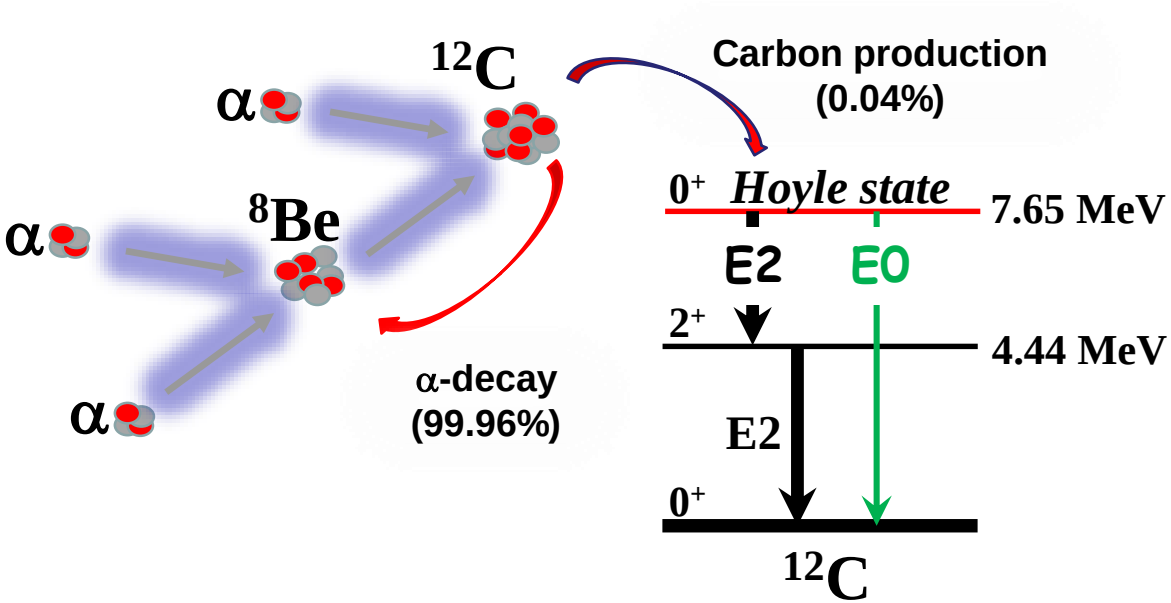
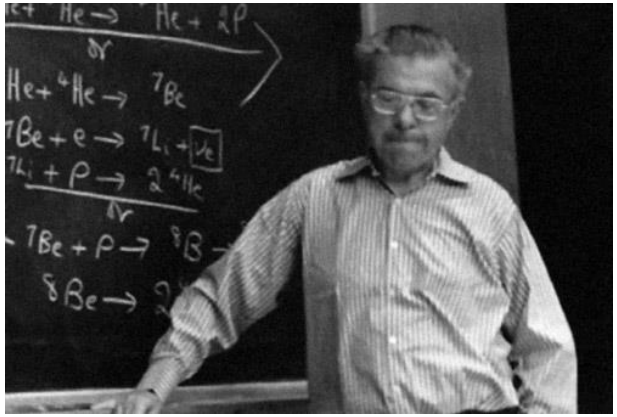
The radiative width of the Hoyle state from pair conversion and proton-gamma-gamma measurements

T. Kibédi

Department of Nuclear Physics
Australian National University
Canberra, Australia
Tibor.Kibedi@anu.edu.au

The triple-α rate in stellar He burning





Sir Fred Hoyle (1915-2001)

The rate per unit volume for the triple-α reaction (Rolfs and Rodney, 1988):

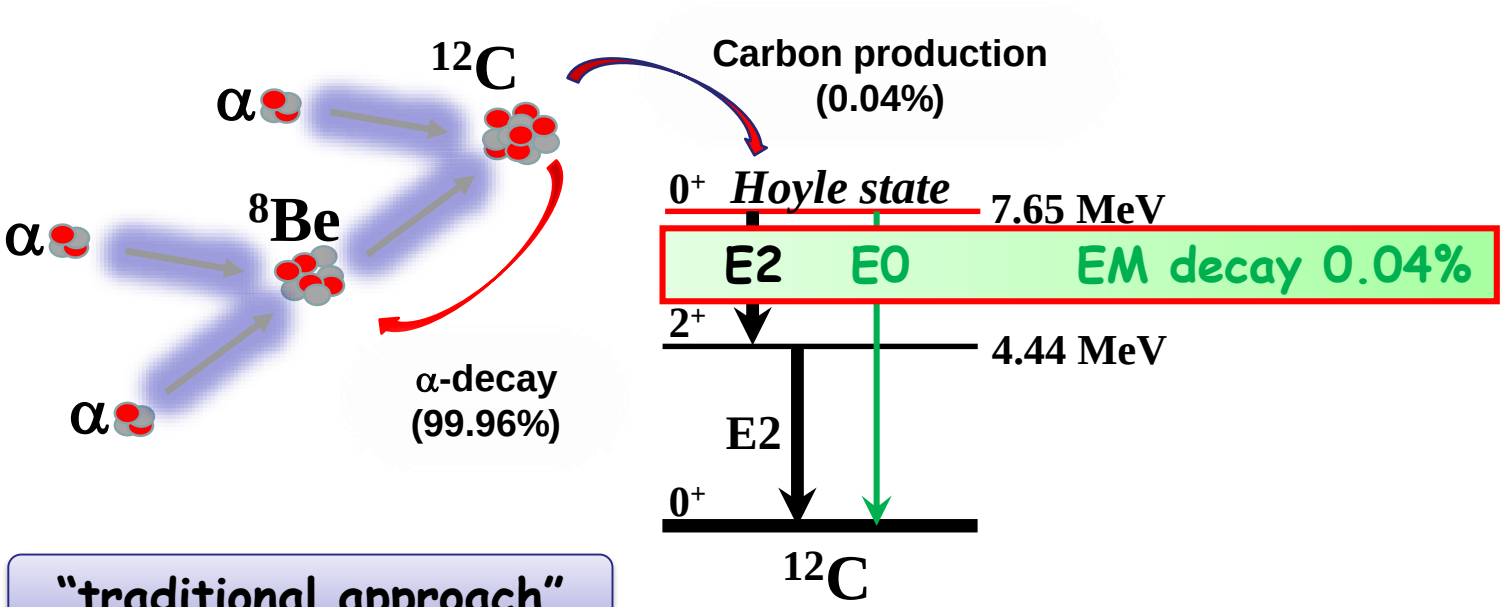
$$r_{3\alpha} = \frac{N_\alpha^3}{2} 3^{3/2} \left(\frac{2\pi\hbar^2}{M_\alpha kT} \right)^3 \frac{\Gamma_\alpha \Gamma_{rad}}{\hbar\Gamma} \exp(-Q_{3\alpha}/kT)$$

$$\textit{where} \qquad Q_{3\alpha} = (M_{12C} - 3 \times M_\alpha)c^2 + E_r$$

Since $\Gamma_{rad} << \Gamma_\alpha \approx \Gamma$, where $\Gamma = \Gamma_\alpha + \Gamma_{rad}$ and T ≈ 10^8 K:

$$r_{3\alpha} \propto \Gamma_{rad} \exp(-Q_{3\alpha}/kT)$$

Determining the triple-α rate



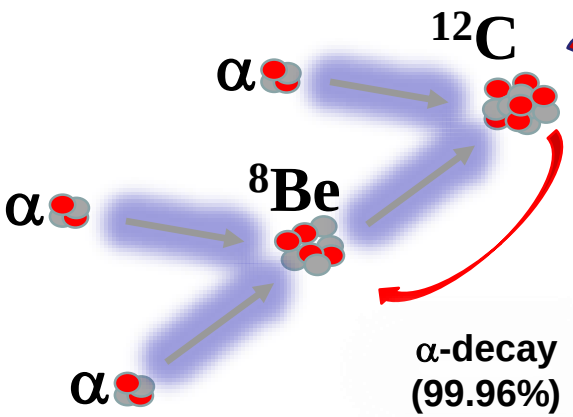
"traditional approach"

$$r_{3\alpha} \propto [\Gamma_{rad}]\exp(-[Q_{3\alpha}]/kT)$$

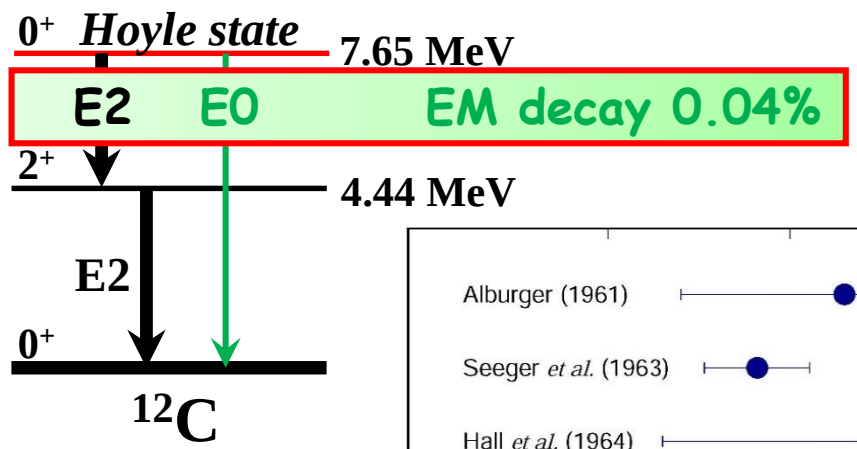
$$\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}(E0)}\right] \times [\Gamma_{\pi}(E0)]$$

Γ_{rad} could not be measured directly!

Determining the triple-α rate



Carbon production
(0.04%)



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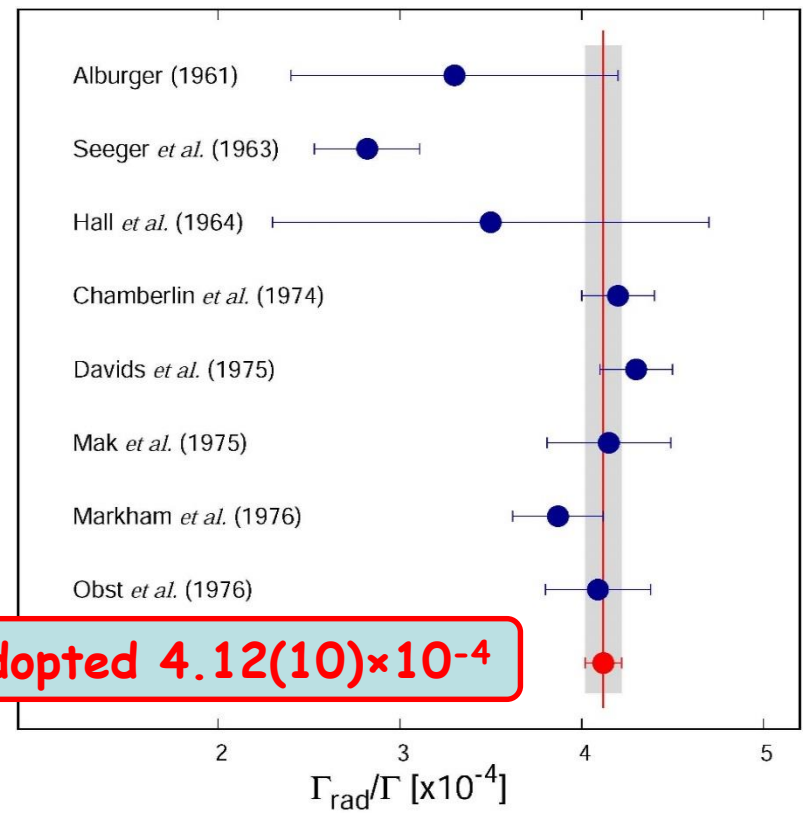
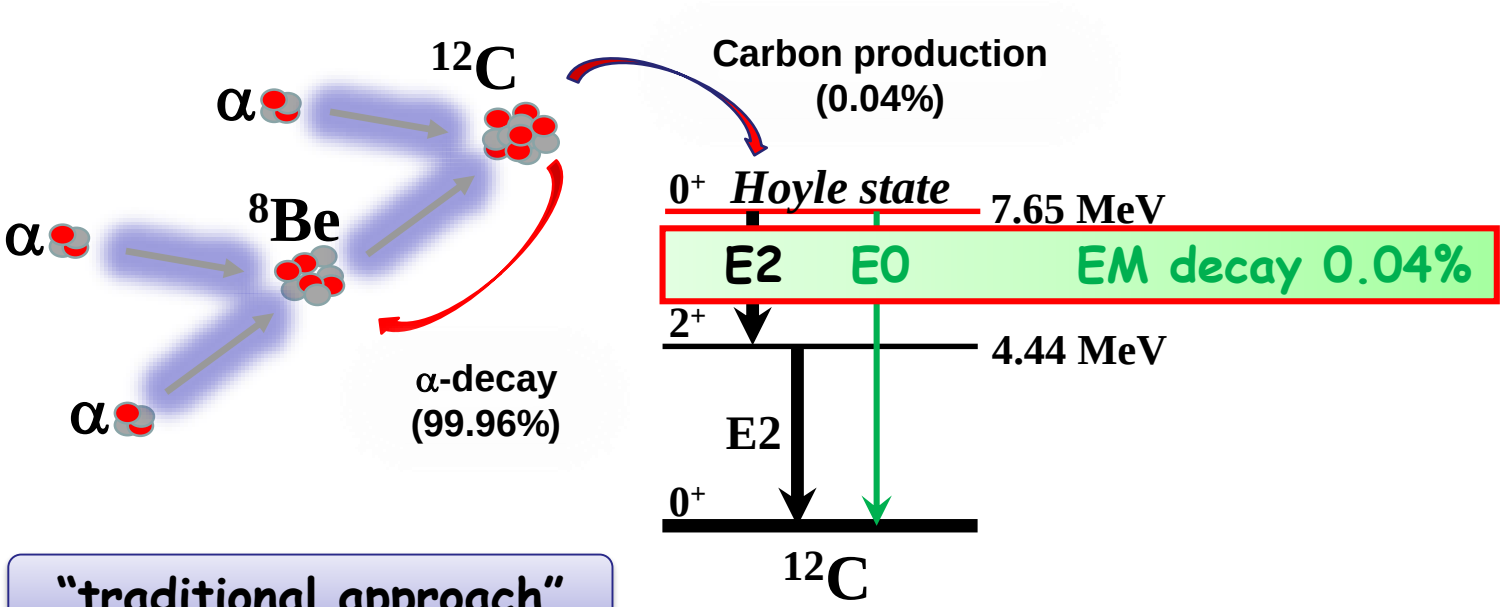


