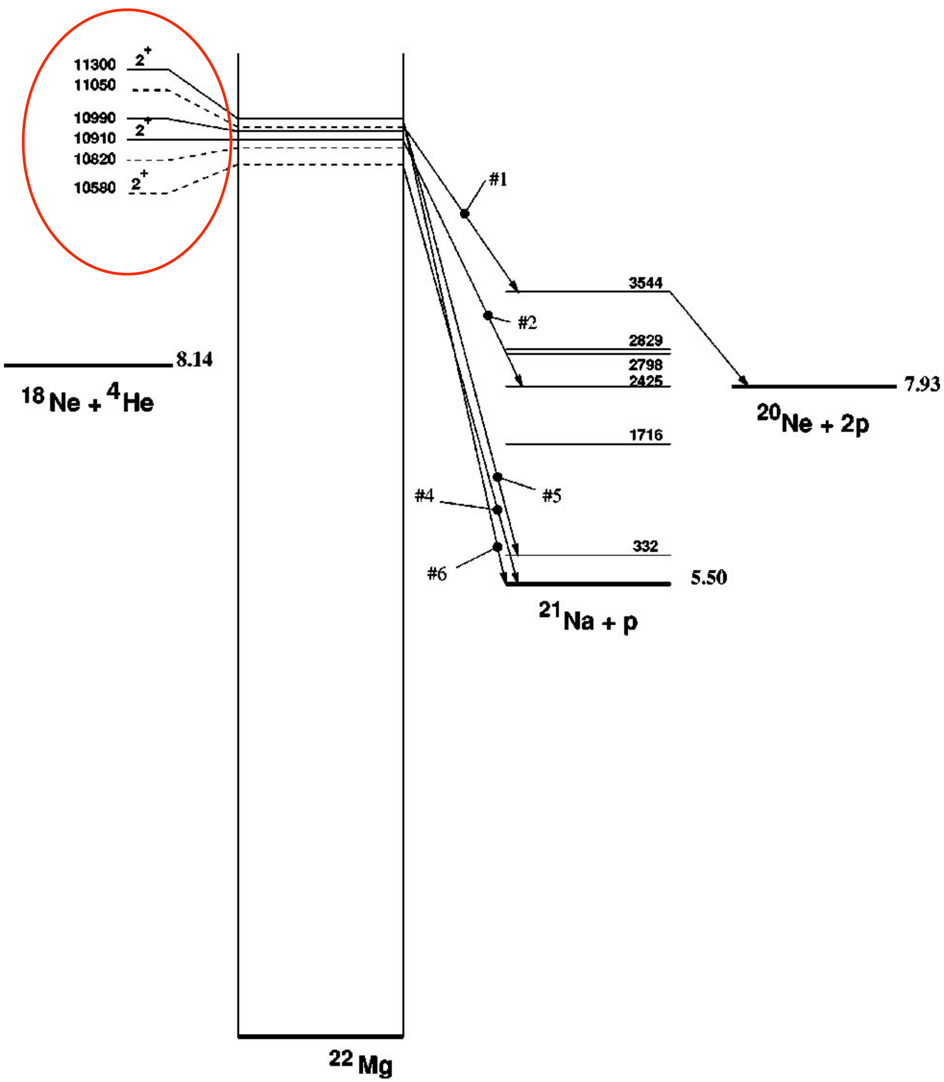


Unique level assignments

E_r (MeV)	Γ (MeV)	E_x (^{22}Mg) (MeV)	Observed channel
1.98±0.14	0.10±0.02	10.12±0.14	$p2$
2.17±0.14	0.13±0.08	10.31±0.14	$p2$
2.28±0.15	0.21±0.10	10.42±0.15	$p0$
2.41±0.14	0.16±0.03	10.55±0.14	$p2$
2.52±0.14	0.10±0.05	10.66±0.14	$p0$
2.72±0.14	0.21±0.01	10.86±0.14	$p3$
2.78±0.14	0.12±0.02	10.92±0.14	$p0$
2.87±0.14	0.10±0.02	11.01±0.14	$p6$

Ambiguous level assignments

E_r (MeV)	Γ (MeV)	E_x (^{22}Mg) (MeV)	Observed channel
2.27±0.15	0.21±0.10	10.41±0.15	$p0$
2.55±0.14	0.19±0.04	10.69±0.14	$p0$
2.74±0.14	0.30±0.04	10.88±0.14	$p1$
2.12±0.14	0.07±0.03	10.26±0.14	$p2$
2.34±0.14	0.16±0.04	10.48±0.14	$p2$
2.63±0.14	0.12±0.07	10.77±0.14	$p3$
2.86±0.14	0.12±0.02	11.00±0.14	$p3$
2.06±0.14	0.09±0.03	10.20±0.14	$p4$
2.52±0.14	0.15±0.02	10.66±0.14	$p4$
2.54±0.14	0.11±0.01	10.68±0.14	$p5$
2.73±0.14	0.13±0.03	10.87±0.14	$p6$
2.84±0.14	0.08±0.02	10.98±0.14	$p7$

W. Bradfield-Smith, *et al.*, Phys. Rev. C **59**(1999)3402

Some facts about $^{18}Ne(\alpha,p)^{21}Na$

- The proton penetration is extremely high compared with the α penetration. Therefore, the α width completely dominates the resonance strength, the cross section, as well as the stellar reaction rate.

- Due to the drastically decreasing α penetration it is impossible to measure this reaction directly or inversely at the astrophysically important region for T_9 = 0.3 - 1. About 10^{10} times higher ^{18}Ne intensities than currently available would be needed.

↓

Indirect methods are needed

Direct measurement vs. alpha transfer

$^{18}Ne(\alpha,p)^{21}Na$

$J(^{18}Ne) = 0$
$J(\alpha) = 0$
$J(^{22}Mg^*) = J$

$^{18}Ne(^6Li,d)^{22}Mg^*$

Resonance strength:

$$\omega\gamma \approx (2J+1)\,\Gamma_\alpha$$

$$\Gamma_\alpha = P(E) \times k_\alpha R \times \gamma_\alpha^2$$

$$\gamma_\alpha^2 = \frac{3\hbar^2}{\mu R^2} \times S_\alpha$$

DWBA zero range approximation

$$\frac{d\sigma}{d\Omega}(\theta) = D_0^2 \sum_{lsj} \frac{2J_B+1}{(2J_A+1)(2j+1)} S_{lsj}\sigma_{lsj}^{DW}(\theta)$$

s = 0 , l = j = **J**, $\pi = (-)^J$

Low penetration
= low cross-section

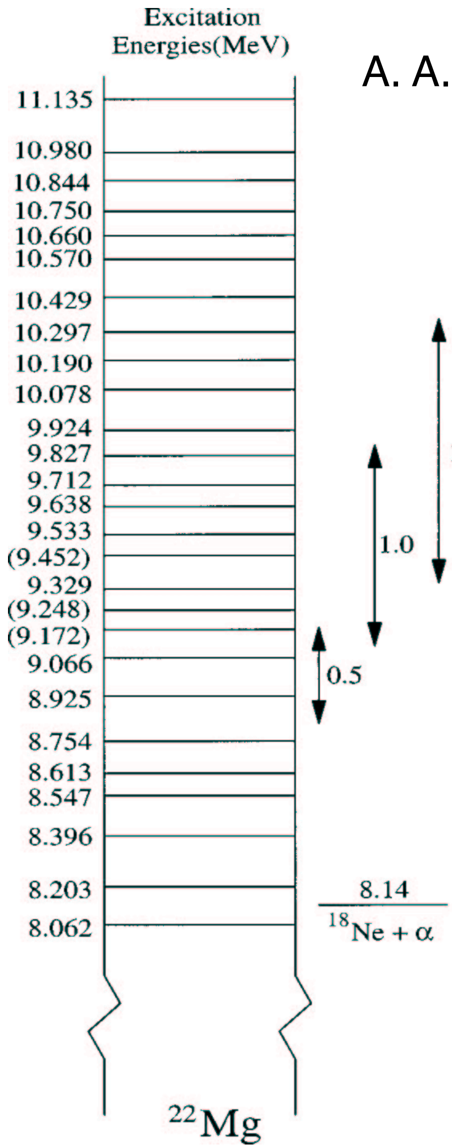
$$\sigma(E) = \pi\,\frac{\mu R^2}{3\hbar^2}(2J+1)\,\Gamma_p\,S_\alpha \times \frac{1}{k_\alpha^2}\,\frac{P(E)}{(E-E_R)^2+(\Gamma/2)^2}$$

