Cascade Transitions in ^{16}O and the $^{12}C(\alpha,\gamma)^{16}O$ Reaction Cross Section

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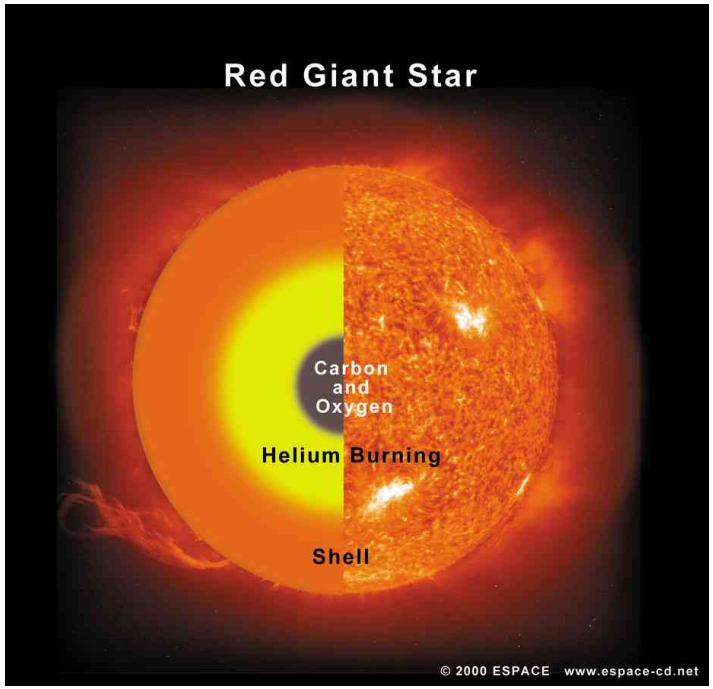
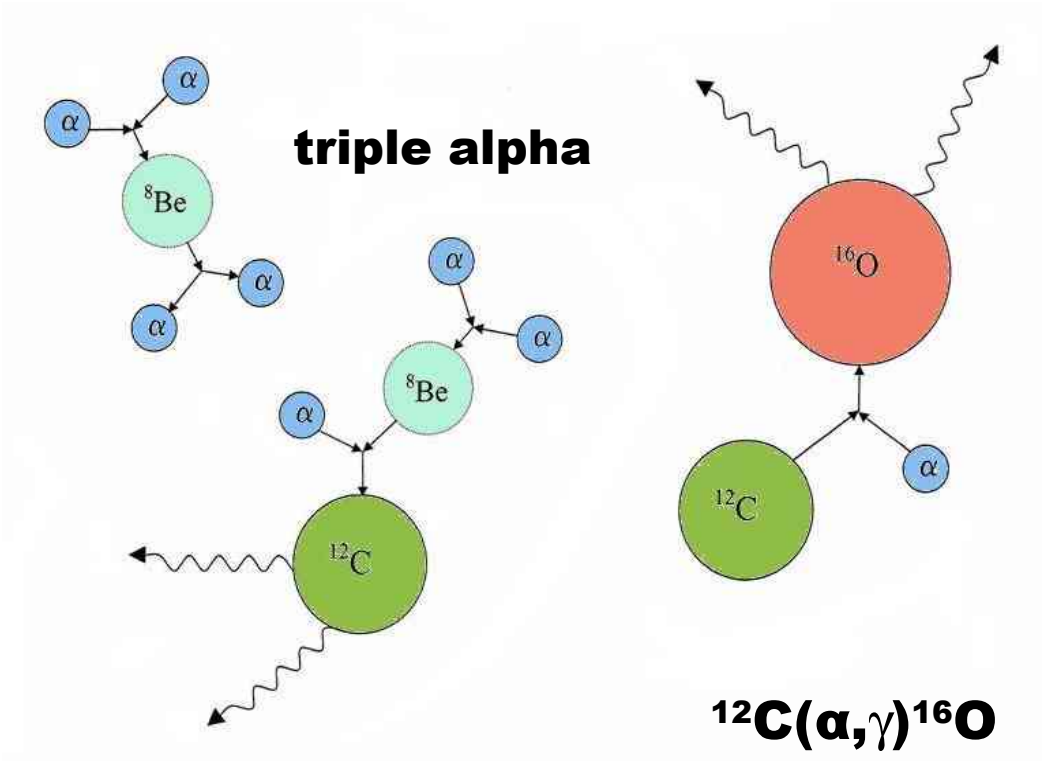
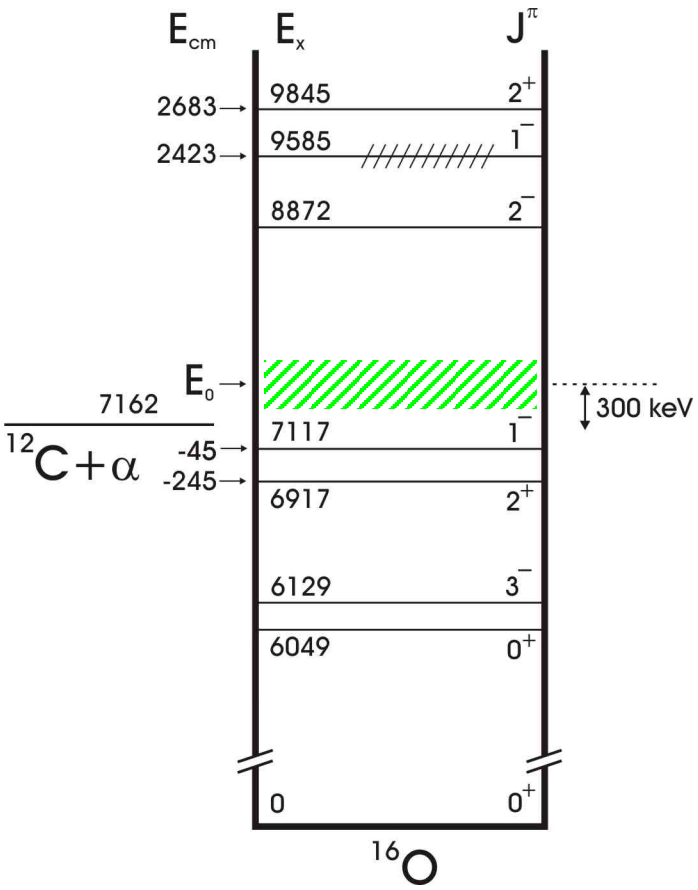
helium burning reactions