Adopted 4.12(10)×10^{-4}

Determining the triple-α rate



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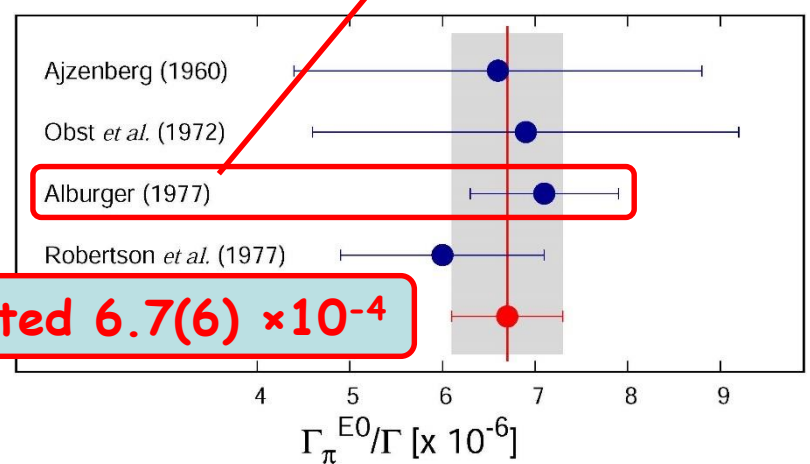
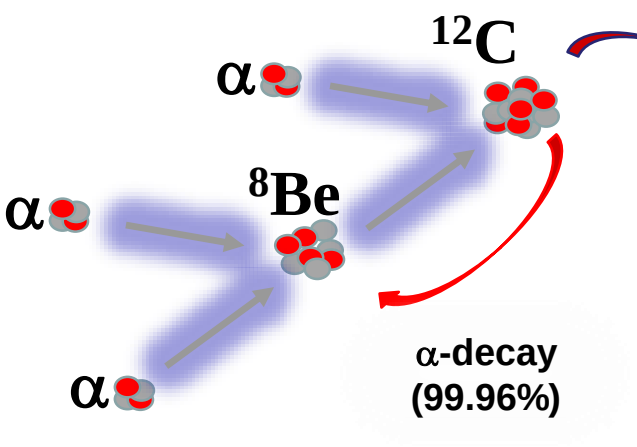
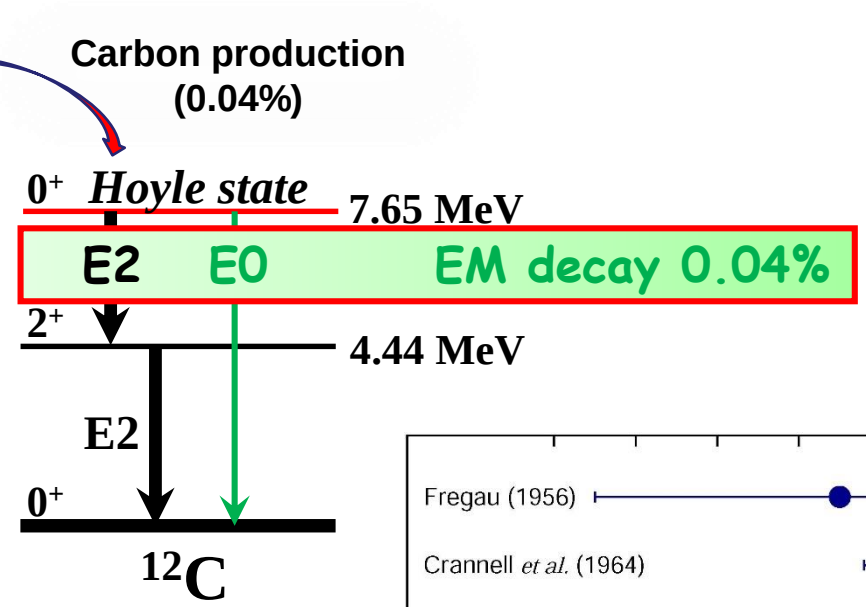
Only experiment using magnetic spectrometer



Determining the triple-α rate





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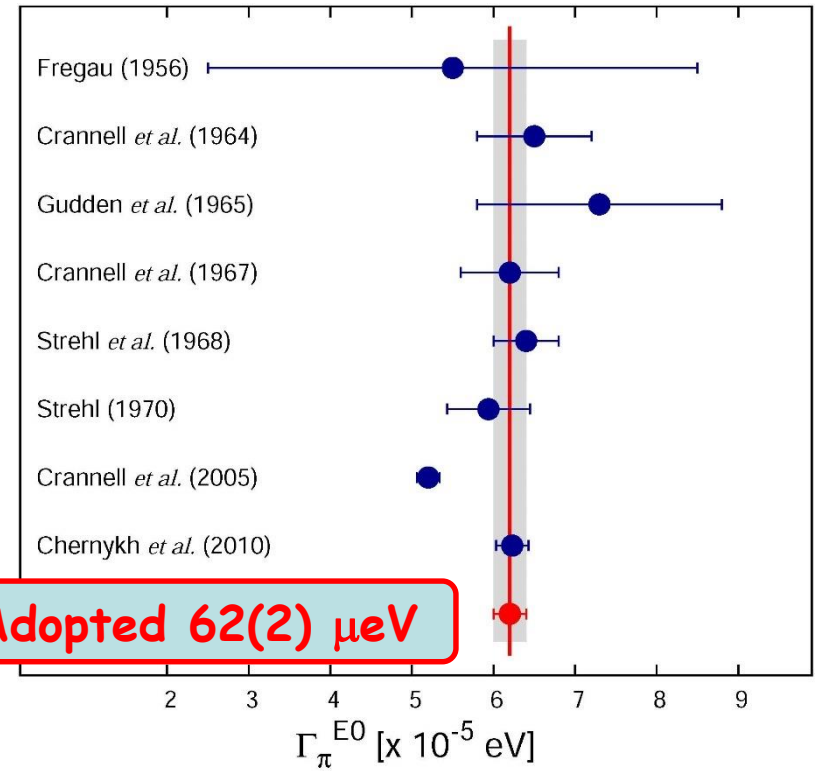
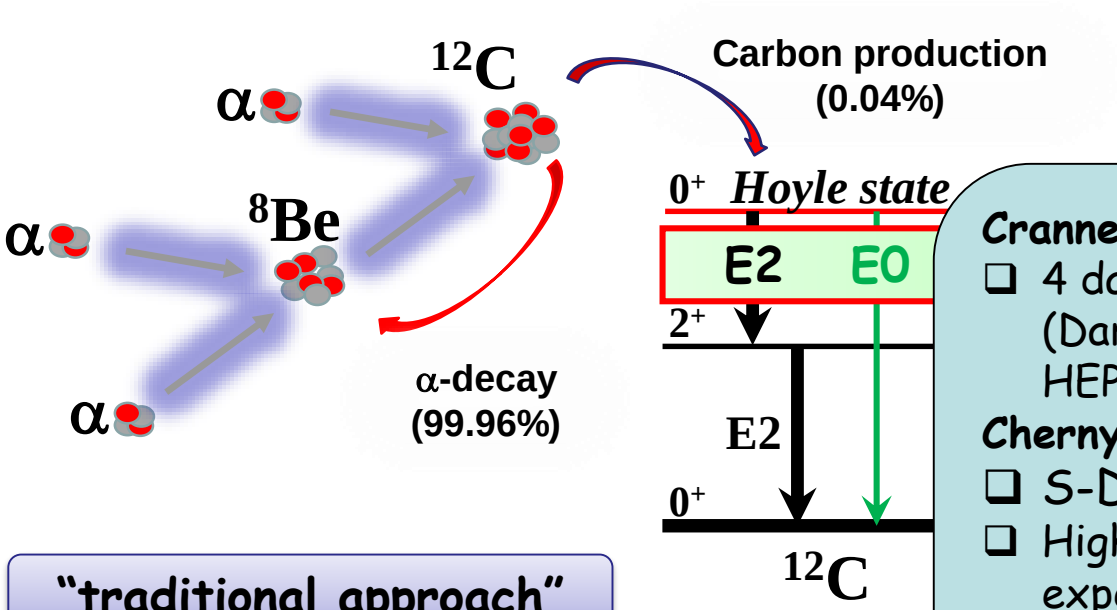


Determining the triple-α rate



Crannel et al NP A785 (2005) 399c

- 4 data sets from different labs (Darmstadt, Bates-CUA, NIKHEF-K, HEPL)

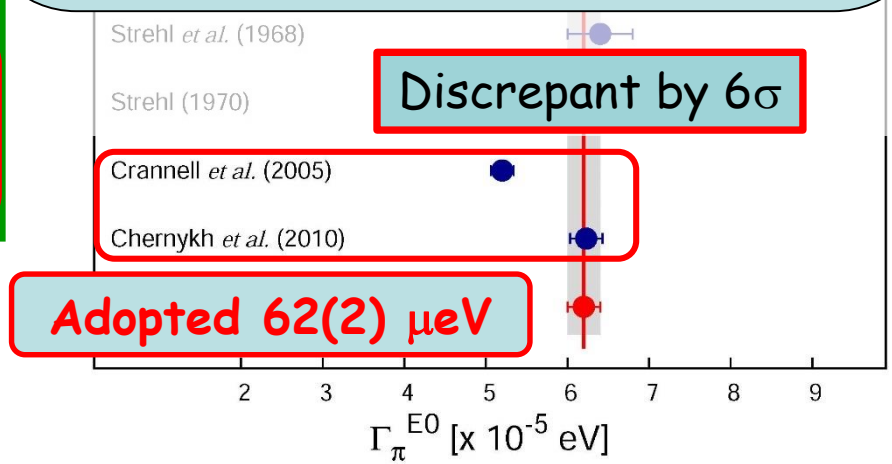
Chernykh et al. PRL 105 (2010) 022501

- S-DALINAC Darmstadt
- High-resolution low momentum transfer experiment
- Model independent and traditional analysis

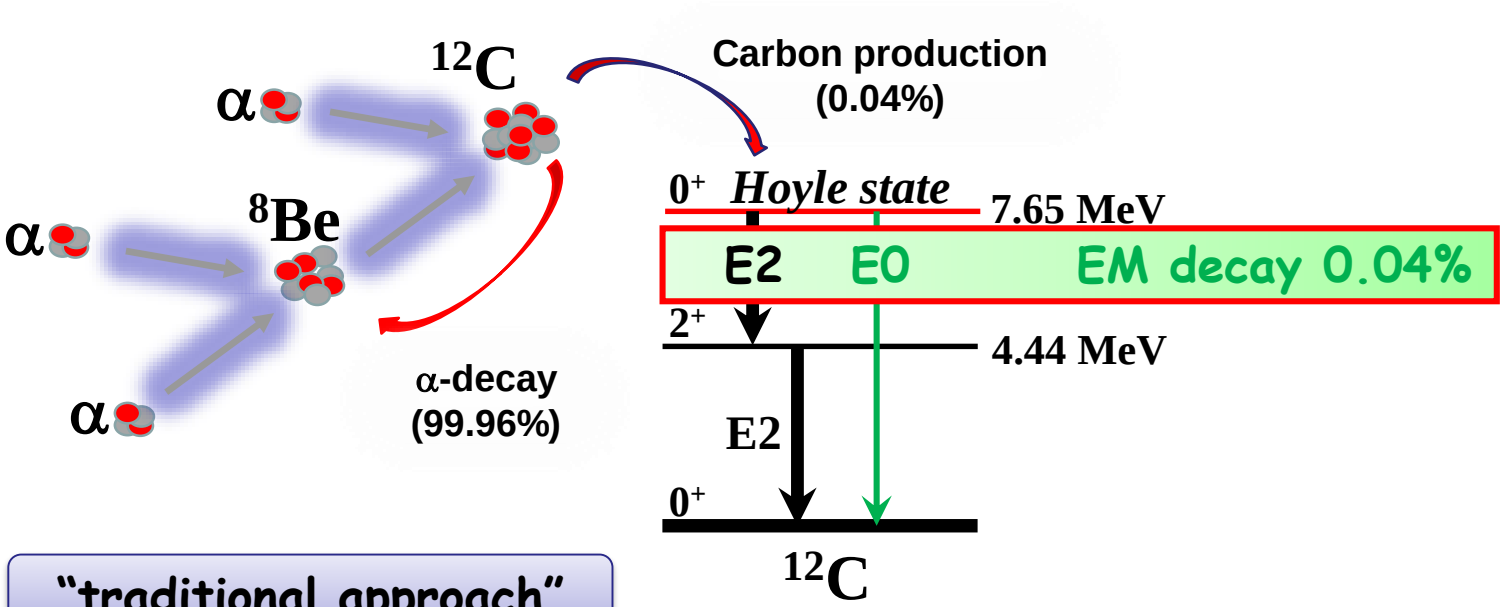
"traditional approach"

$$r_{3\alpha} \propto [\Gamma_{rad}]\exp(-[Q_{3\alpha}]/kT)$$

$$\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}(E0)}\right] \times [\Gamma_{\pi}(E0)]$$



Determining the triple-α rate



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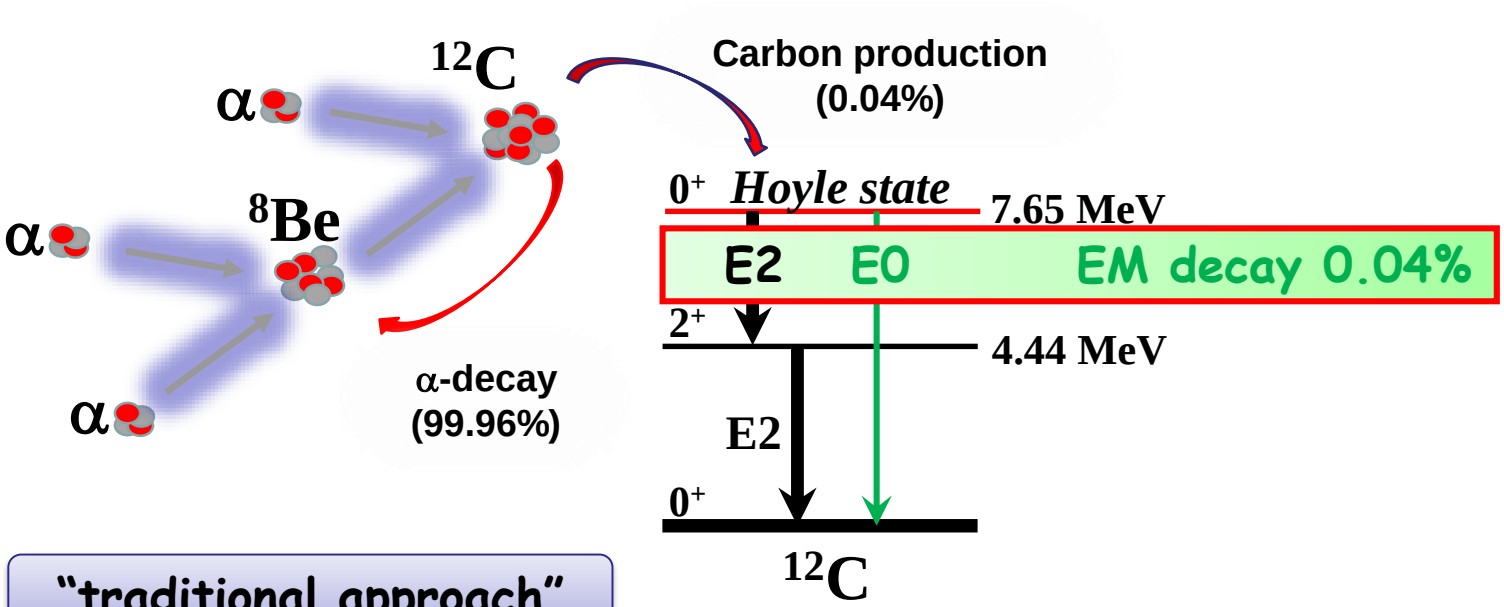
	Value	[%]	#
$Q_{3\alpha}$	379.35(20) keV	0.05	6
Γ_{rad}/Γ	4.19(11) $\times 10^{-4}$	2.7	8
$\Gamma_{\pi}(E0)/\Gamma$	6.7(6) $\times 10^{-6}$	8.9	4
$\Gamma_{\pi}(E0)$	6.2(2) $\times 10^{-5}$ eV	3.2	8
Γ_{rad}	3.9(4) $\times 10^{-3}$ eV	10.3	

Determining the triple-α rate



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AIM 1: Γ_{rad}/Γ from pγγ measurements