Needs energy scan

$$\sigma(E) = D_0^2\,S_\alpha\,\sigma_{lsj}^{DW}(E)$$

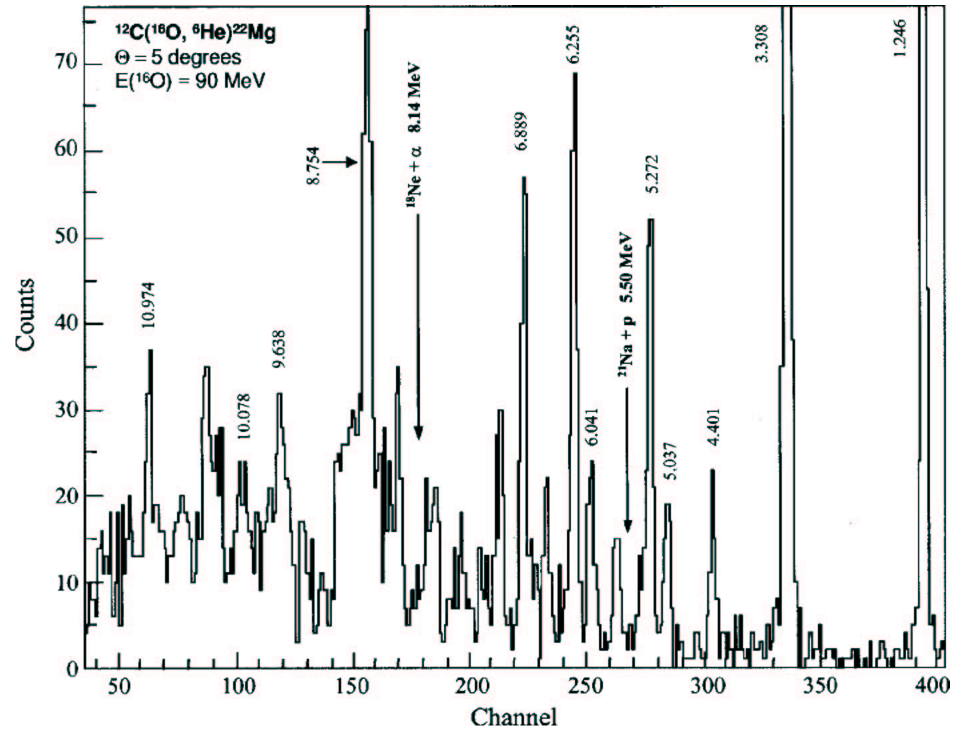
Model dependent,
Needs optical potential parameters,
but independent from resonance parameters

Indirect Measurements



A. A. Chen, *et al.*, Phys. Rev. C **68**(2001)065807

$^{12}C(^{16}O,^{6}He)^{22}Mg$



G.P.A. Berg, *et al.*, Nuc. Phys. **A718**(2003)608c

$^{24}Mg(^{4}He,^{6}He)^{22}Mg$

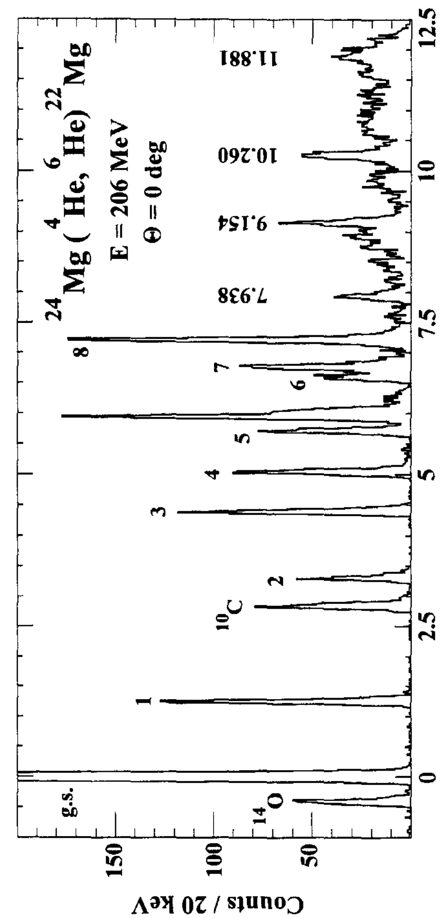


Table 1

Energy levels of ^{22}Mg , in units of keV

E_x[7]	this work	E_x[7]	this work	E_x[7]	this work	E_x[7]	this work
6041 *11*	6059 *9*	8203 *23*	8197 *10*	9533 *24*	9542 *12*	10750 *31*	10776 *20*
6255 *10*	6244 *9*	8396 *15*	8380 *10*	9638 *21*	9640 *10*	10844 *38*	(10915 *20*)
6606 *11*	6606 *9*	8547 *18*	8512 *10*	9712 *21*	9746 *10*	10980 *31*	(11015 *20*)
6767 *20*	6766 *12*	8613 *20*	(8644 *18*)	9827 *44*	9853 *11*	11135 *31*	(11118 *20*)
6889 *10*		8754 *15*	8771 *9*	9924 *28*	9953 *13*		(11231 *20*)
7169 *18*	7216 *9*	8925 *19*	8921 *9*	10078 *24*	(10128 *20*)		11313 *20*
7402 *13*		9066 *18*	(9029 *20*)	10190 *29*			11581 *20*
7674 *18*	7614 *9*	(9172 *23*)	9154 *10*	10297 *25*	10260 *10*		(11742 *20*)
7784 *18*		(9248 *20*)		10429 *26*	(10389 *20*)		11881 *20*
7964 *16*	7938 *9*	9329 *26*	(9378 *22*)	10570 *25*			(12003 *20*)
8092 *16*		(9452 *21*)		10660 *28*	10627 *20*		(12169 *20*)

Errors in keV in italics. Levels in parenthesis are tentative assignments.