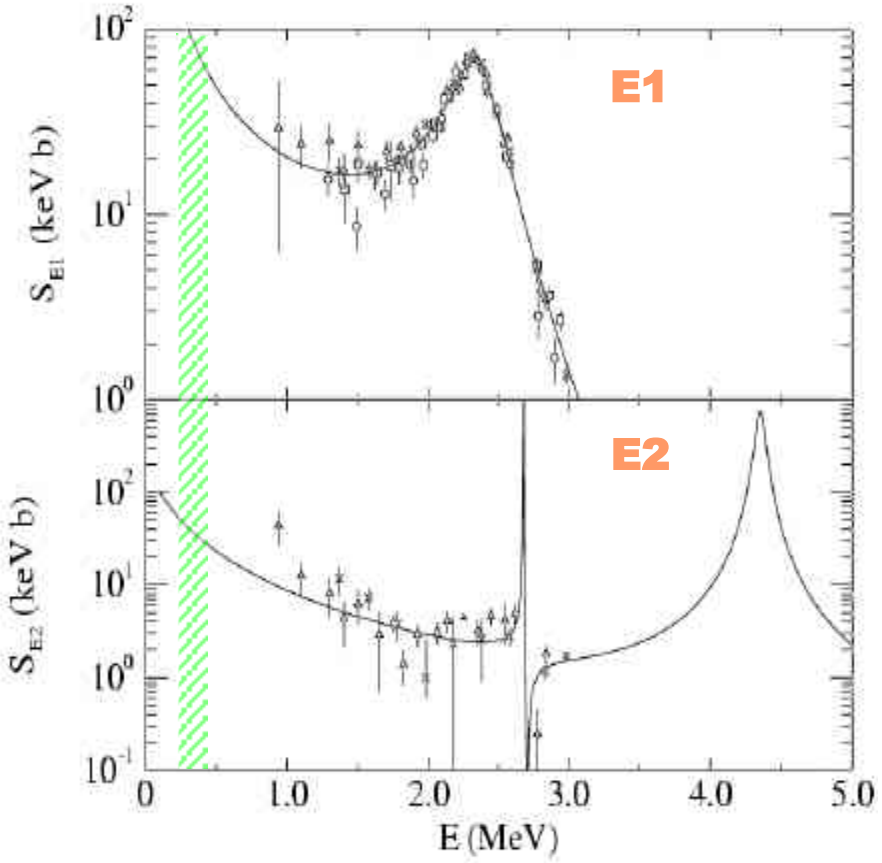




The relative rates of these two reactions determine the $^{12}C/^{16}O$ ratio at the end of He burning and beyond.

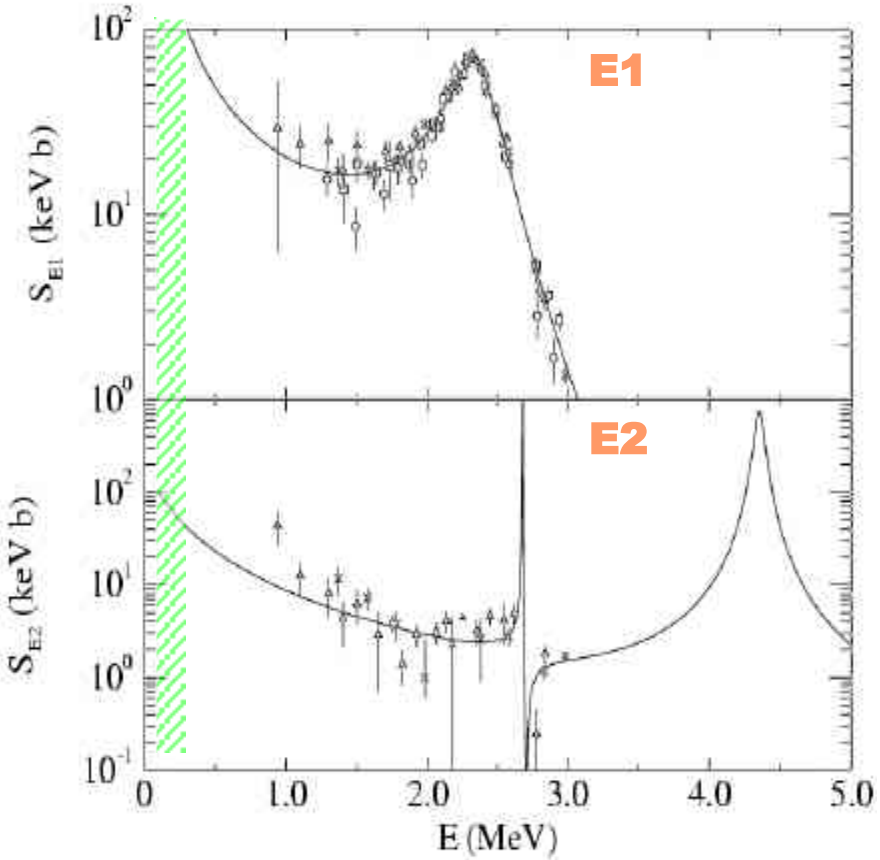
ground state transitions





C.R. Brune PRL 83 (1999)

ground state transitions



C.R. Brune PRL 83 (1999)

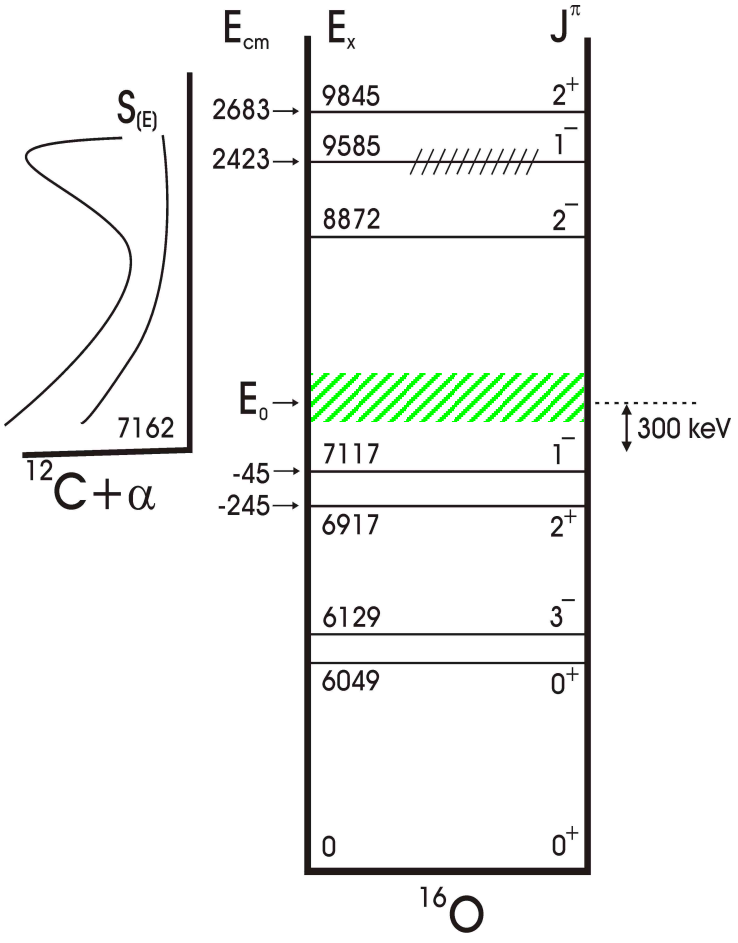
E1 ground state cross section:

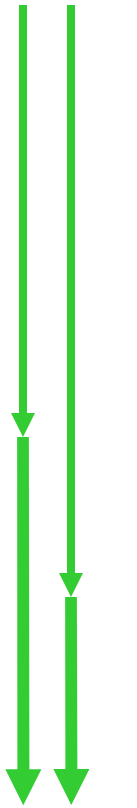
- resonant capture through 1^- states
- σ at 300 keV dominated by the high-energy tail of 7.12-MeV state
- a-reduced width constrained
- $S_{E1}(300)=79\pm21$ keVb (Buchmann 94)

E2 ground state cross section:

- resonant capture through 2^+ states
- direct capture (d→s)
- σ at 300 keV dominated by the high-energy tail of 6.92-MeV state
- a-reduced width uncertain
- $S_{E2}(300)=53\pm18$ keVb (Tischhauser 02)

cascade transitions





cascades

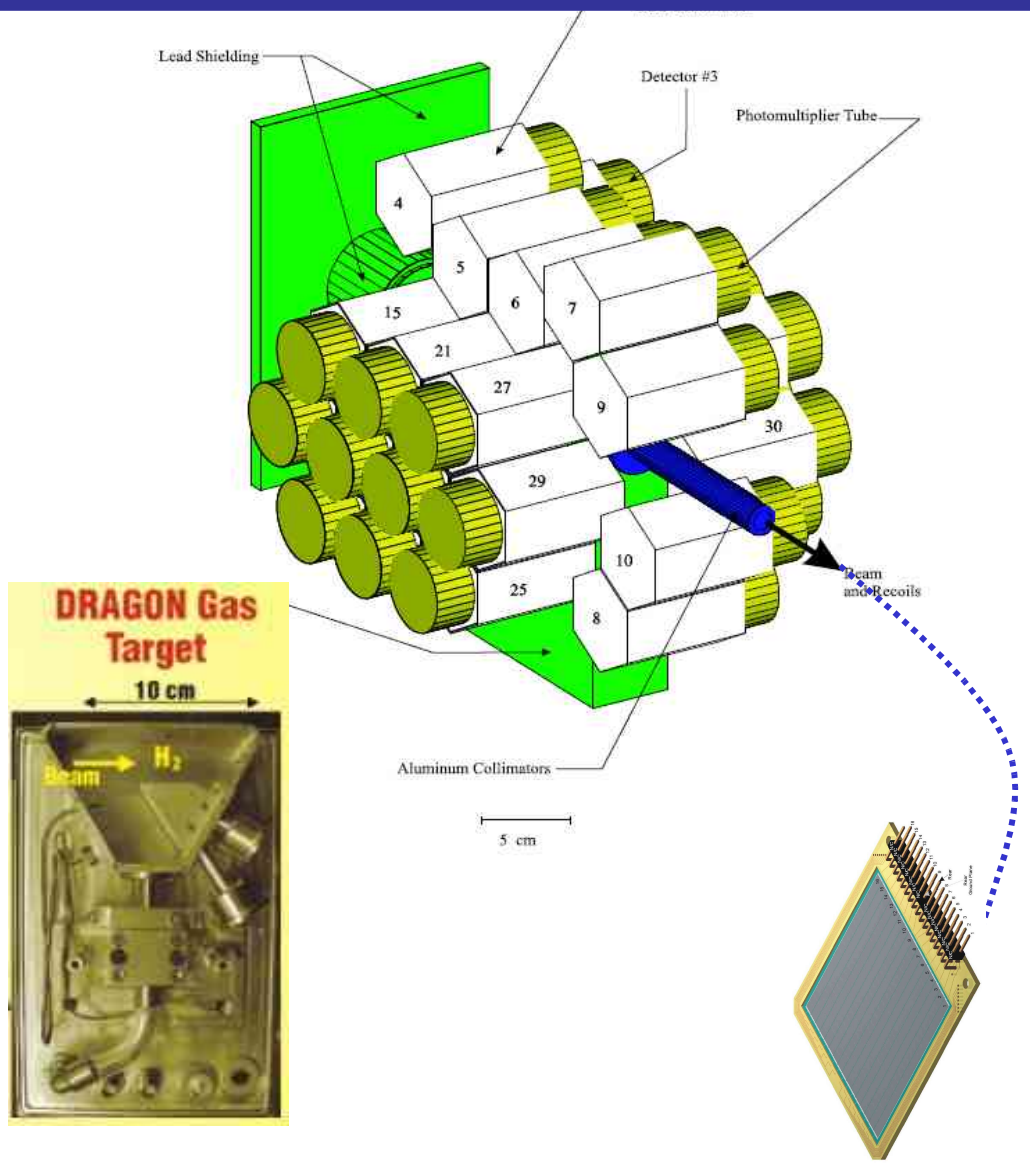
Cascade cross section:

- 15-20% of total σ
- 6.05, 6.92, 7.12-MeV levels
- direct process
- $S_{6.9}(300) \sim 7$ keVb
- $S_{7.1}(300) \sim 1\text{-}2$ keVb
- $S_{casc}(300) \sim 15$ keVb