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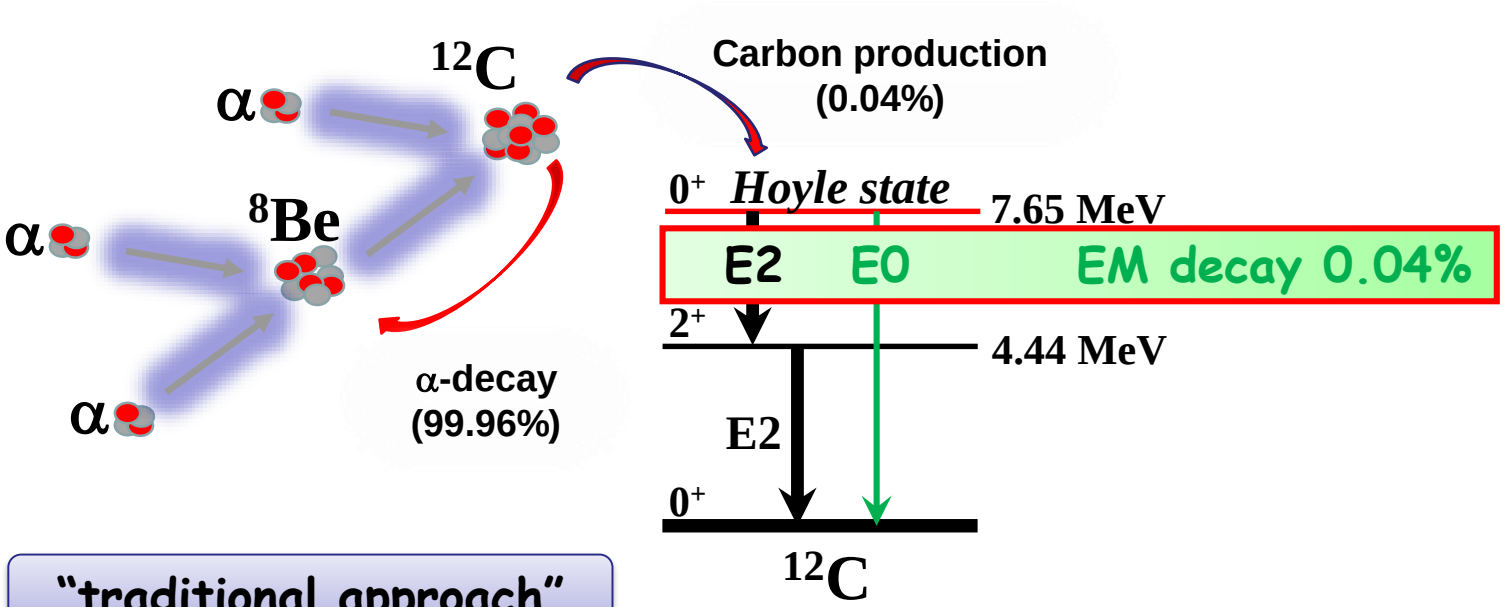

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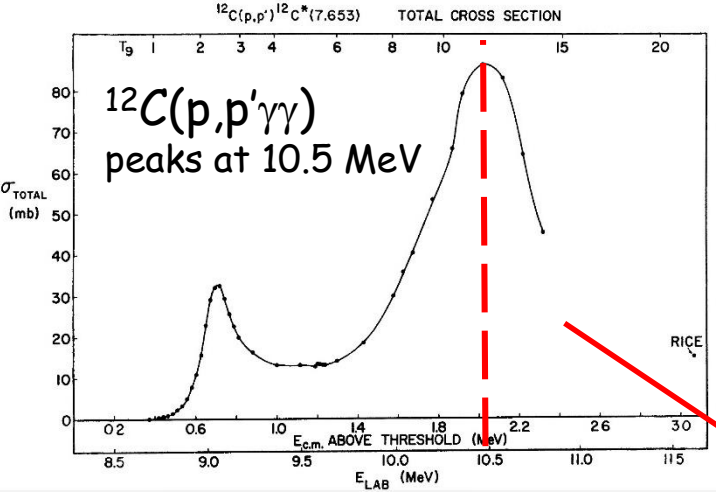
Replace formulae!

AIM 2: from direct measurement of the E0 and E2 transitions

	Value	[%]	#
$Q_{3\alpha}$	379.35(20) keV	0.05	6
Γ_{rad}/Γ	4.19(11) $\times 10^{-4}$	2.7	8
$\Gamma_{\pi}(E0)/\Gamma$	6.7(6) $\times 10^{-6}$	8.9	4
$\Gamma_{\pi}(E0)$	6.2(2) $\times 10^{-5}$ eV	3.2	8
Γ_{rad}	3.9(4) $\times 10^{-3}$ eV	10.3	

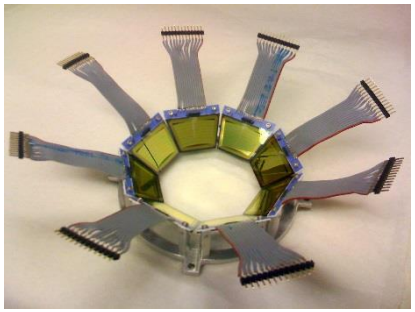
pγγ Measurements to determine Γ_{rad}/Γ

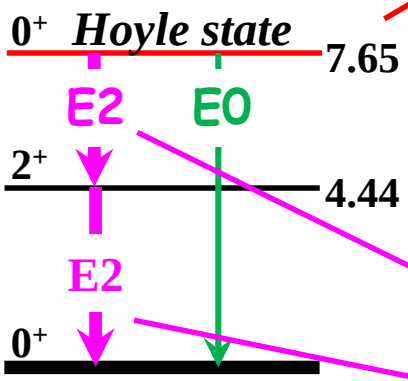
Badriah Alshahrani`s thesis (ANU)



Davis and Bonner, Astrophys. J. **166** (1971) 405.

SiRi - particle detection
64 ΔE(130 μm)-E(1550 μm)
M. Guttormsen, et al.
NIM **648** (2011) 168





Run at 10.7 MeV to get above the energy threshold in ΔE

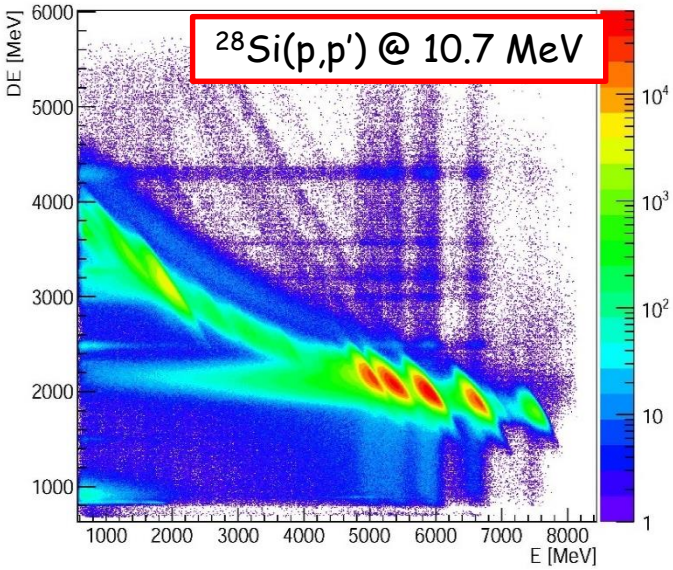
Γ_{rad}/Γ from pγγ/p rates

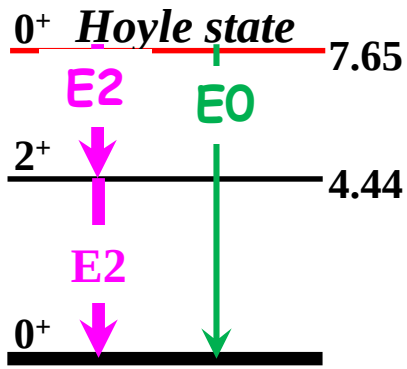
Oslo Cyclotron Laboratory

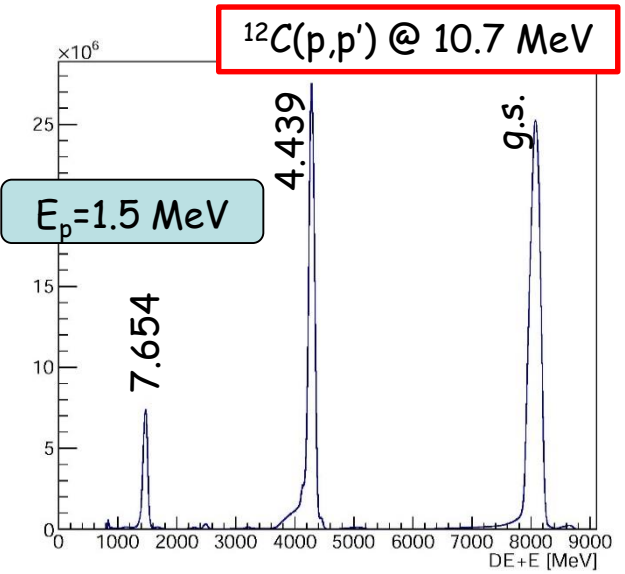
- 12 days, ~5 nA
- 6.0E+9 events (total)
- 2.56(5)E+8 (E*=7.65 MeV)
- $^{28}Si(p,p'\gamma\gamma)$ for calibration

CACTUS – photon detection
26 5″ by 5″ NaI
M. Guttormsen, et al.
Phys. Scr. **T32** (1990) 54

pγγ Measurements to determine Γ_{rad}/Γ







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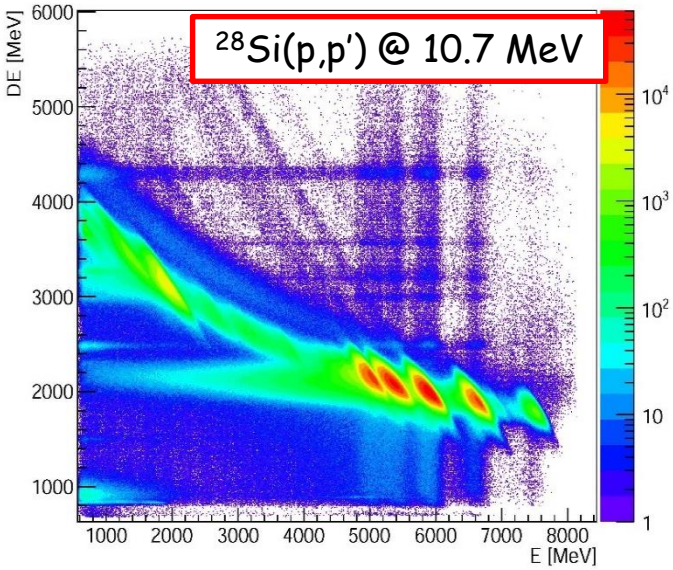

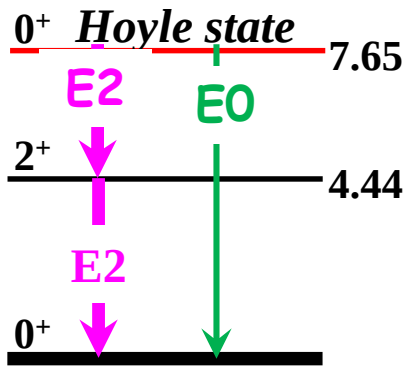

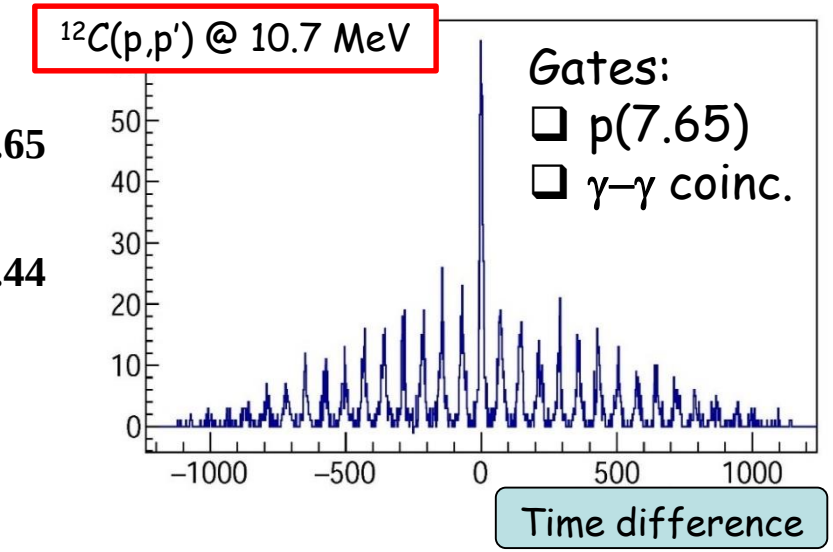

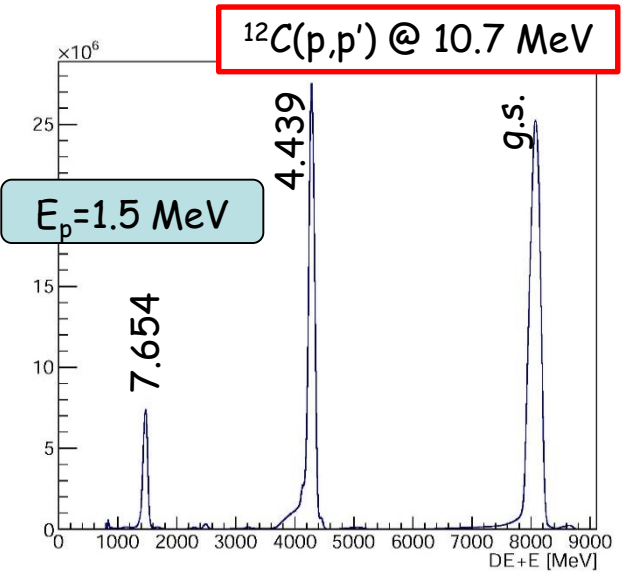

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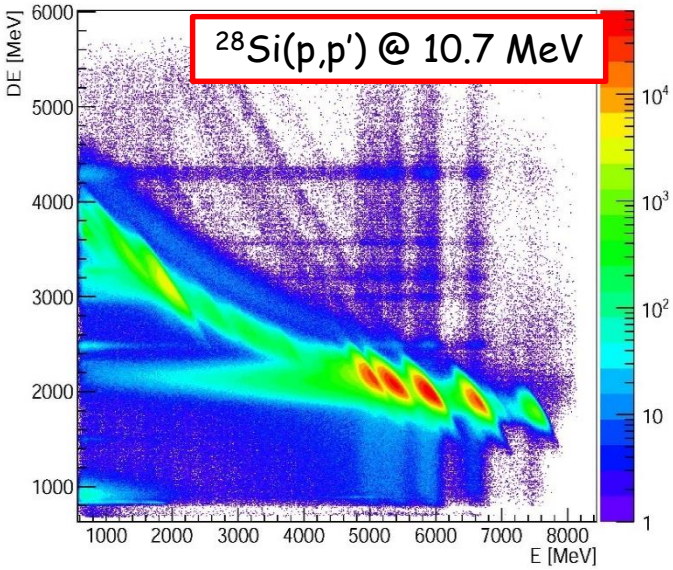