All measurements so far

10 orders of magnitude deviation at $T_9 = 0.5$

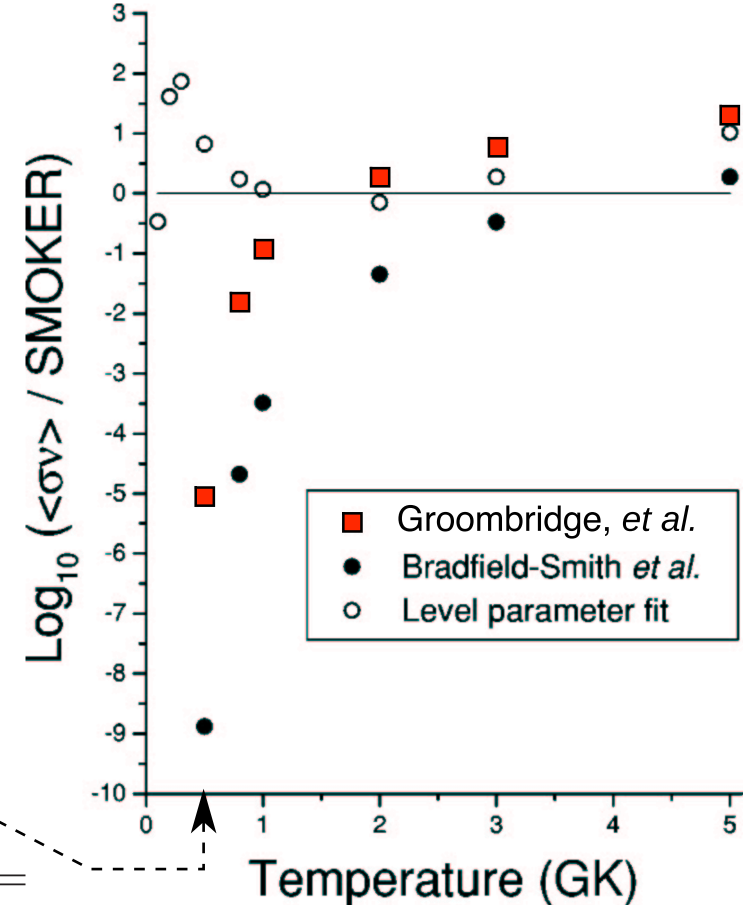


TABLE III. Excitation energies in ^{22}Mg with $E_x \geqslant 10.00$ MeV.

^{16}O(^{12}C,^{6}He)^{22}Mg [a]	^{18}Ne(α,p)^{21}Na [b]	^{18}Ne(α,p)^{21}Na [c]	J^{π}
10.078 ± 0.024		10.12 ± 0.14	2^{+} $(3^{-},5^{-})$
10.190 ± 0.029			
10.297 ± 0.025		10.31 ± 0.14	2^{+} $(3^{-},5^{-})$
10.429 ± 0.026		10.42 ± 0.15	2^{+} $(1^{-},3^{-})$
10.570 ± 0.025	(10.580 ± 0.050)	10.55 ± 0.14	2^{+} $(3^{-},5^{-})$
10.660 ± 0.028		10.66 ± 0.14	2^{+} $(1^{-},3^{-})$
10.750 ± 0.031			
10.844 ± 0.038	(10.820 ± 0.060)	10.86 ± 0.14	0^{+} (1^{-})
	10.910 ± 0.050	10.92 ± 0.14	2^{+} $(1^{-},3^{-})$
10.980 ± 0.031	10.990 ± 0.050		
	(11.050 ± 0.050)	11.01 ± 0.14	2^{+} $(1^{-},3^{-})$
11.135 ± 0.040	11.130 ± 0.050		

[a]Reference [4]

Problems with previous measurements

- Direct measurements require a radioactive beam of extremely high intensity. Currently, only 5×10^5 pps can be achieved.

- Only one impact energy. Energy changed by energy loss in the target
  --> Problem of vertex localization and straggling

- Indirect measurements done so far have not been sensitive to α widths
  ---> No spectroscopic information

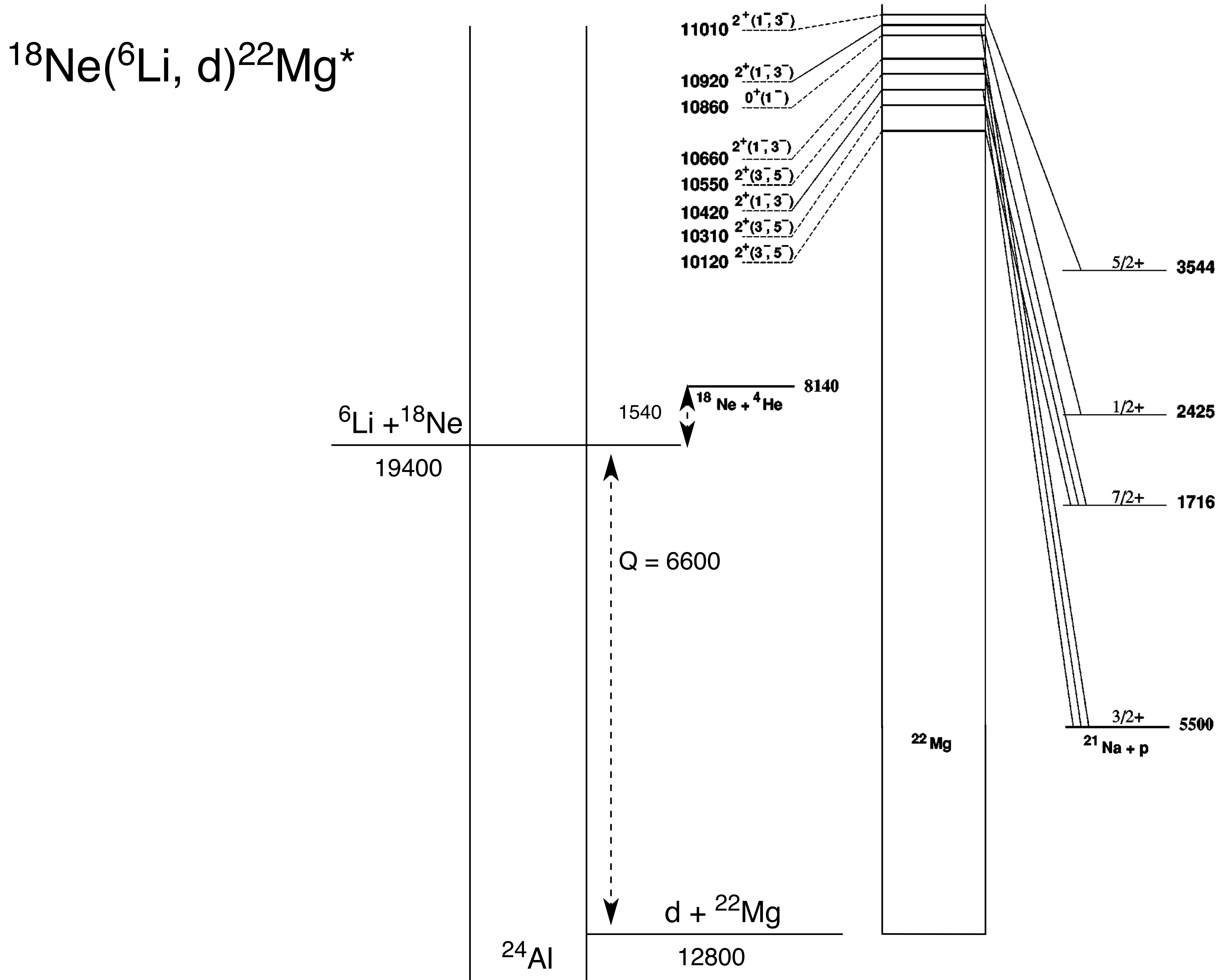
Problem with previous E870 proposal

- Intensities of at least 10^8 pps are needed
  This can **not** be achieved in the near future. But even if, the region below $E_{c.m.} < 1.0$ can never be measured directly

  The new **FEBIAD** source can presumably provide 5×10^5 pps at the target.