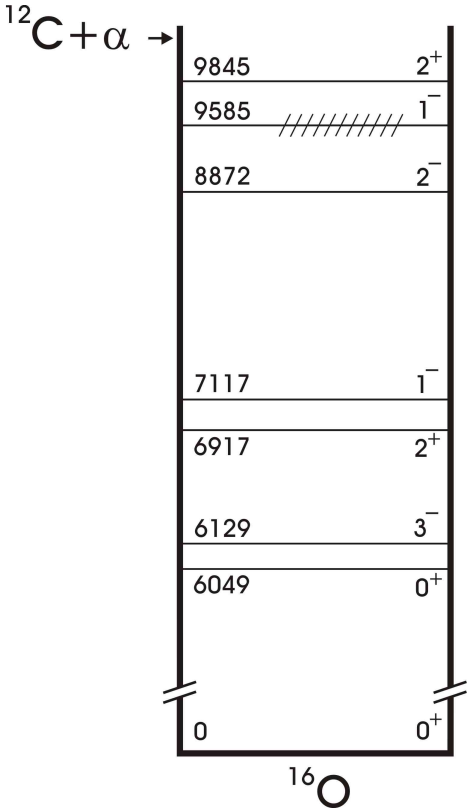
$^{12}C(a,\gamma)^{16}O$ at DRAGON

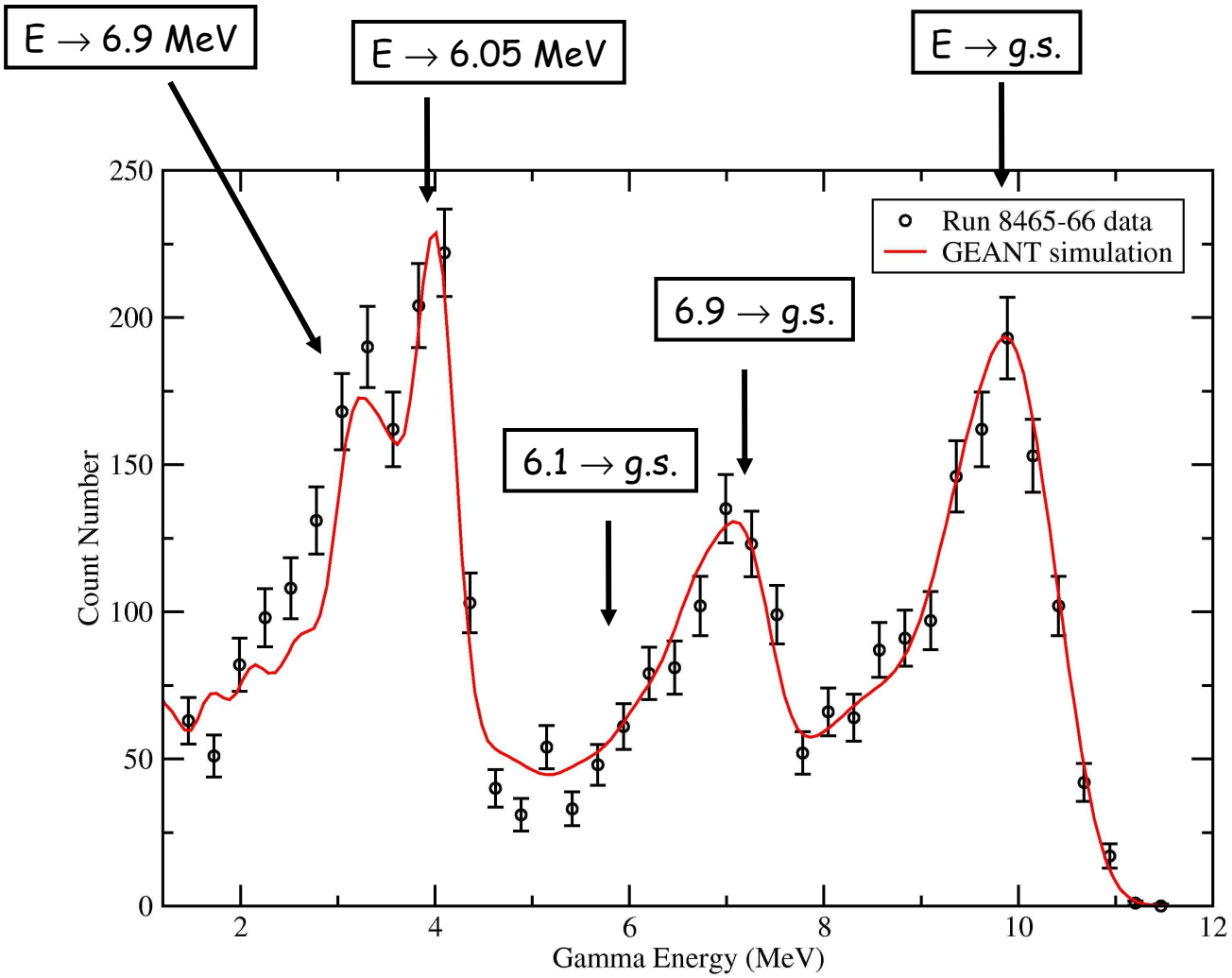
6.05 cascade at DRAGON

- 30-50 pnA of ^{12}C beam
- P_{He} = 4 and 8 Torr
- 2.25 < E < 5.5 MeV
- l_{target} = 12.1-12.3 cm
- 8, 10 mm exit apertures