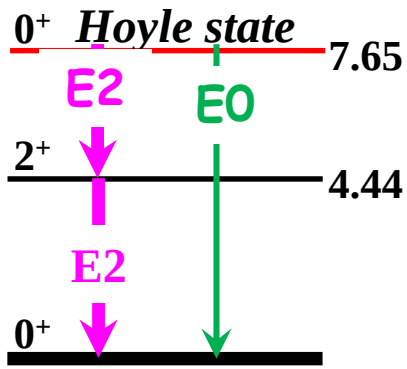

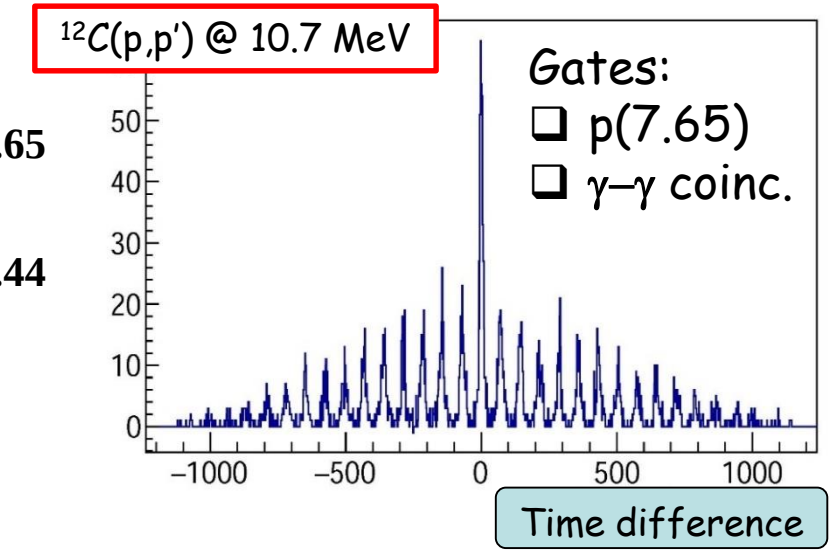

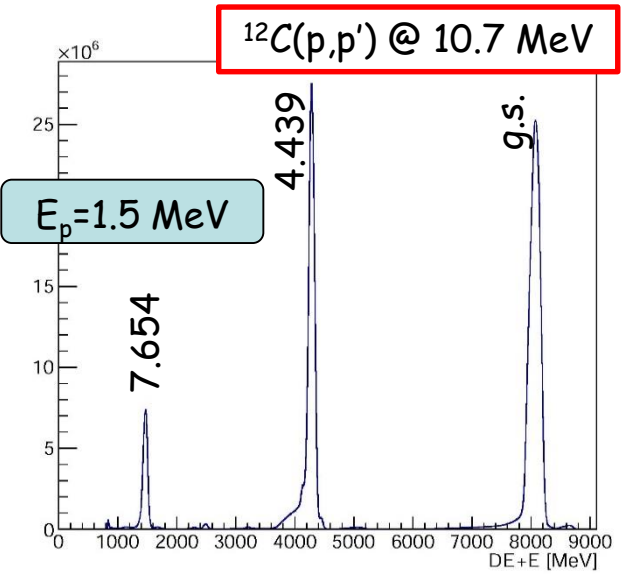

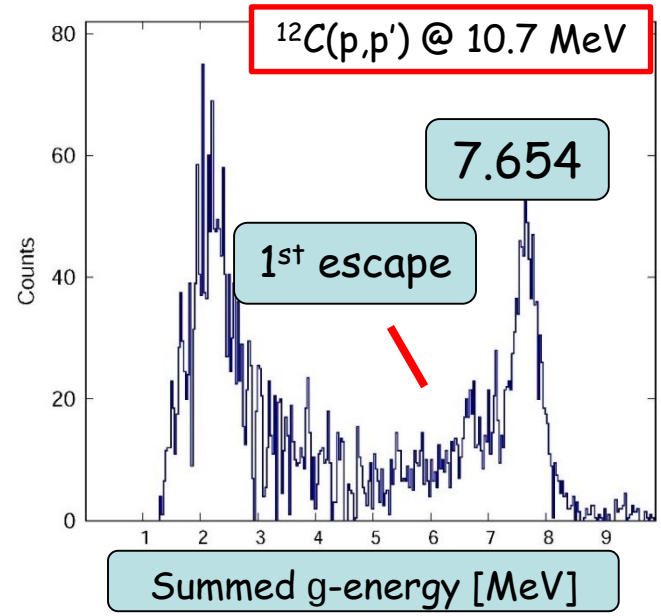

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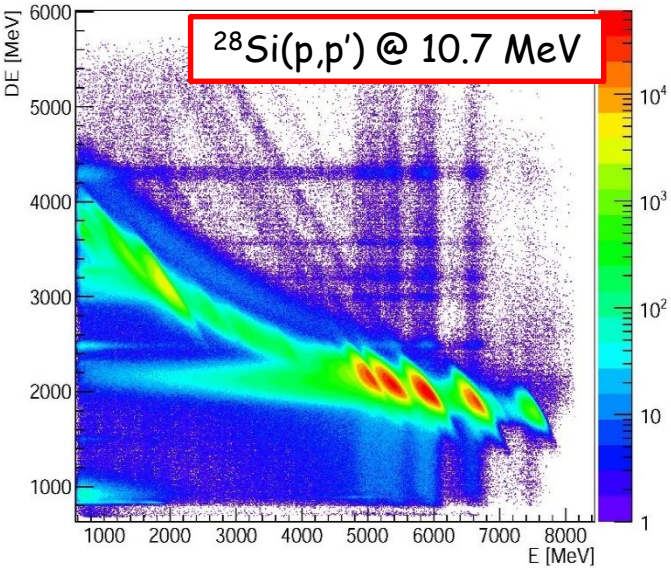
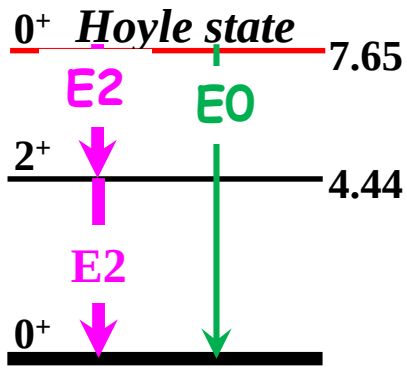
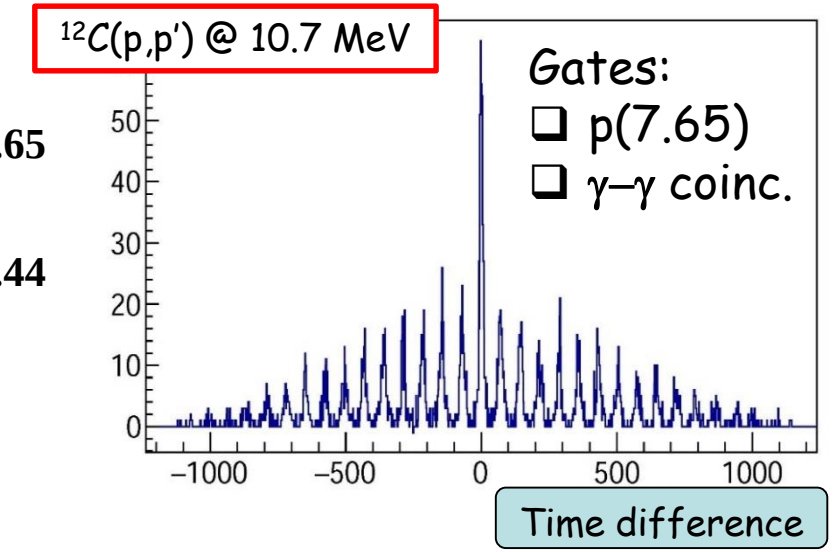
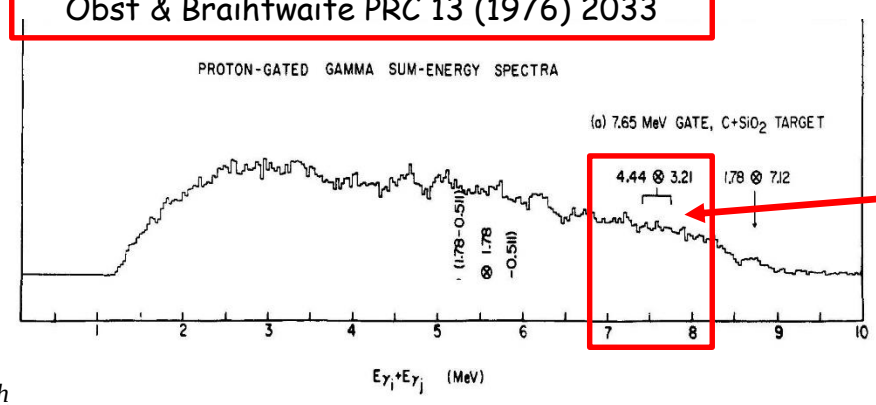
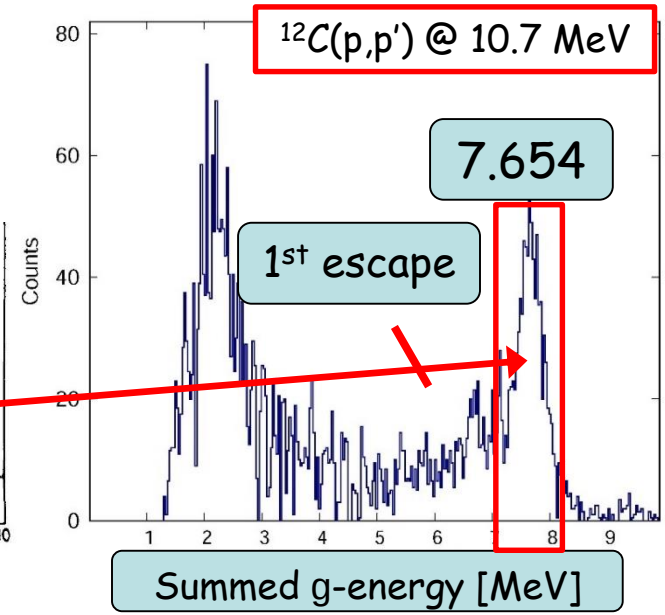






Obst & Braihtwaite PRC 13 (1976) 2033

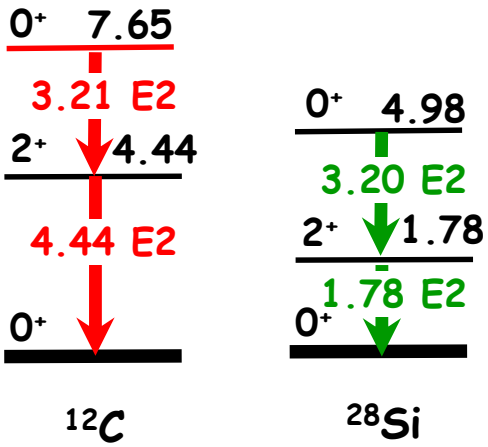




Determining Γ_{rad}/Γ

^{12}C
Γ_γ/Γ=0.0004

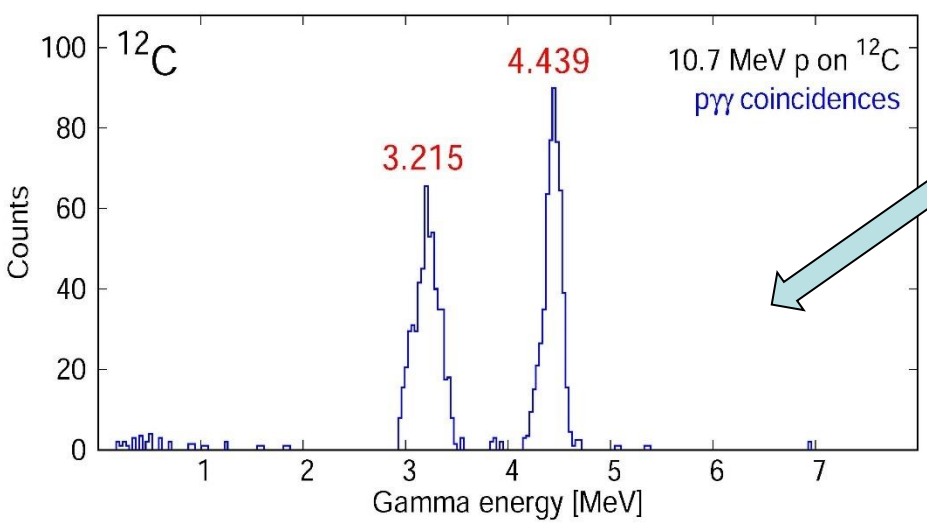
^{28}Si
Γ_γ/Γ=1



$$\left[\frac{\Gamma_\gamma}{\Gamma}\right]^{7.65} = \frac{N_{020}^{7.65}}{N_{020}^{4.98}} \times \frac{N_{singles}^{4.98}}{N_{singles}^{7.65}} \times \frac{\epsilon_{1.78}}{\epsilon_{4.44}} \times \frac{\epsilon_{3.20}}{\epsilon_{3.21}} \times \frac{W_{020}^{4.98}}{W_{020}^{7.65}}$$

Detector efficiency (ε) and angular correlation (W) from Penelope simulation

- pγγ triple coincidences
- Gates: proton energy, DE-E 2D ("banana"); TDC time difference; summed gamma energy, gamma energy difference
- 130 Gb data



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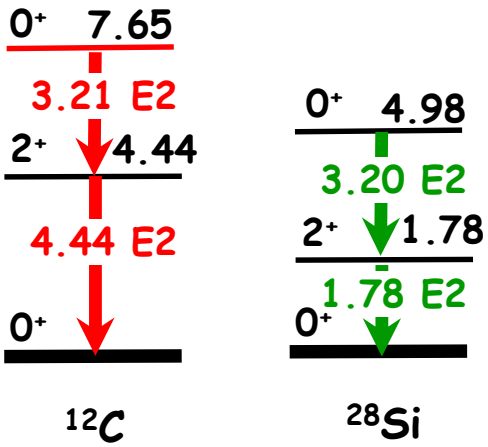

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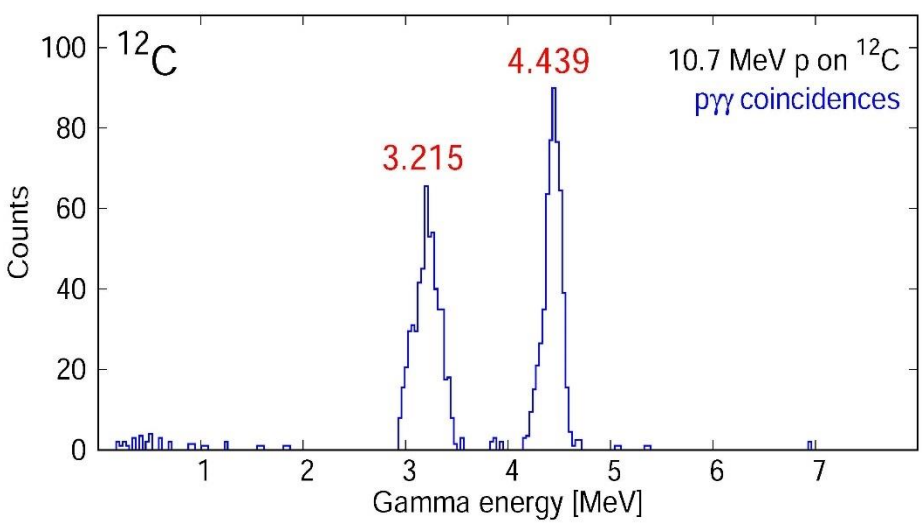
Detector efficiency (ε) and angular correlation (W) from Penelope simulation

State	$N_{020}(p\gamma\gamma)$	$N_{singles}$
7.654 (^{12}C)	529(23)	2.56(5)E+8
4.98 (^{28}Si)	2617(51)	3.13(6)E+5



$$\left[\frac{\Gamma_\gamma}{\Gamma}\right]^{7.65} = 3.99(22) \times 10^{-4}$$

$$\left[\frac{\Gamma_{rad}}{\Gamma}\right]^{7.65} = \left[\frac{\Gamma_\gamma}{\Gamma}\right]^{7.65} \times (1 + \alpha_{CE} + \alpha_\pi)$$

preliminary

$$4.07(22) \times 10^{-4}$$

Tibor Kibèdi , Dep. of Nuclear Physics, ANU, Canberra

Determining Γ_{rad}/Γ

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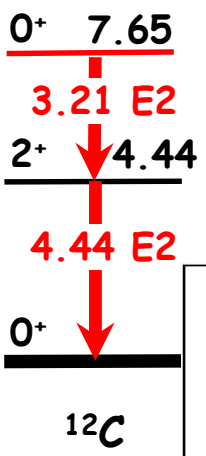
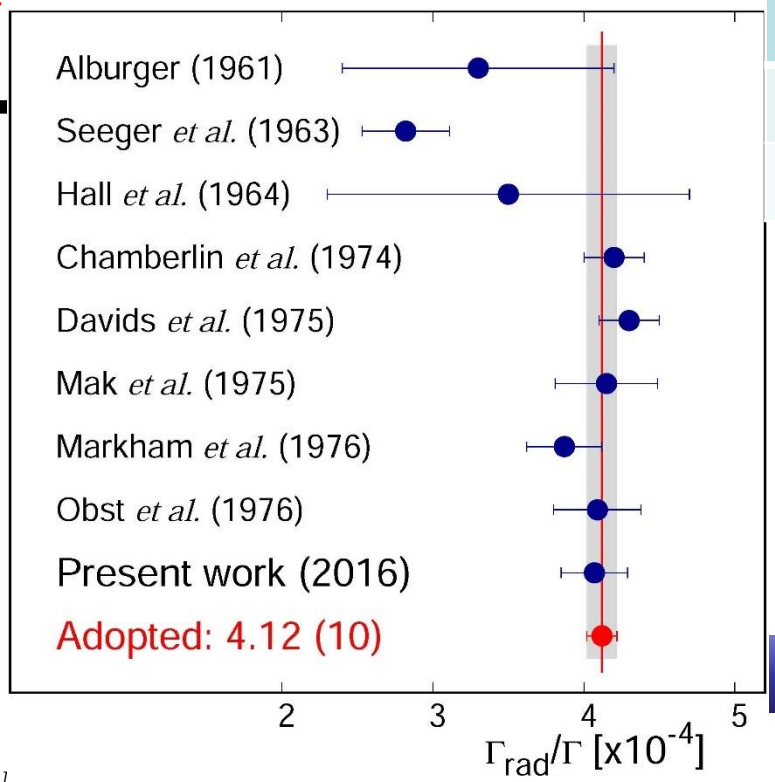
Γ_γ/Γ=0.0004



$$\left[\frac{\Gamma_\gamma}{\Gamma}\right]^{7.65} = \frac{N_{020}^{7.65}}{N_{020}^{4.98}} \times \frac{N_{singles}^{4.98}}{N_{singles}^{7.65}} \times \frac{\epsilon_{1.78}}{\epsilon_{4.44}} \times \frac{\epsilon_{3.20}}{\epsilon_{3.21}} \times \frac{W_{020}^{4.98}}{W_{020}^{7.65}}$$