The current proposal

Instead of higher intensities we use higher energies available now at **ISAC II**



18Ne(6Li, d)22Mg*
11010 2+(1−, 3−)
10920 2+(1−, 3−)
10860 0+(1−)
10660 2+(1−, 3−)
10550 2+(3−, 5−)
10420 2+(1−, 3−)
10310 2+(3−, 5−)
10120 2+(3−, 5−)
8140
18 Ne + 4 He
1540
6Li + 18Ne
19400
Q = 6600
d + 22Mg
24Al
12800
22 Mg
5/2+ 3544
1/2+ 2425
7/2+ 1716
3/2+ 5500
21 Na + p

DWBA calculation

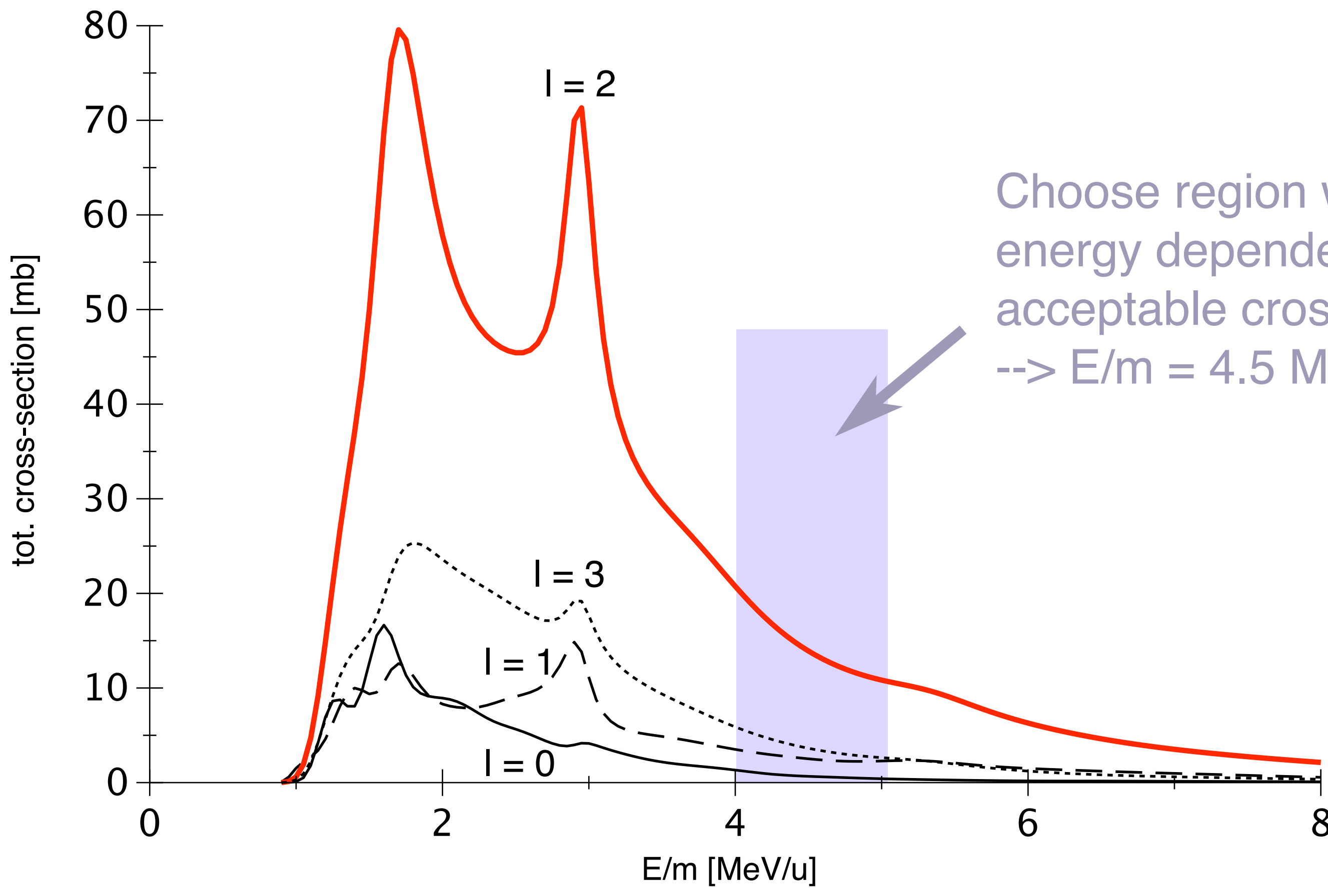
$$\frac{d\sigma}{d\Omega}(\theta) = D_0^2\, S_\alpha\, \sigma_{lsj}^{\mathrm{DW}}(\theta)$$ → Needs optical potential for...

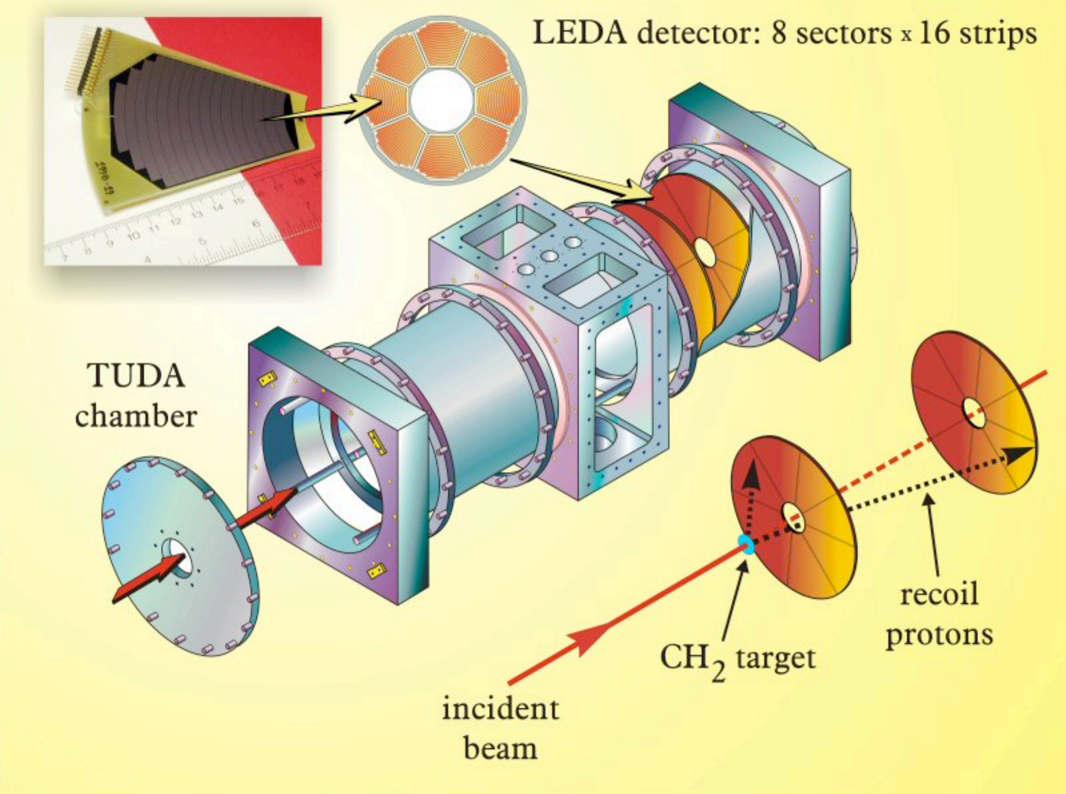
Entrance channel: $^{6}Li + ^{18}Ne$ ← critically — M. F. Vineyard, et al., Phys. Rev. C 30(1984)916

Transfer channel: $\alpha + ^{18}Ne$ (unbound α state) ← well-known — M. Nolte, et al., Phys. Rev. C 36(1987)1312

Exit channel: $d + ^{22}Mg$ ← fairly known — G. R. Satchler, Nuc. Phys. 85(1966)273