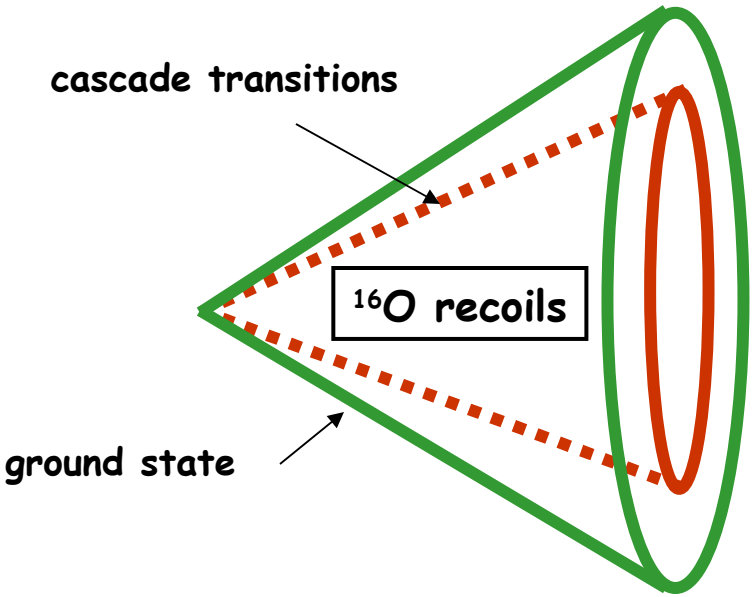


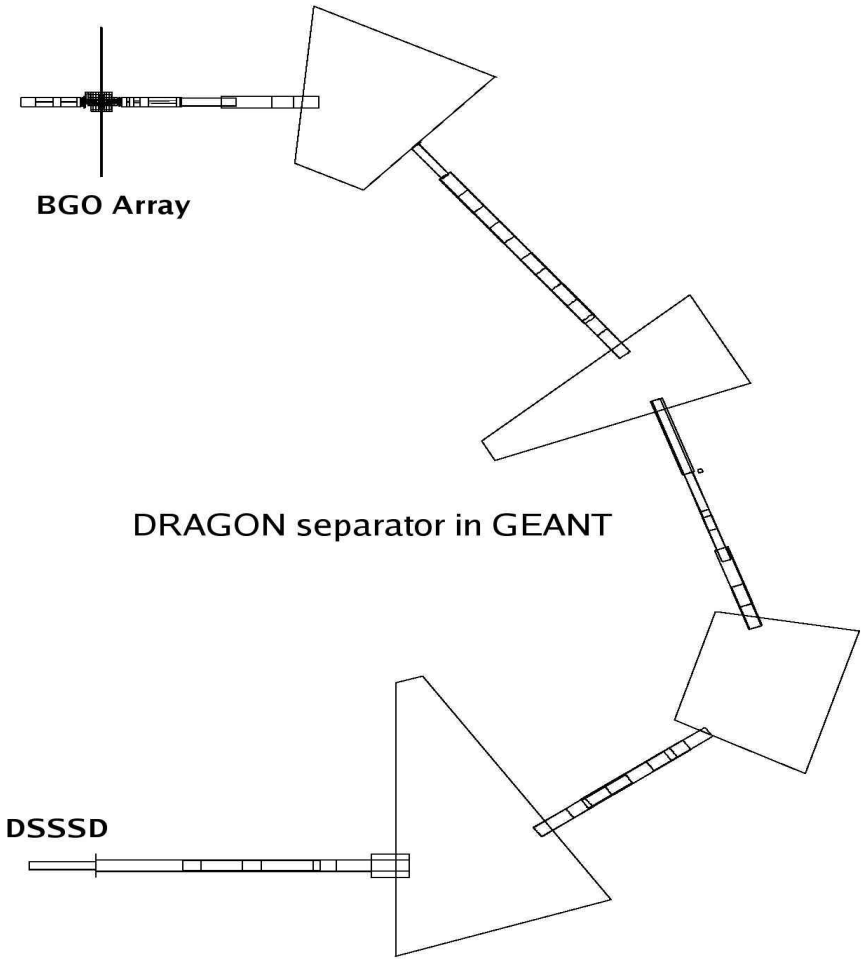
6.05 cascade at DRAGON





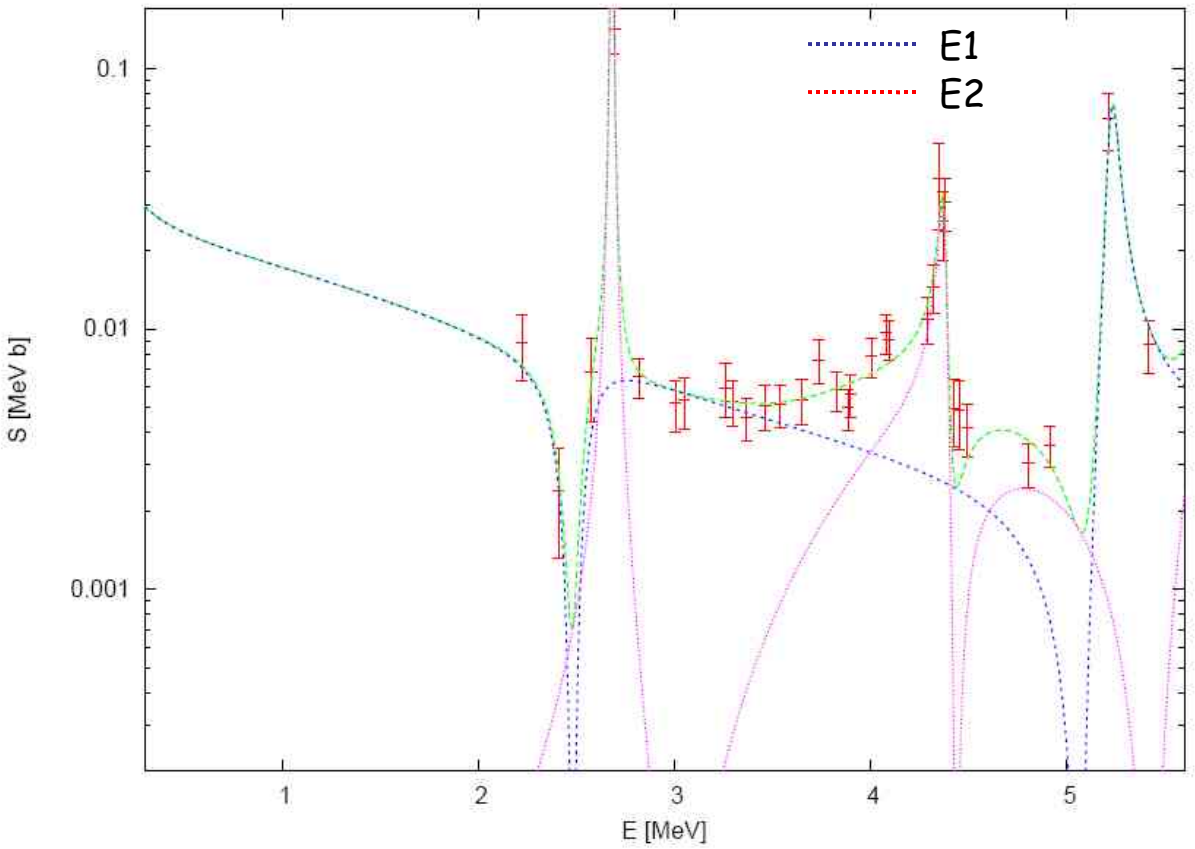
Dragon acceptance





- magnetic steerers
- mistuning tests
- lateral, angular displacement
- 1st run: 70-90% acceptance
- 2nd run: 90-95% acceptance