Detector efficiency (e) angular correlation (W) from Penelope simulation



State	$N_{020}(p\gamma\gamma)$	$N_{singles}$
7.654 (^{12}C)	529(23)	2.56(5)E+8
4.98 (^{28}Si)	2617(51)	3.13(6)E+5

$$\left[\frac{\Gamma_\gamma}{\Gamma}\right]^{7.65} = 3.99(22) \times 10^{-4}$$

$$\left[\frac{\Gamma_{rad}}{\Gamma}\right]^{7.65} = \left[\frac{\Gamma_\gamma}{\Gamma}\right]^{7.65} \times (1 + \alpha_{CE} + \alpha_\pi)$$

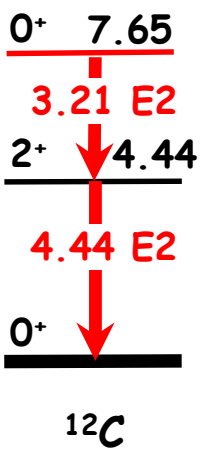
preliminary

$$4.07(22) \times 10^{-4}$$

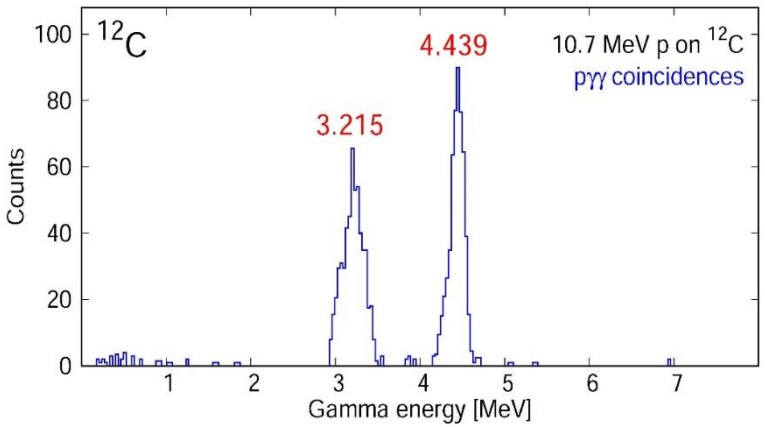
Angular correlation of the 3.21 – 4.44 MeV E2 cascade

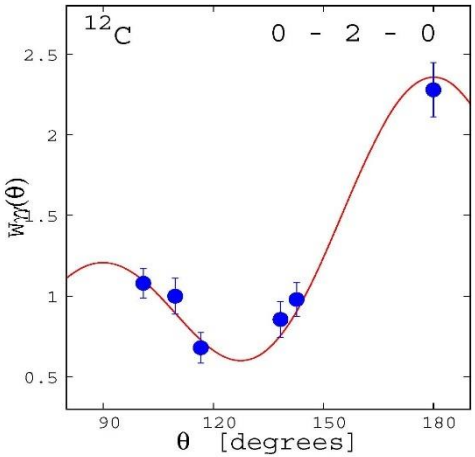
^{12}C

Γ_γ/Γ=0.0004



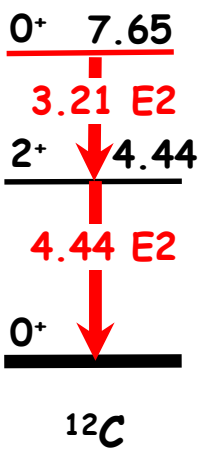
$N_{p\gamma\gamma}$=529(23) cts





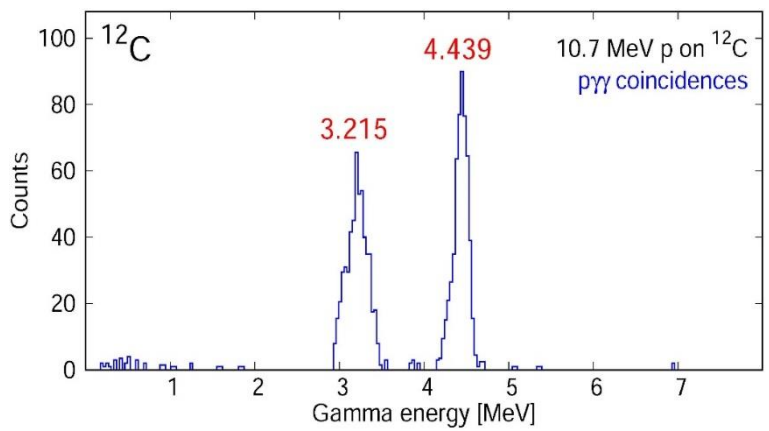
Angular correlation of the 3.21 – 4.44 MeV E2 cascade

^{12}C
Γ_γ/Γ=0.0004

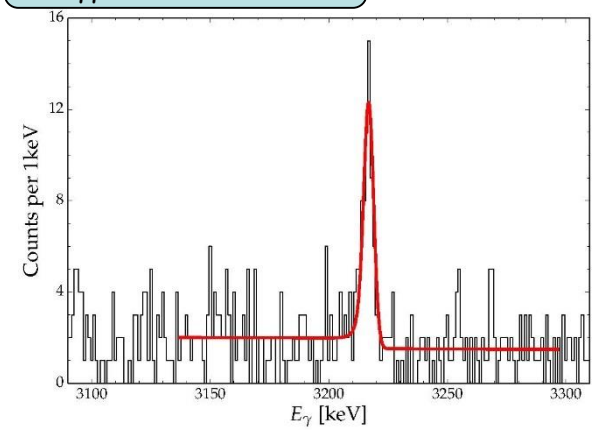


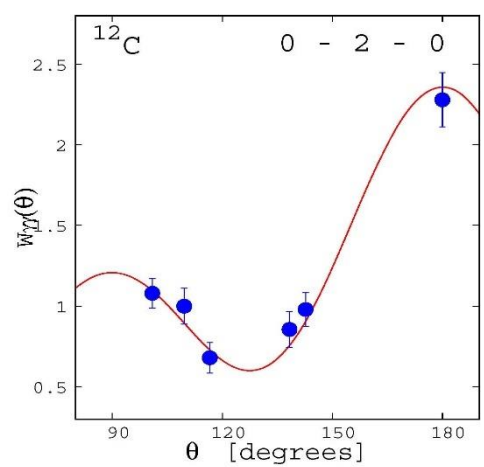
Munich et al., PRC 93 (2016) 065803
^{12}B β^- decay, $\gamma\gamma$ with GAMMASPHERE

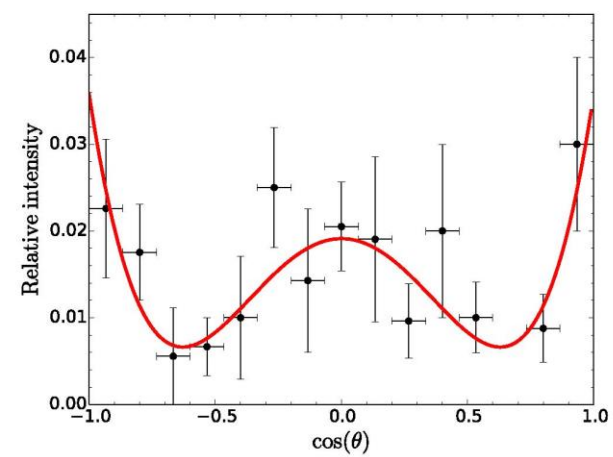
$N_{p\gamma\gamma}$=529(23) cts



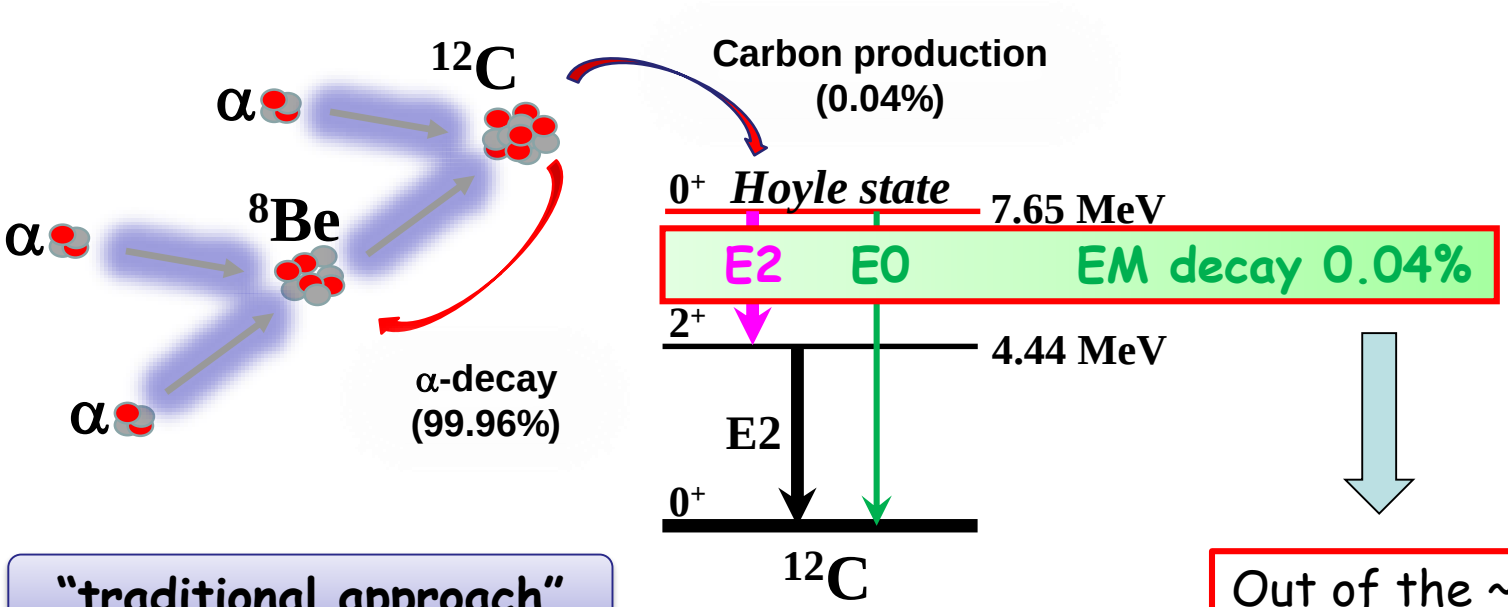
$N_{\gamma\gamma}$=58(9) cts







Determining the triple-α rate



"traditional approach"

$$r_{3\alpha} \propto [\Gamma_{rad}]\exp(-[Q_{3\alpha}]/kT)$$

$$\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}(E0)}\right] \times [\Gamma_{\pi}(E0)]$$

Replace formulae!

Out of the ~0.04%

Γ_{γ}(E2) = 98.5%

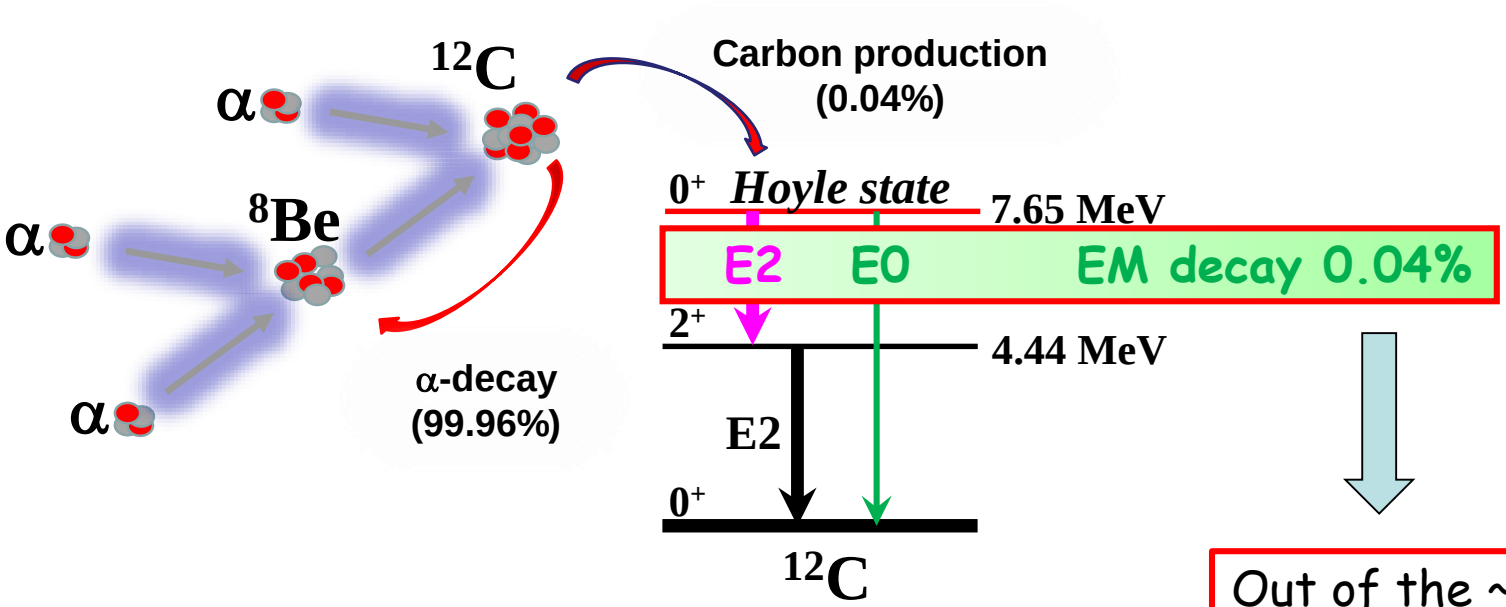
Γ_{π}(E0) = 1.5%

Γ_{π}(E2) = 0.088%

Γ_{CE}(E2), Γ_{CE}(E0) ~0

AIM 2: from direct measurement of the E0 and E2 transitions

Determining the triple-α rate



Out of the ~0.04%

Γ_γ(E2)=98.5%

Γ_π(E0)=1.5%

Γ_π(E2)=0.088%

Γ_{CE}(E2), Γ_{CE}(E0) ~0

Internal pair conversion

$$r_{3\alpha} \propto [\Gamma_{rad}]\exp(-[Q_{3\alpha}]/kT)$$

$$\Gamma_{rad} = \left(\left[\frac{\Gamma_\pi(E2)}{\Gamma_\pi(E0)}\right] \times \left(1 + \frac{1}{[\alpha_\pi(E2)]}\right) + 1\right) \times [\Gamma_\pi(E0)]$$