E_X (^{22}Mg) = 10.12 MeV





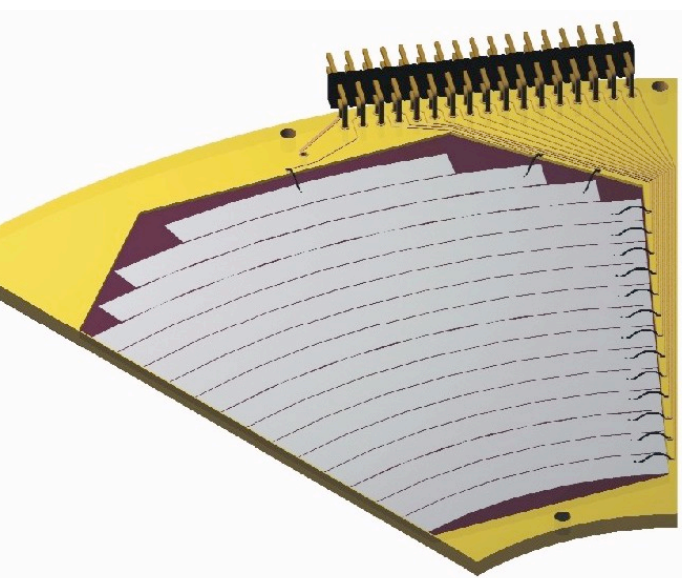
Proposed set-up

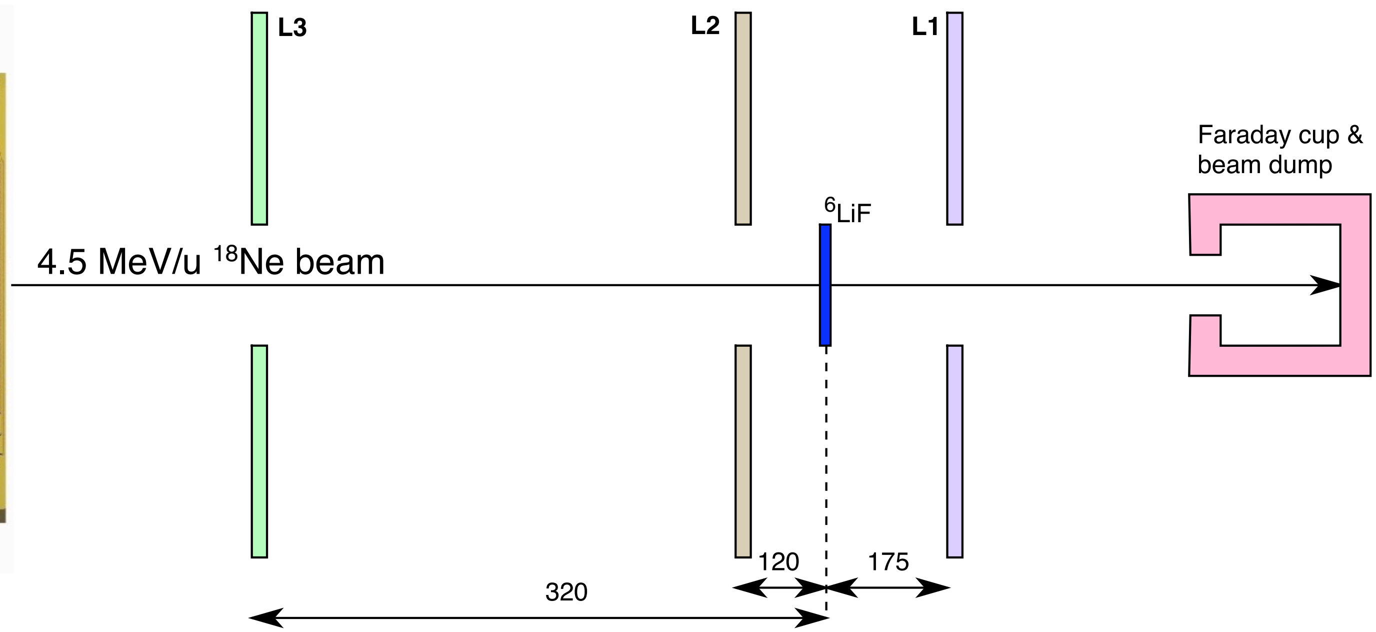
Location: TUDA II @ ISAC II

Beam: 4.5 MeV/u ^{18}Ne, 5 x 10^5 pps

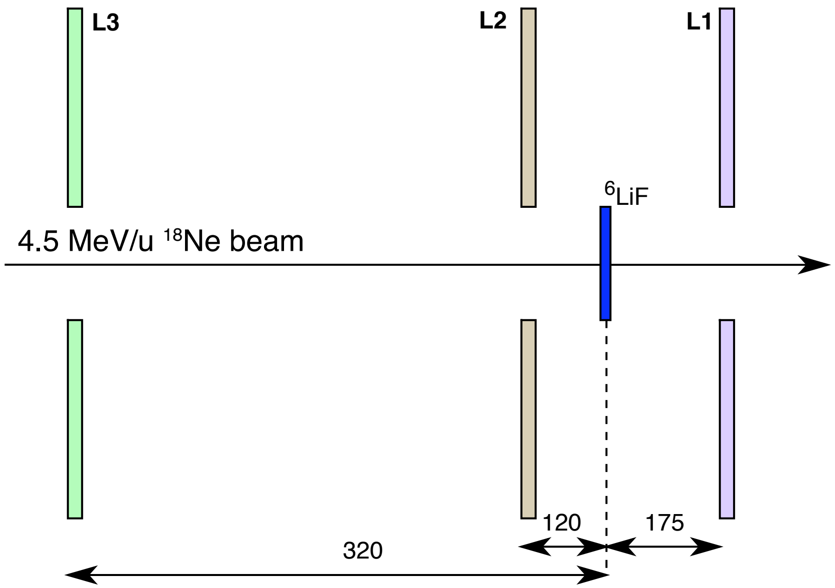
Target: 25 μg/cm^2 (0.1 μm) ^{6}Li-F on carbon backing

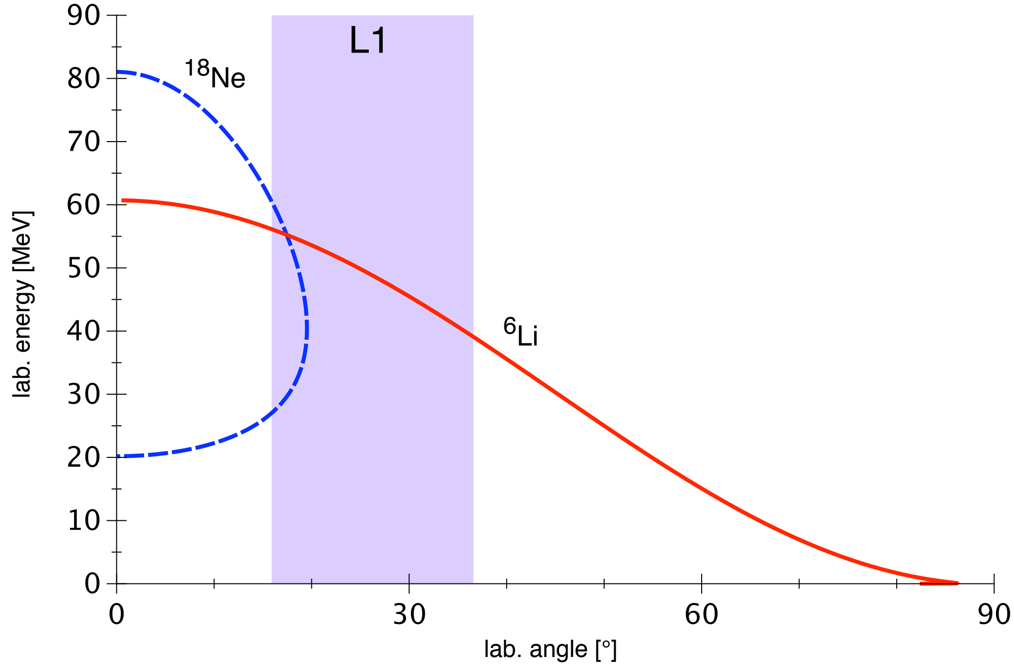
Detectors: 300 or 100 μm thick LEDA arrays (3 arrays à 8 sectors à 16 strips)