r-matrix



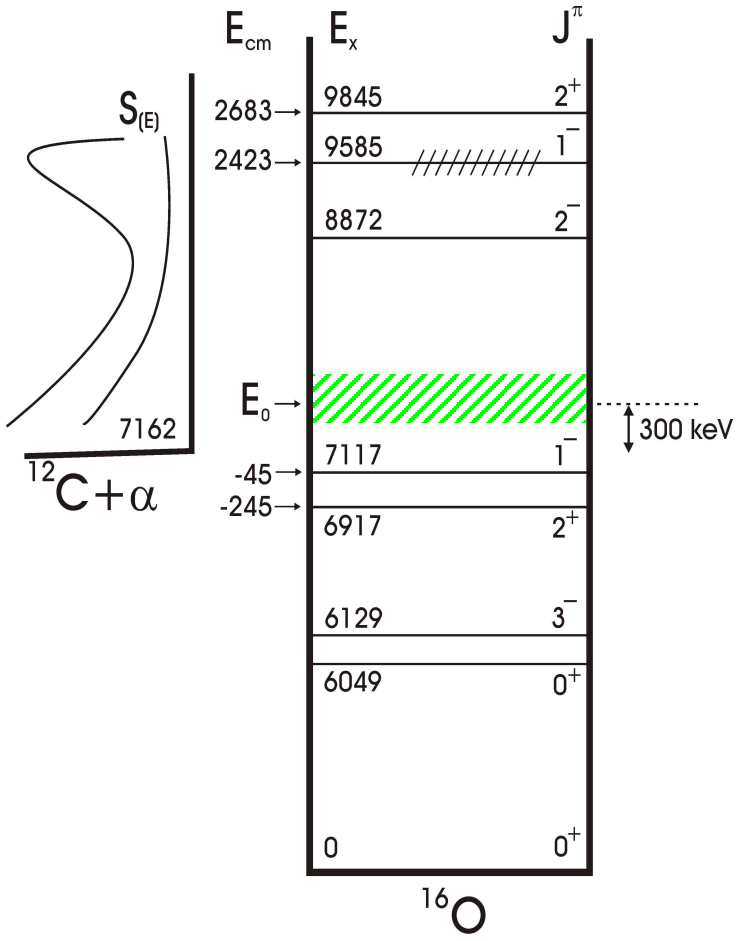
$S_{6.0}^{+}(300)=29\pm12$ keVb

$S_{6.0}^{-}(300)=20\pm10$ keVb

$S_{6.0}(300)=25\pm16$ keVb

C. Matei, L. Buchmann, et al. PRL 97, 242503 (2006)

transitions revisited

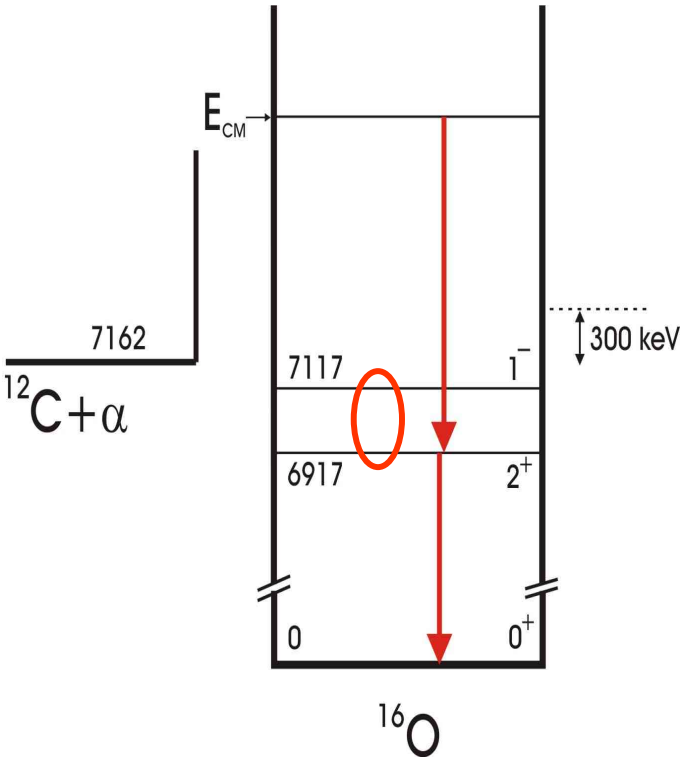


- $S_{E1}(300) = 79 \pm 21$ keVb (Buchmann 94)
- $S_{E2}(300) = 53 \pm 18$ keVb (Tischhauser 02)

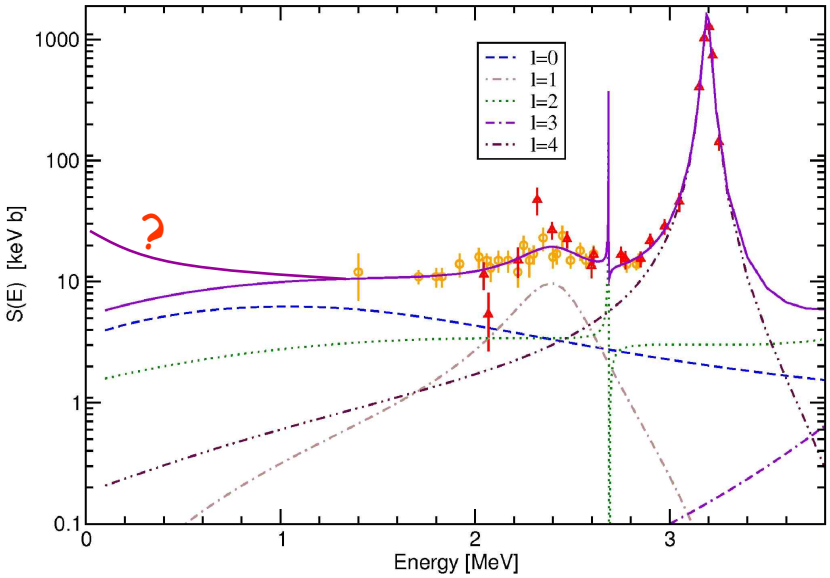
Cascade cross section:

- $S_{6.05}(300) \sim 25$ keVb
- $S_{6.9}(300) \sim 7$ keVb
- $S_{7.1}(300) \sim 1\text{-}2$ keVb
- $S_{casc}(300) \sim 35 \pm 20$ keVb