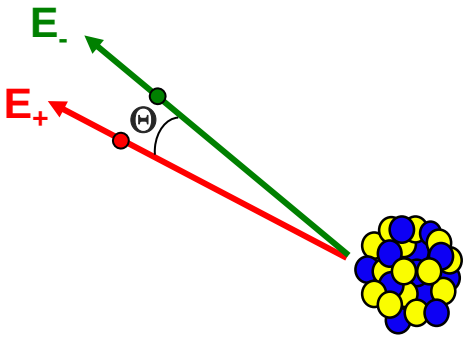
α_π(E2)=8.765E-4

AIM 2: from direct measurement of the E0 and E2 transitions

Measuring electron-positron pairs

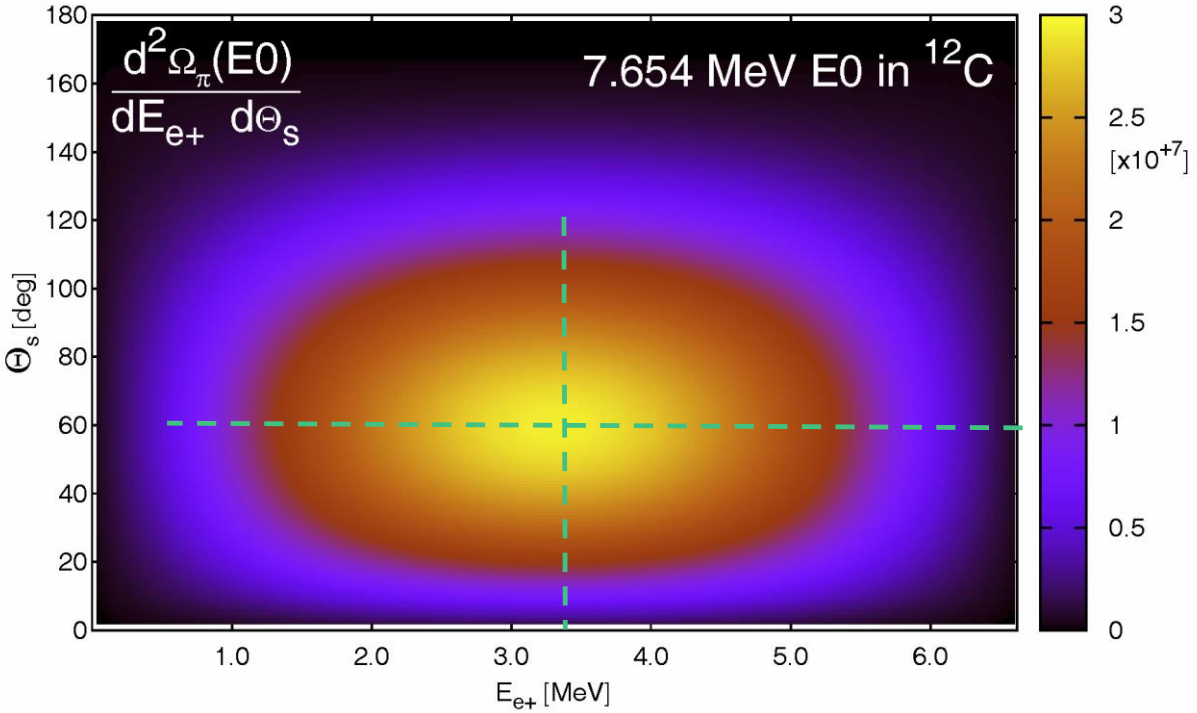
- $e^- - e^+$ particles share the available kinetic energy:

$$E_{kin}=E_+ + E_-=E_\gamma - 2\, m_o c^2$$



Need to observe both particles

- Pair emission rate: function of Z, E_γ, E_+, Θ and multipolarity; Born approx.



$\Gamma_\pi(E0) \sim \rho^2(E0) \times \Omega_\pi(E0)$

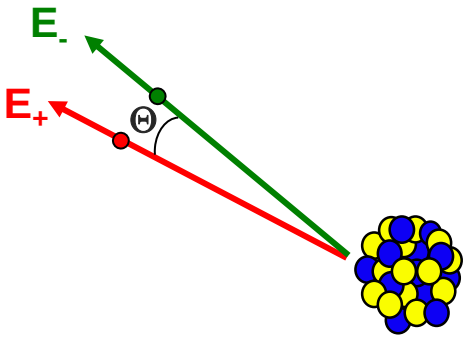
$E_+ \approx E_-$

$\theta_{sep} \approx 60°$

Measuring electron-positron pairs

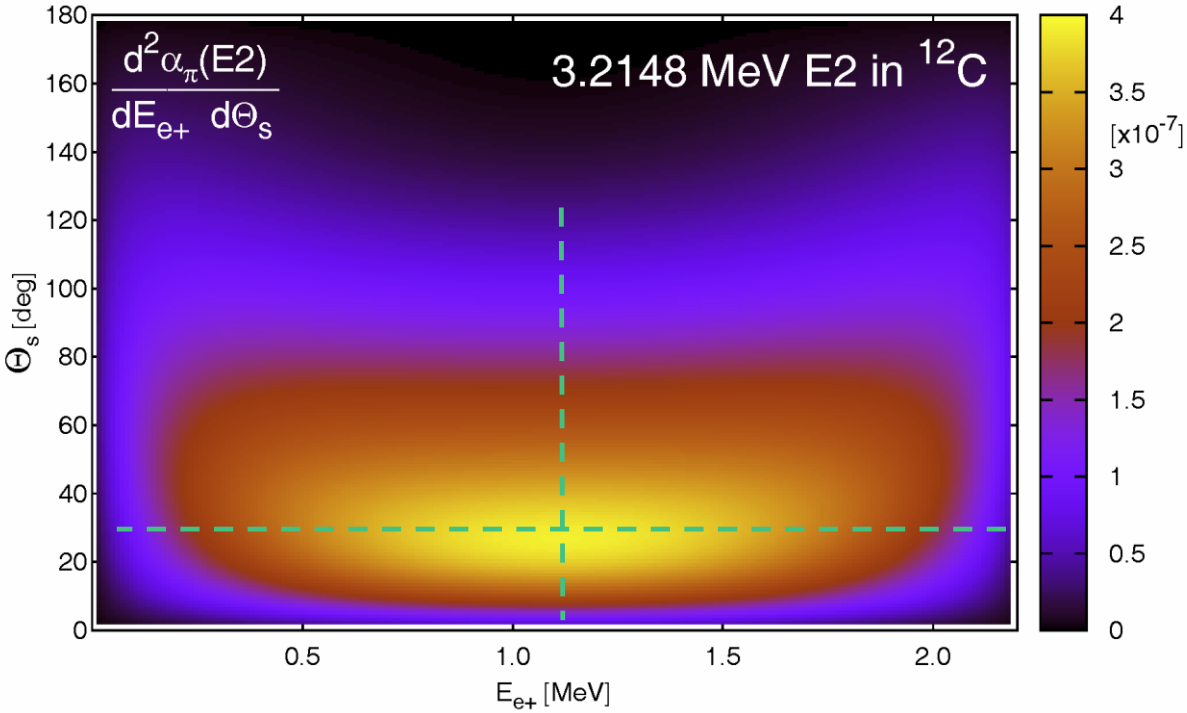
- $e^- - e^+$ particles share the available kinetic energy:

$$E_{kin} = E_+ + E_- = E_\gamma - 2\, m_o c^2$$



Need to observe both particles

- Pair emission rate: function of Z, E_γ, E_+, Θ and multipolarity; Born approx.



$\alpha_\pi(E2) = \Gamma_\pi(E2)/\Gamma_\gamma(E2)$

$E_+ \approx E_-$

$\theta_{sep} \approx 30°$

$W_\pi(E0) \sim \rho^2(E0) \times \Omega_\pi(E0)$

$W_\pi(E2) = \Gamma_\gamma(E2) \times \alpha_\pi(E2)$

ICC

ANU pair spectrometer

Acceptance angles: 15.9º- 46.9 º

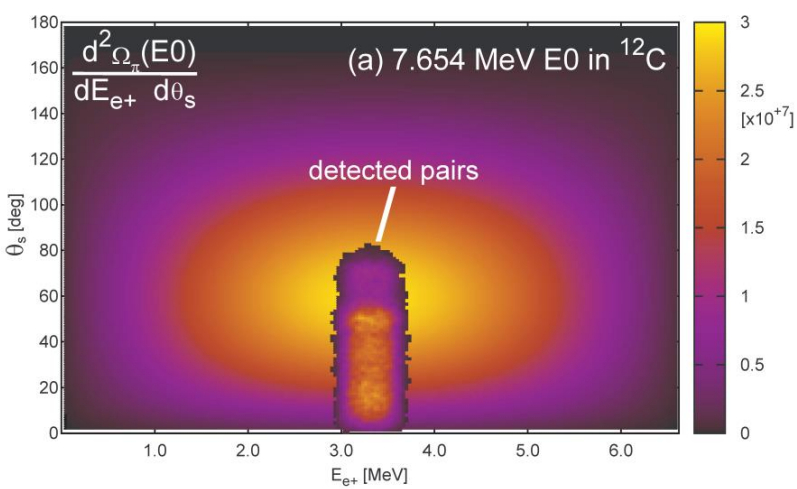
Efficiency – singles (swept): 0.5%

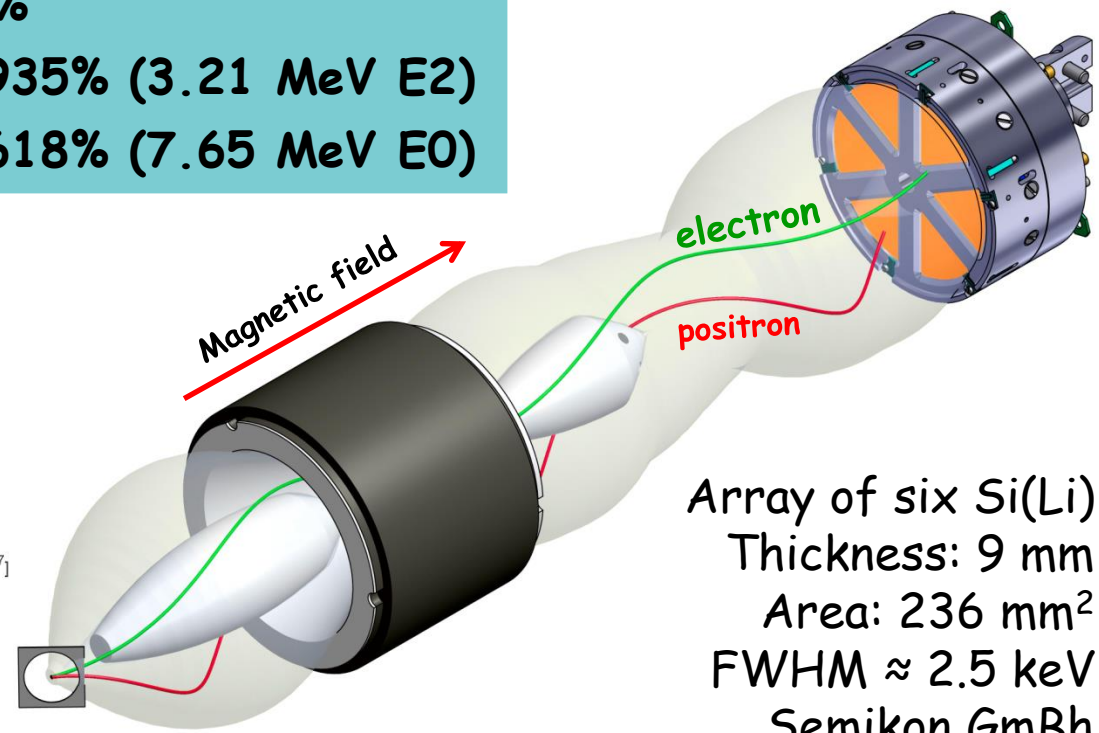
- singles (fixed): 3.0%

Efficiency – pairs: 0.0935% (3.21 MeV E2)

(simulated) 0.0618% (7.65 MeV E0)

Spectrometer response from simulations





Array of six Si(Li)
Thickness: 9 mm
Area: 236 mm^2
FWHM ≈ 2.5 keV
Semikon GmBh

Absorbers made from HeavyMet
Density: 18 gr/cm^3
Minimum path for photons: 8.2 cm
1 mm thick low Z skin

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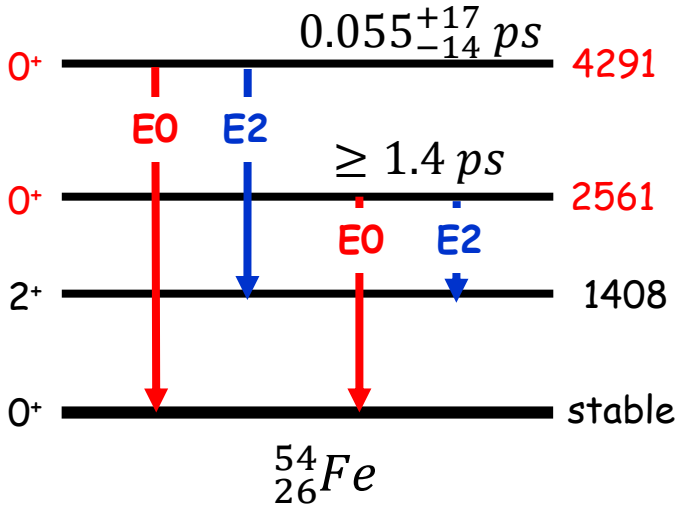
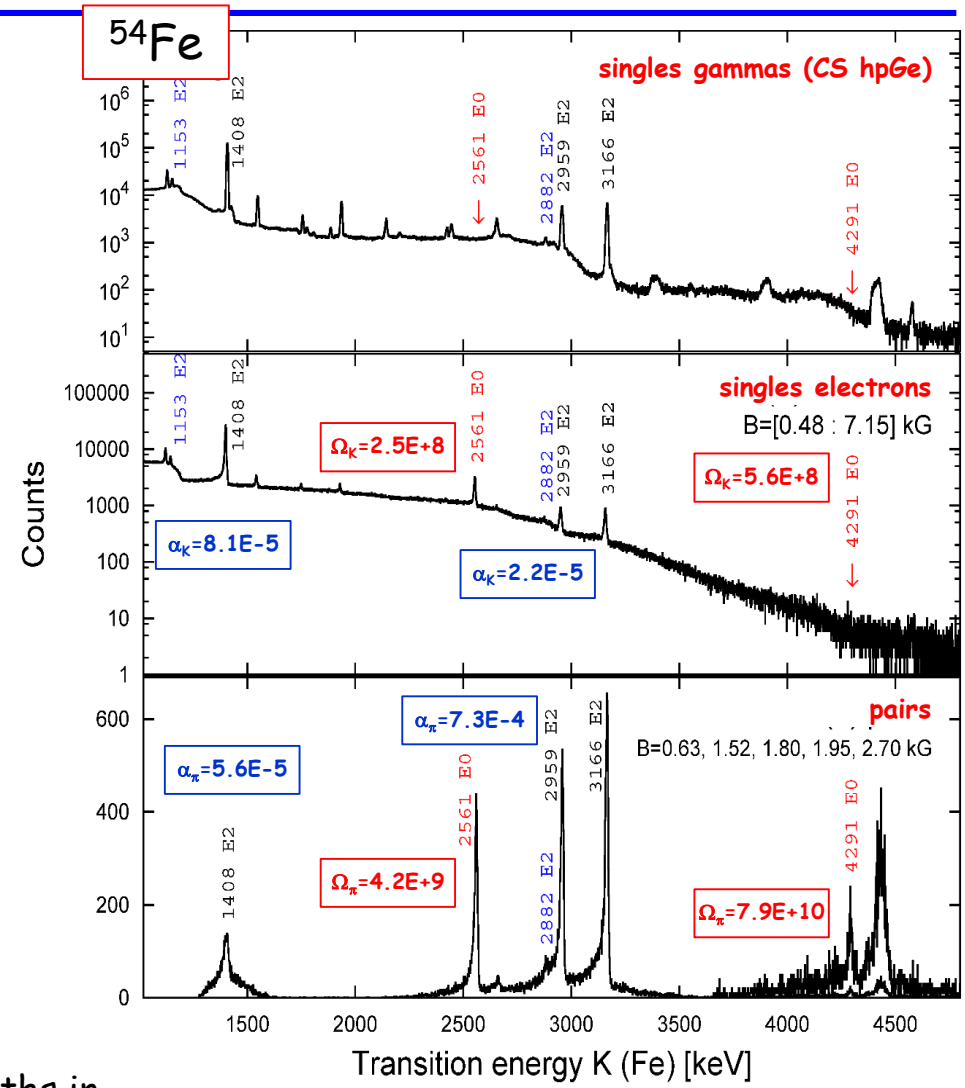
^{54}Fe(p,p'γ) @ 6.9 MeV