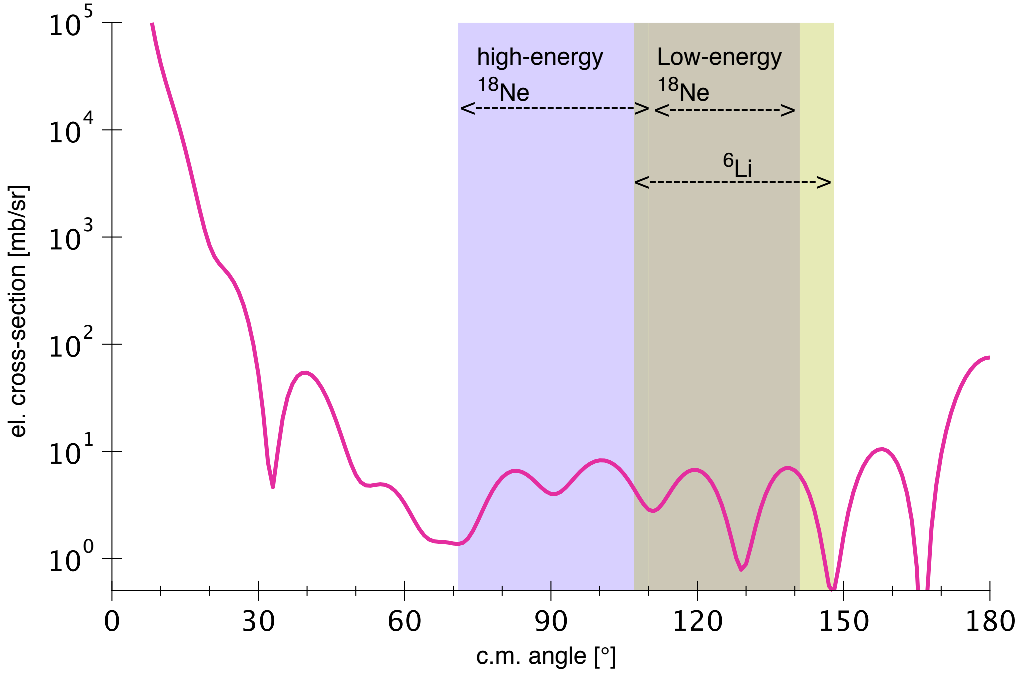


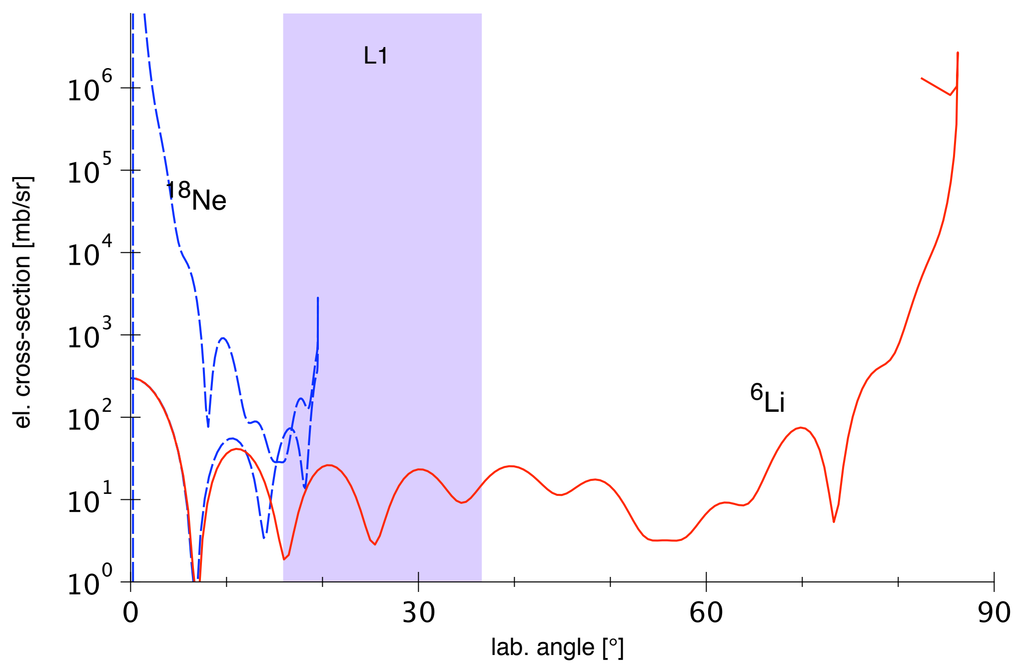


Elastics

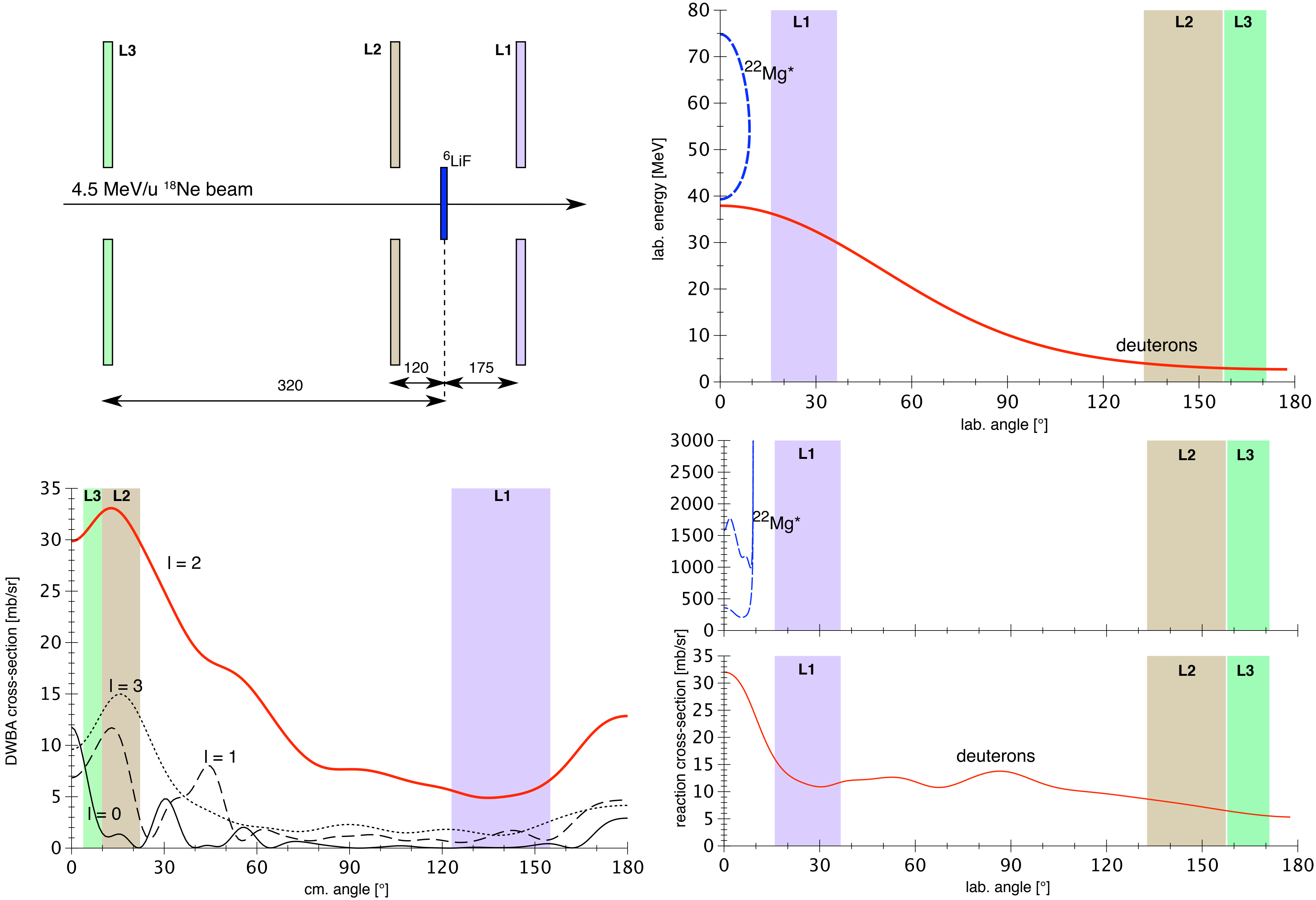

L3
L2
L1
6LiF
4.5 MeV/u 18Ne beam
120
175
320


L1
18Ne
6Li
lab. energy [MeV]
lab. angle [°]


high-energy
18Ne
Low-energy
18Ne
6Li
el. cross-section [mb/sr]
c.m. angle [°]