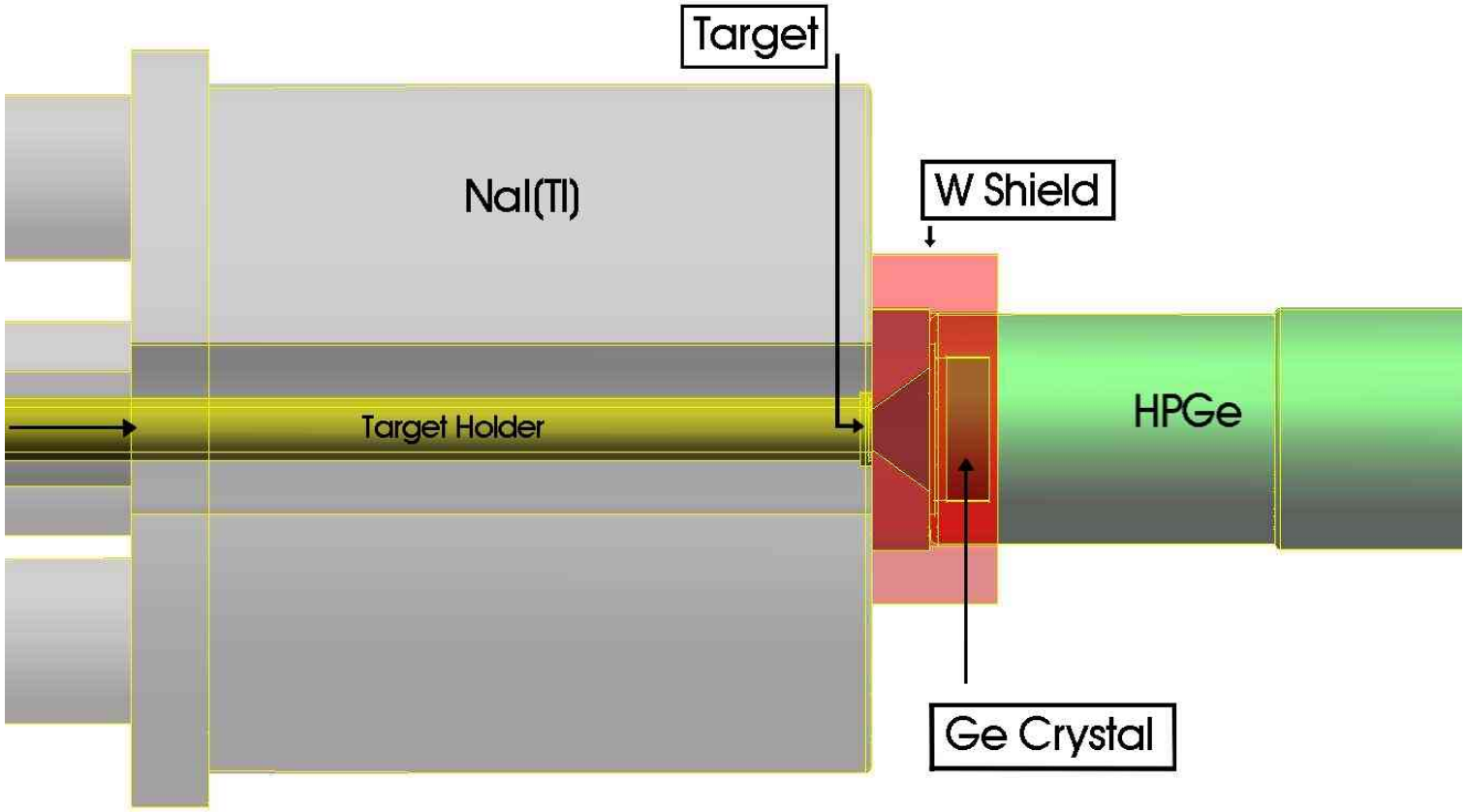
6.92 branching at Ohio U



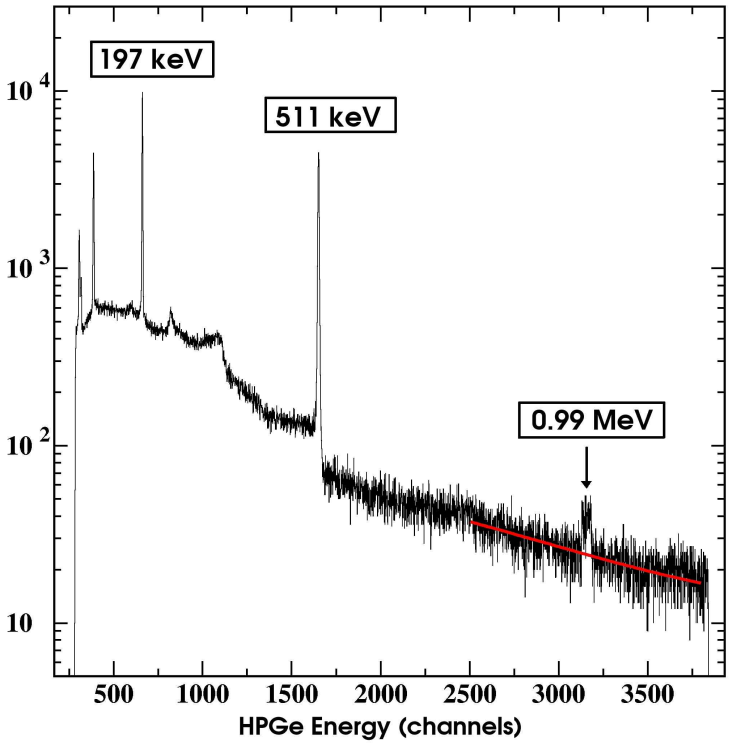
- α-particle width of the 6.92-MeV state uncertain
- 7.12→6.92 branching unknown
- finite branching => $\theta_\alpha^{6.9}$ uncertain
- finite branching => $S_{6.9}$ extrapolation error

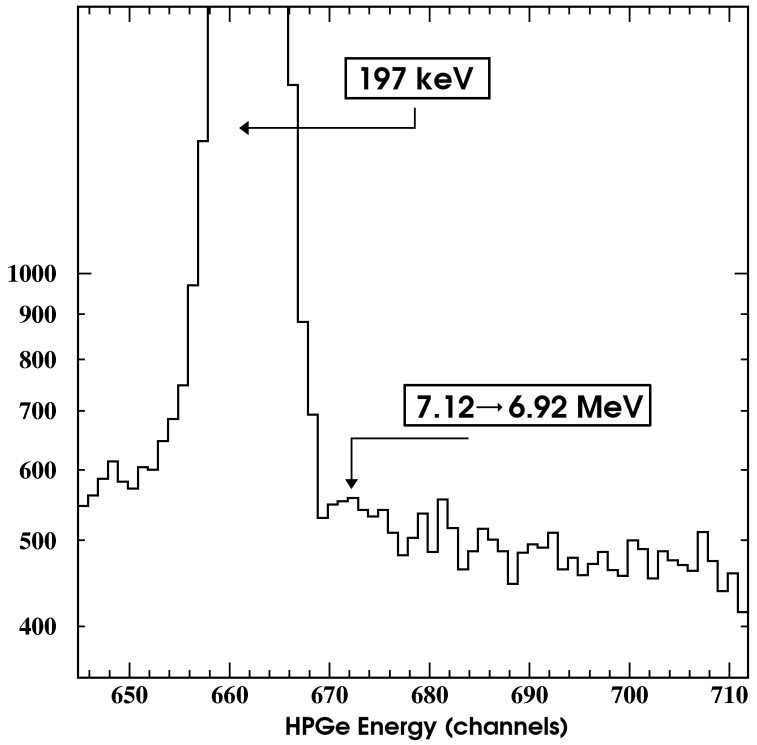


the experiment



branching ratios





$$f = \frac{N_{1\,MeV}/\varepsilon_{HPGe}}{0.7 N_{NaI}/\varepsilon_{NaI}} = (8.3 \pm 0.4) \times 10^{-4}$$

r-matrix formalism

- summation over all incoming angular momenta l_i=0,1,2,3,4

$$\sigma_E = \frac{\pi}{k_\alpha^2} \sum_{l_i} (2l_i + 1) \left| U_{l_i} \right|^2 ,$$

with

$$U_{l_i} = -ie^{i(\omega_{l_i} - \phi_{l_i})} 2P_{l_i}^{1/2} k_\gamma^{L+1/2} \times \frac{R_{l_i\gamma} + R_{l_i\gamma}^{ext}}{1 - (S_{l_i} - B_{l_i} + iP_{l_i}) R_{l_i}},$$

$$R_{l_i} = \sum_\lambda \frac{\gamma_{\lambda l_i}^2}{E_{\lambda l_i} - E}, \qquad R_{l_i\gamma} = \sum_\lambda \frac{\gamma_{\lambda l_i} \gamma_{\lambda l_i \gamma}}{E_{\lambda l_i} - E}$$