Tomas Eriksen PhD



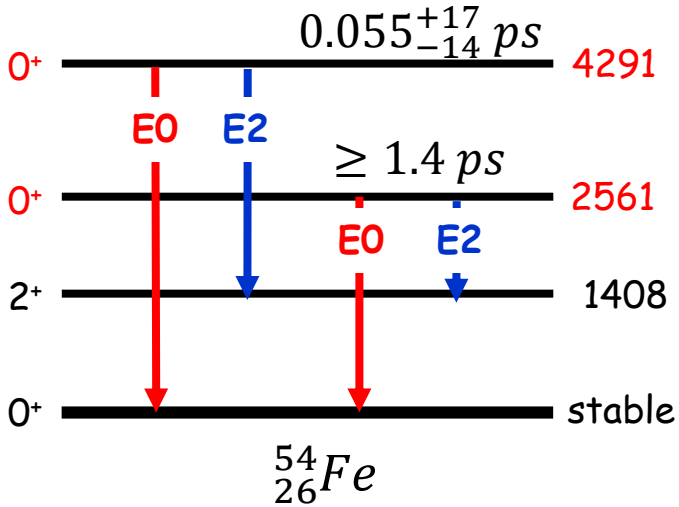


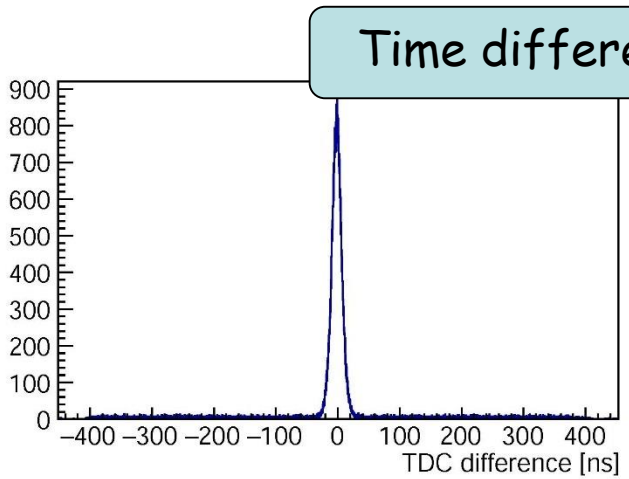
Lee Evits, Electric monopole transition strengths in stable Nickel Isotopes (talk on Wednesday)

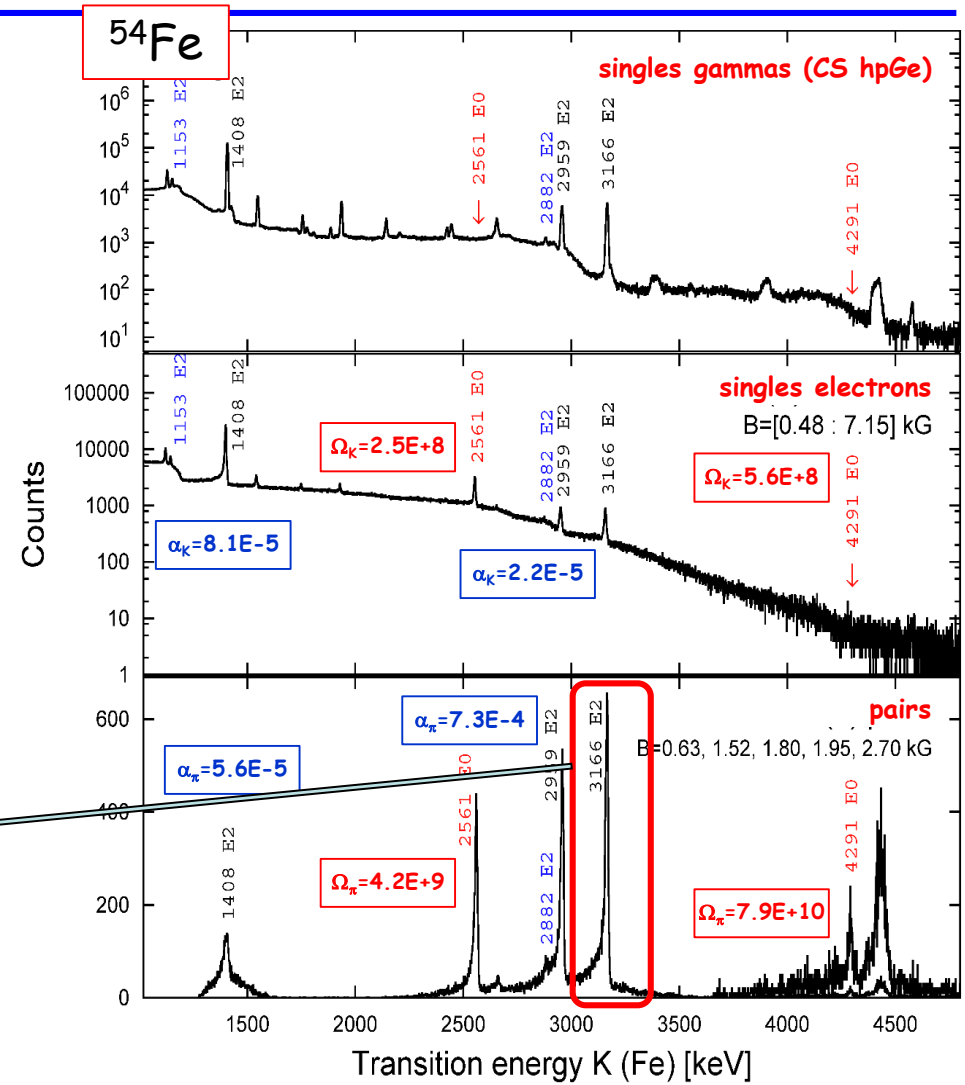
$$W_{K,\pi}(ML) = W_\gamma(ML) \times \alpha_{K,\pi}(ML)$$
$$W_{K,\pi}(E0) = \rho^2(E0) \quad \times \Omega_{K,\pi}(E0)$$

$^{54}Fe(p,p'\gamma)$ @ 6.9 MeV

Tomas Eriksen PhD







$$W_{K,\pi}(ML) = W_\gamma(ML) \times \alpha_{K,\pi}(ML)$$
$$W_{K,\pi}(E0) = \rho^2(E0) \quad \times \Omega_{K,\pi}(E0)$$

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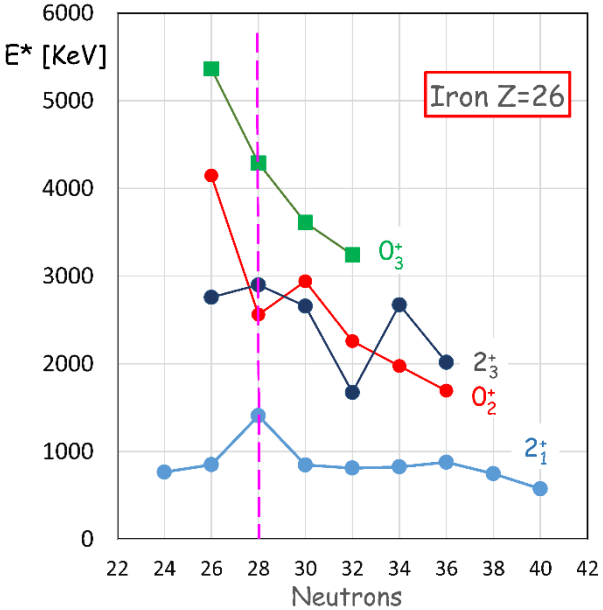
E0 transitions around N=Z=28 nuclei

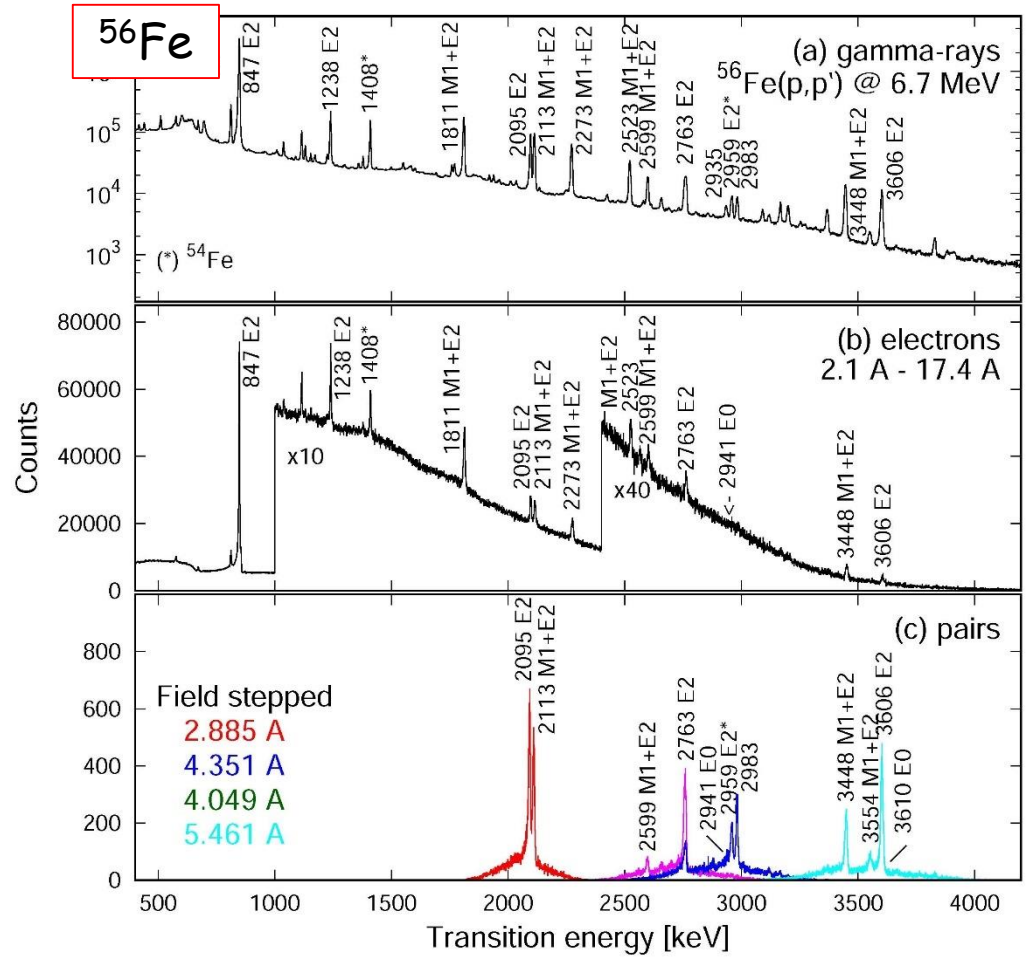
^{54,56,58}Fe

Energy systematics



E0 strengths (preliminary)

	$10^3\ \rho^3(E0)$	
	54Fe	56Fe
0_2 - 0_1	≤250	3.2(11)
0_3 - 0_1	23(8)	500(200)



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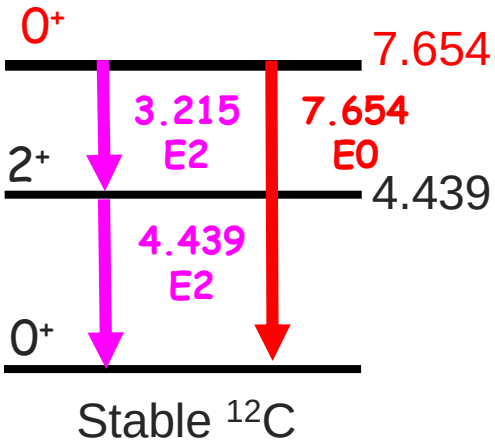
$^{12}C(p,p`\gamma)^{12}C^*$ pair measurements

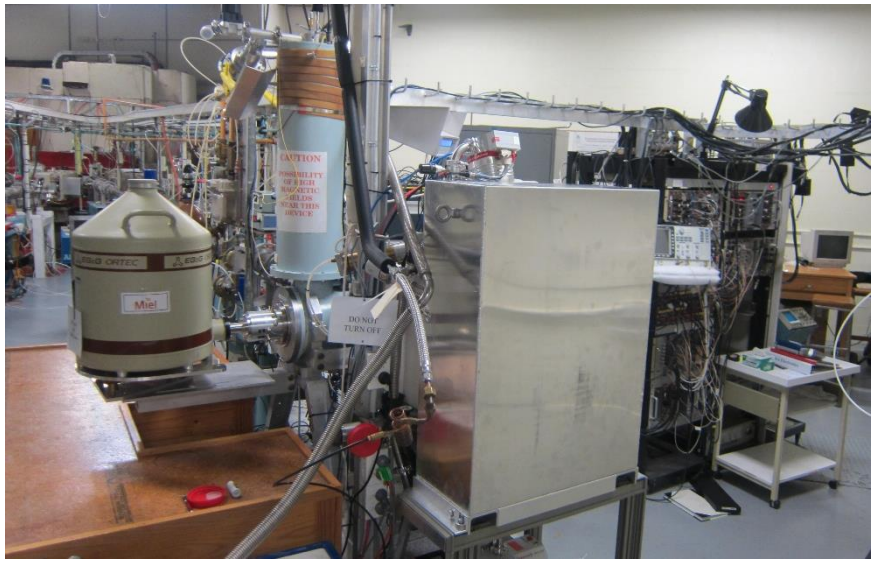
(2015-2016)



- $^{12}C(p,p')$ @ 10.5 MeV, 2 mg/cm^2 target, 500 nA
- 4-6 days experiments
- Magnetic field set for $E^+ \sim E^-$
- Counting at each field according to expected yields: 1000(3.21E2); 25(4.44E2); 50(6.05E0, 16O); 250(7.65E0)
- hpGe detector to monitor bombardment
- Singles measurement, but sum coincidence helps

Estimated rates

	gamma	pairs
4.439 E2	= 1	1.32E-3
3.215 E2	1.1E-4	9.2E-8
7.654 E0	--	1.6E-6



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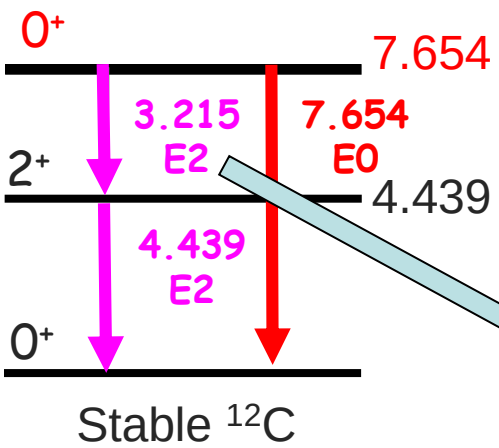
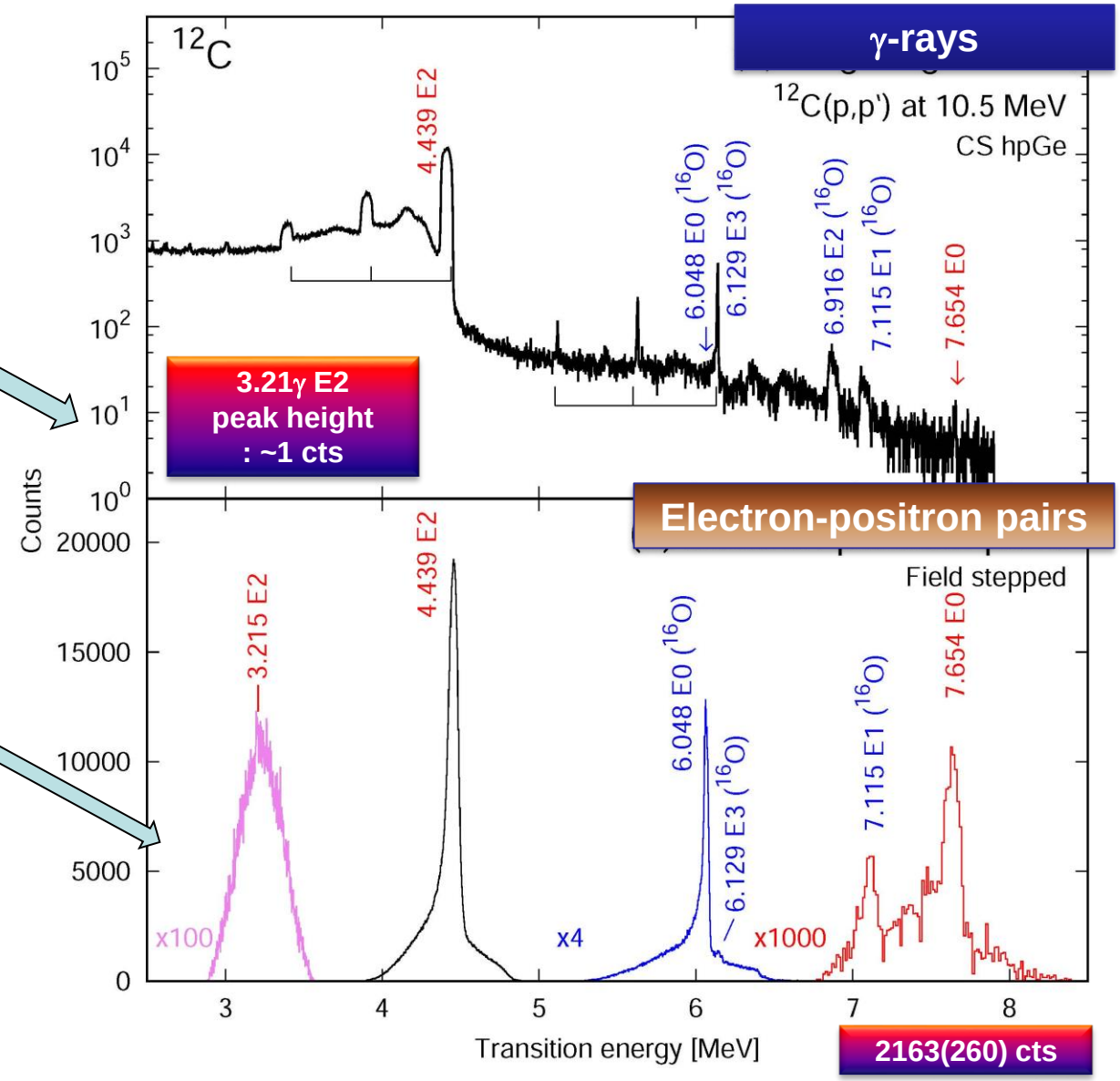
$^{12}C(p,p`\gamma)^{12}C^*$ pair measurements