L1
18Ne
6Li
el. cross-section [mb/sr]
lab. angle [°]

$^{18}Ne(^{6}Li,d)^{22}Mg[10.12\ MeV,\ 2^{+}]$ reaction products



Good news

Even if only a bad DWBA fit can be achieved, the spectroscopic factors **can still be normalized** to states at higher energies, as detected in the **direct measurements**.

This makes the analysis almost independent from the optical model parameters

Estimated required beam time

Limiting factor: Level density that has to be resolved in the spectrum

Level spacing from A. Chen, *et al.*: 120 keV

46 keV in deuteron spectrum

Energy shift should not be more than 15 keV

Requires beam energy stability of 200 keV

Limits target thickness to 25 $\mu g/cm^2$ ^6LiF

Beam intensity: 5 x 10^5 pps
Cross-section: 10 mb/sr (for $S_\alpha = 1$)
One LEDA angle: 0.06 sr

0.65 deuterons / hour / angle / level

About 1 week of continuous run for 100 deuterons

10 % statistical error

Reduces to 10 deuterons for $S_\alpha = 0.1$

32 % statistical error

(Bad case scenario)

Estimated required beam time

- 5×10^5 pps ^{18}Ne, 4.5 MeV/u are sufficient to identify levels in ^{22}Mg above the alpha threshold in the important region for $T_9 = 0.4$ with 2 weeks of beam time.

- 5×10^5 pps could also provide a rough estimate (50% error) of the spectroscopic factors.
  --> Great improvement compared with 8-10 orders of magnitude current uncertainty for the stellar reaction rate.

- With higher intensities, more energies could be measured. This improves the statistics but also reduces uncertainties from the model.

Therefore, we need **24 12-hour shifts** (2 weeks) of continuous ^{18}Ne beam with an intensity of at least 5×10^5 pps.

Conclusion

- The experiment can be performed with the available intensity of 5 x 10^5 pps in a 2 weeks run.

- A higher intensity (factor 10) is highly desirable. This is still far from the intensity of 10^8 required for the direct measurement E870.

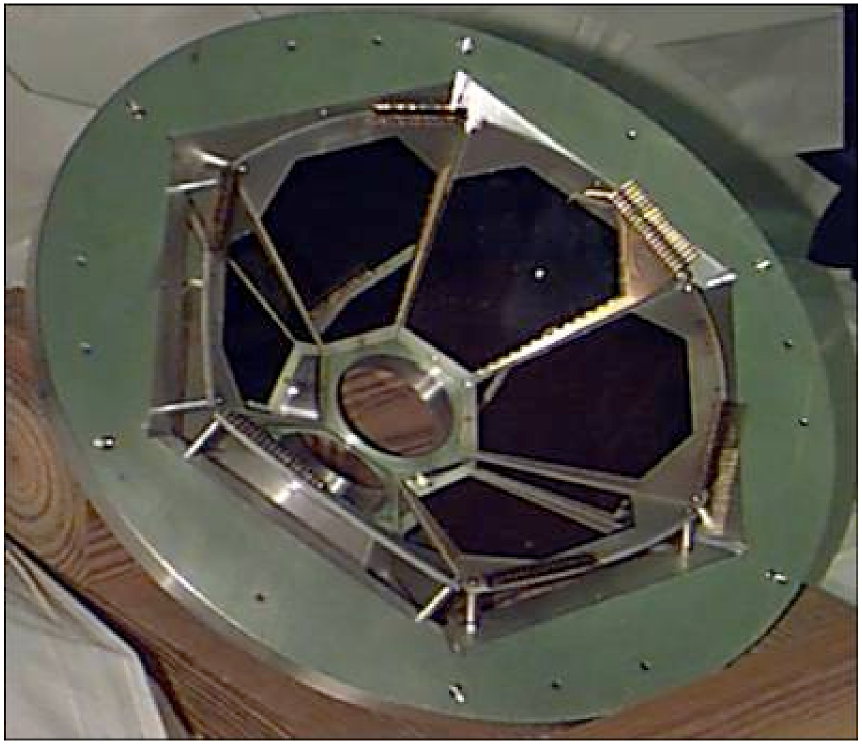
- Problems in the analysis are model dependencies. This can be improved by detection of elastically scattered deuterons.

- All levels relevant for the ^{18}Ne + α channel can be detected simultaneously. From the angular distribution, J^{π} can be derived, from the intensity, the α widths can be determined

- Also low-lying levels relevant for ^{21}Na(p,γ) can be detected.

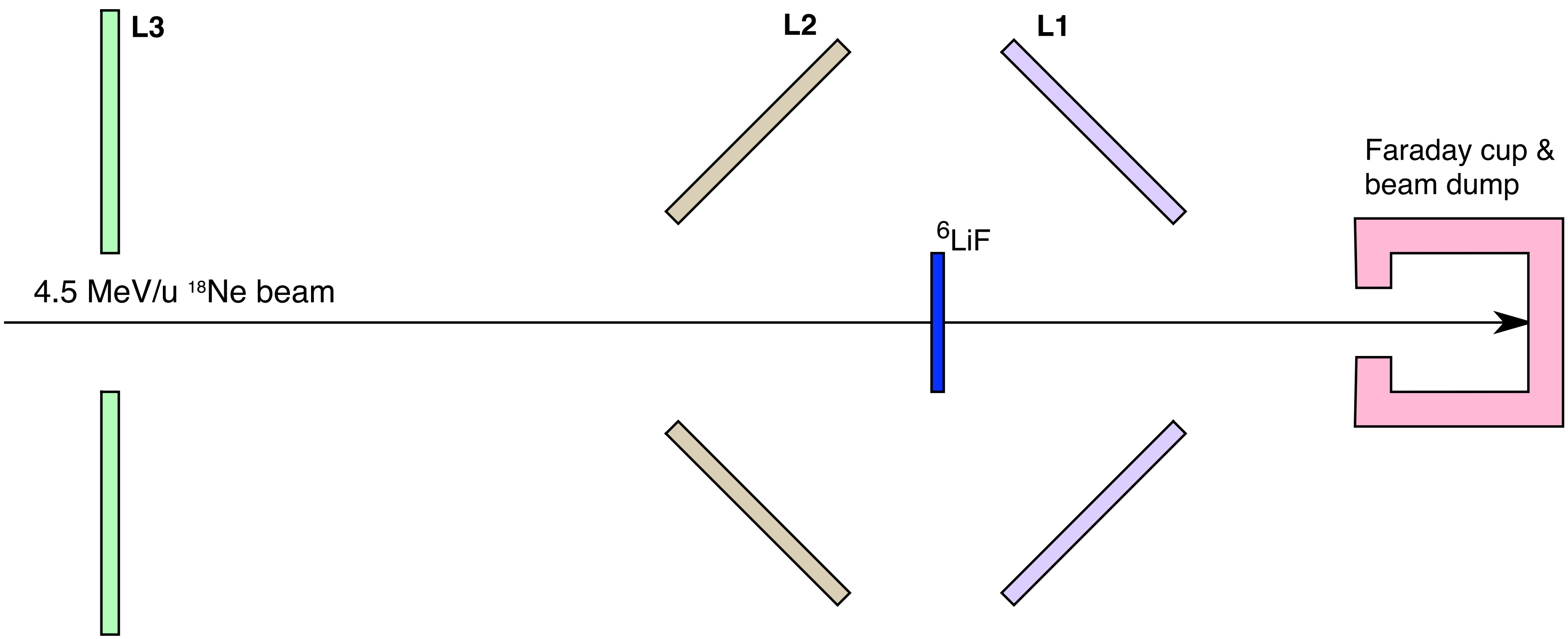
- Despite the model uncertainties, the relative strength of the levels is rather model independent. This makes a normalization to known levels possible.