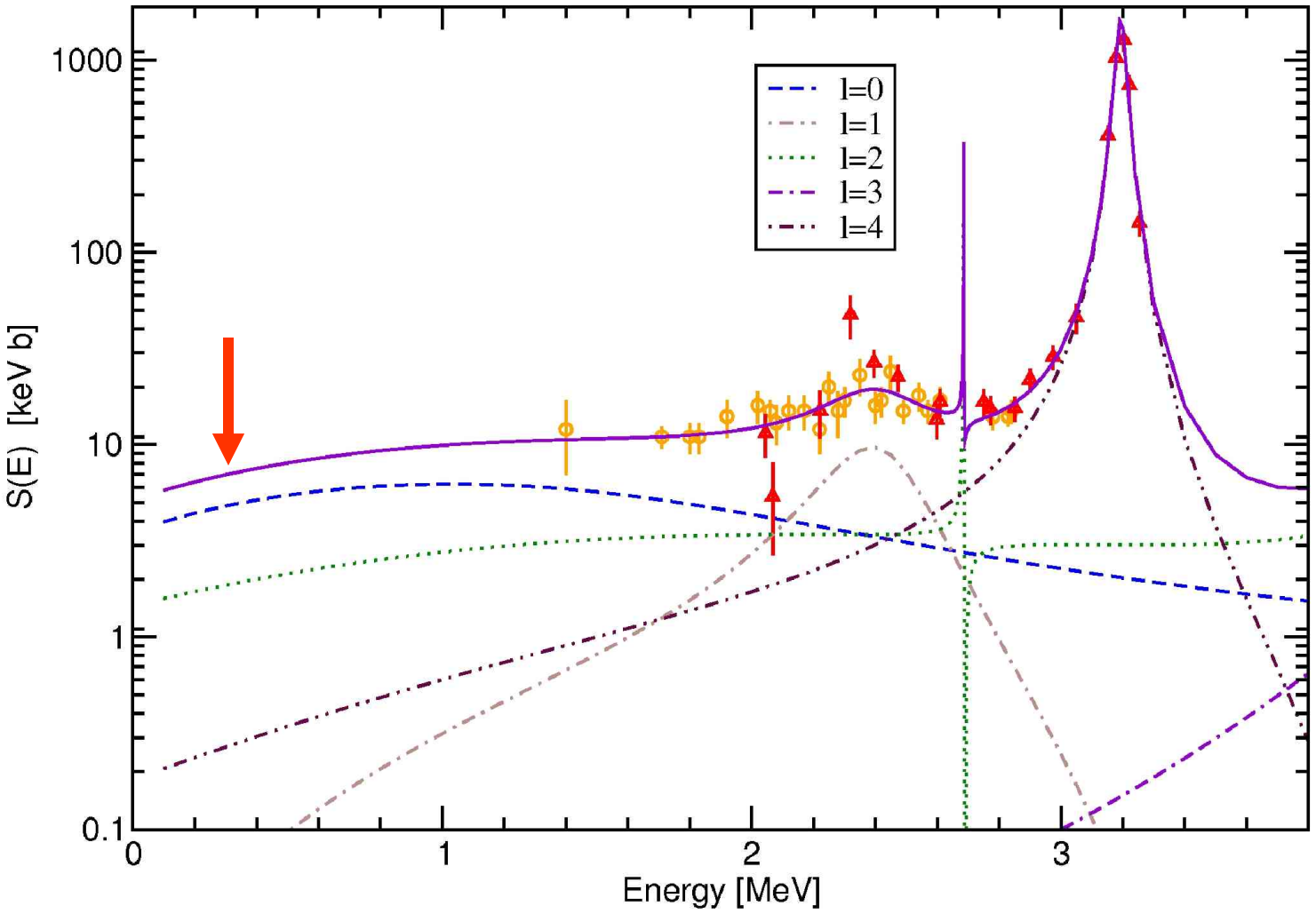
r-matrix formalism

- parametrization equivalent to Barker & Kajino 1991

$$R^{ext}_{l_i\gamma} = \frac{C_{l_f} W_{l_f}(a)}{k_\alpha} \left(\frac{\alpha\mu c}{15\hbar}\right)^{1/2} i^{l_i+2-l_f} (l_i 200|l_f 0)$$
$$\times \left(\frac{a}{\hbar c}\right)^{5/2} \mu^2 \left(\frac{Z_1}{M_1^2} + \frac{Z_2}{M_2^2}\right)$$
$$\times \{[1-(S_{l_i}-B_{l_i})R_{l_i}]F_{l_i}G_{l_i}J'_{l_i l_f} + k_\alpha a R_{l_i} J''_{l_i l_f}\},$$

$$C_{l_f} = \sqrt{\frac{2\mu a}{\hbar^2 W^2_{l_f}(a)}} \left(\frac{\gamma_{l_f}}{\sqrt{1+\gamma^2_{l_f}\frac{dS_{l_f}}{dE}}}\right)$$

r-matrix fit



branching influence

summary

- upper limit on the 7.12 $\rightarrow$ 6.92 branching ratio
- R-Matrix fits give:
  - $\gamma_{6.9}$= 0.74±0.12 MeV$^{1/2}$
  - $S_{6.9}$(300)= 7.1±1.6 keV b
- calculate influence on the E2 ground state extrapolation

- measured capture cross section through 6.05-MeV level
  - $S_{6.0}$(300)=25±16 keVb
- analyze cascade through 6.92-MeV state

thank you

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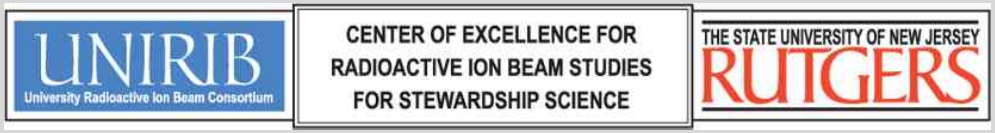
M. J. Hornish

L. Buchmann

D. Hutcheon

M. Trinczek

J. D'Auria

C. Ruiz

J.A. Cizewski