Thanks

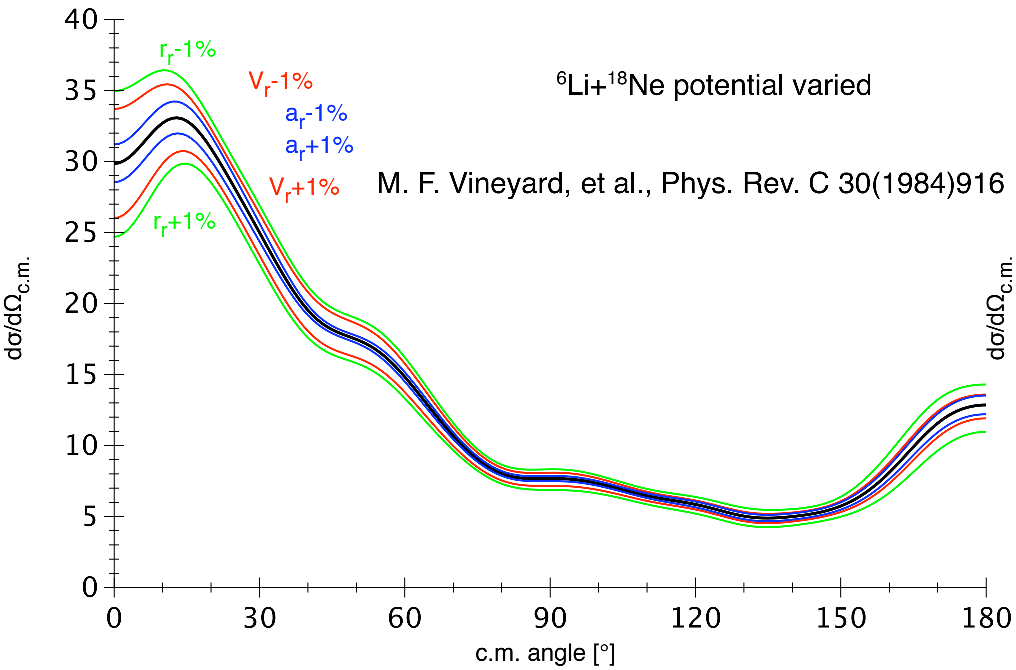


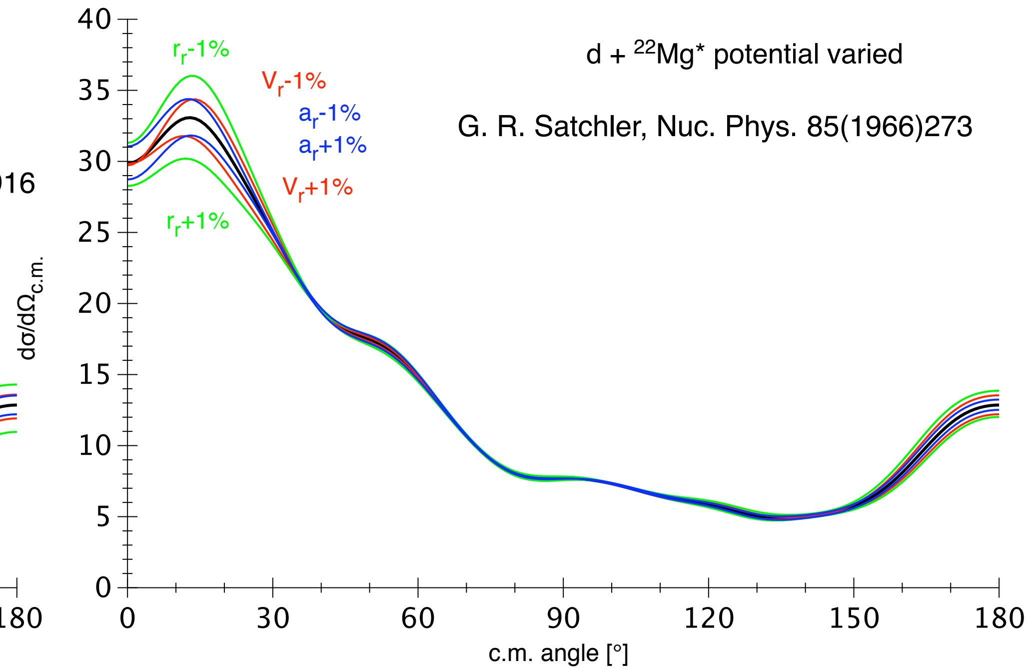
Improved Set-up

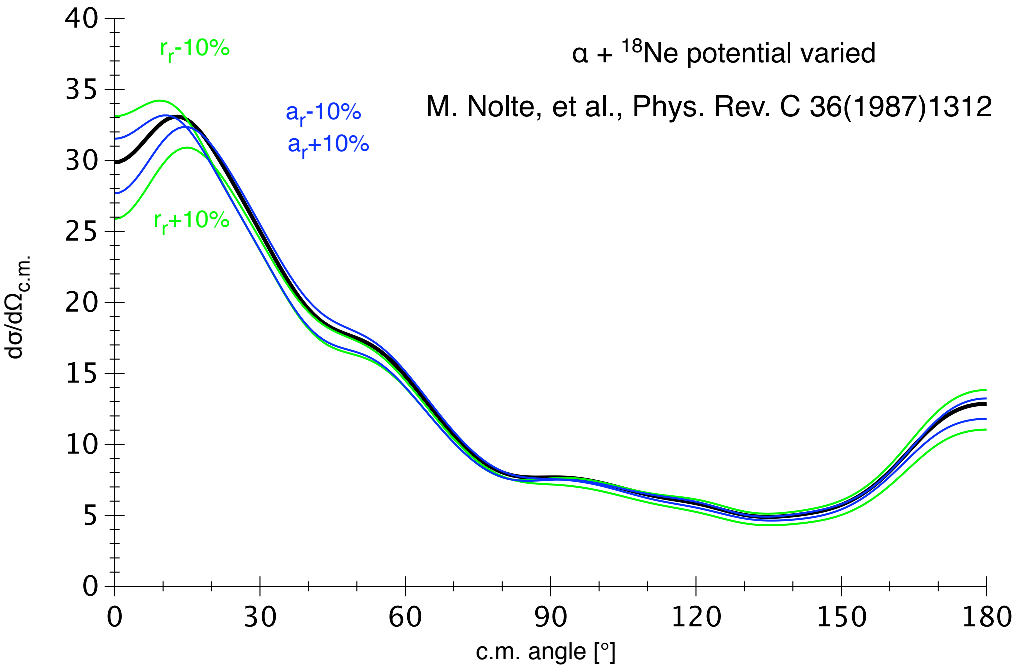
LEDAs in “lampshade” arrangement



Model uncertainties







- Woods-Saxon potentials

- Imaginary potential parts have a much smaller effect

- Largest uncertainty from 6Li+18Ne potential --> Can be reduced by parallel measurement of elastics