(2015-2016)





Estimated rates

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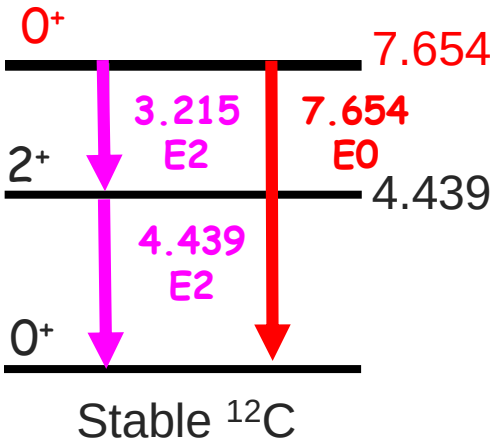
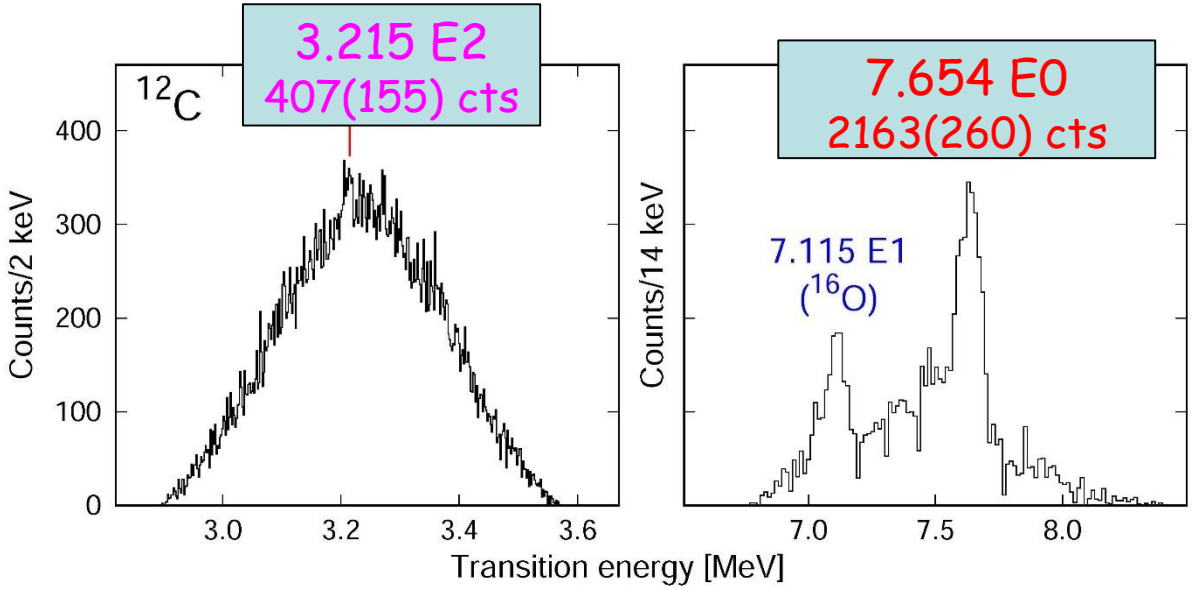
$^{12}C(p,p`\gamma)^{12}C^*$ pair measurements

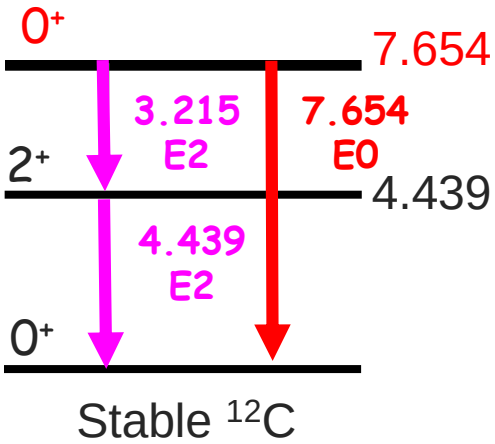
(2015-2016)

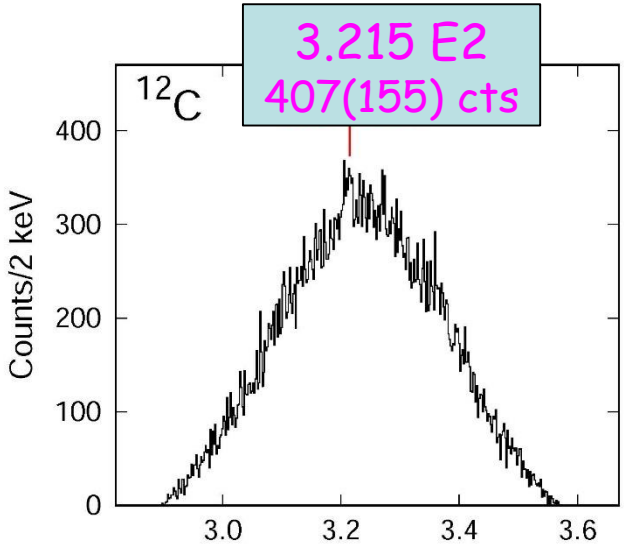


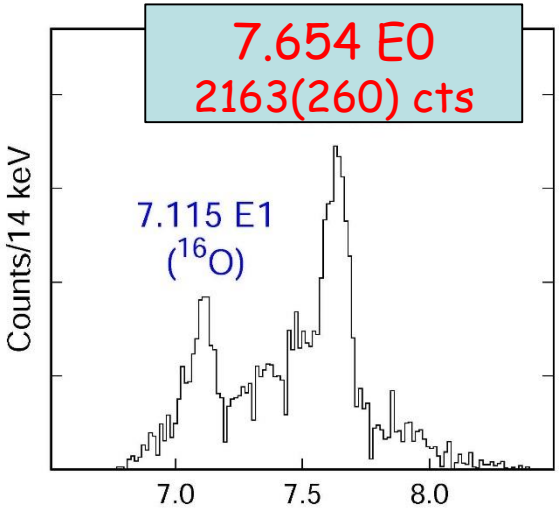


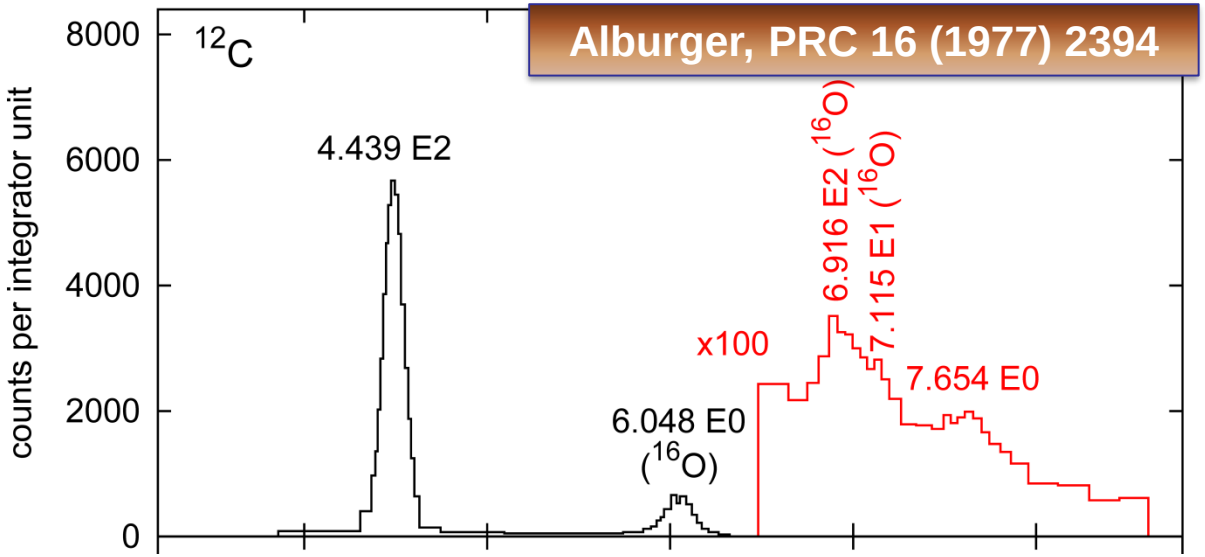
$^{12}C(p,p`\gamma)^{12}C^*$ pair measurements

(2015-2016)

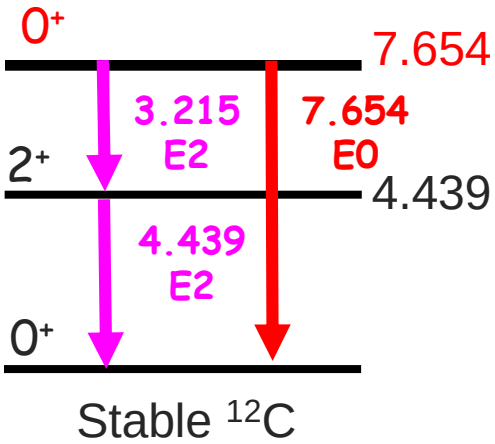


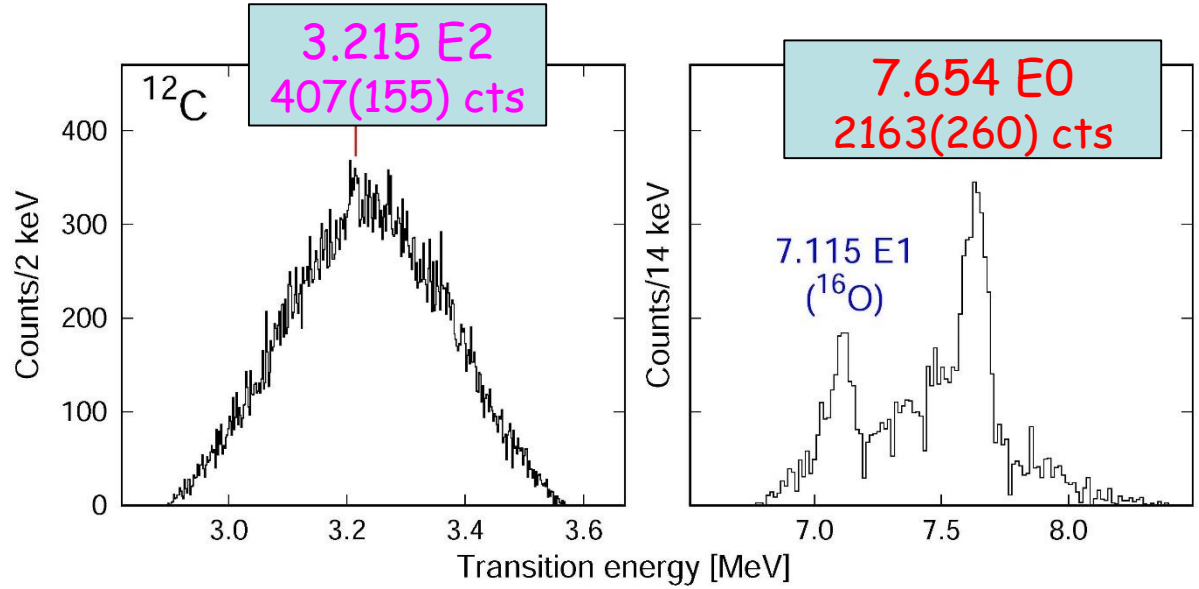






The radiative width of the Hoyle state from pair measurements





$$\Gamma_{rad} = \left(\left[\frac{\Gamma_\pi(E2)}{\Gamma_\pi(E0)} \right] \times \left(1 + \frac{1}{[\alpha_\pi(E2)]} \right) + 1 \right) \times [\Gamma_\pi(E0)]$$

$\Gamma_\pi(E2)/\Gamma_\pi(E0)$: 0.030(12)

E0 to E2 ratio: 33(13)

expected: ~18

preliminary

$\alpha_\pi(E2)$: 8.765E-4 (BrIcc)

$\Gamma_\pi(E0)$: 6.2(2)E-5 eV (adopted)

Γ_{rad} : 0.0022(9) eV

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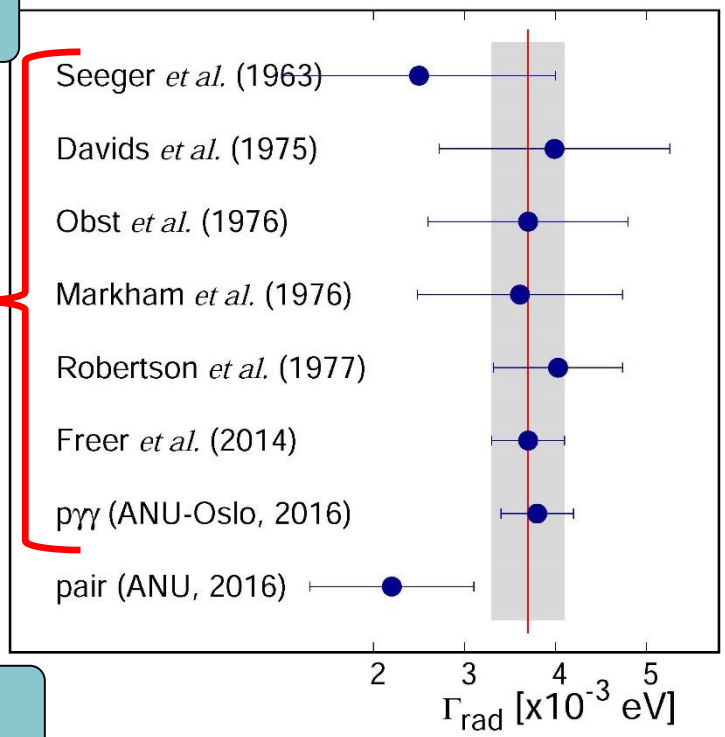
Summary and Outlook

$$\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}(E0)}\right] \times \left[\Gamma_{\pi}(E0)\right]$$

Traditional



Direct

$$\Gamma_{rad} = \left(\left[\frac{\Gamma_{\pi}(E2)}{\Gamma_{\pi}(E0)}\right] \times \left(1 + \frac{1}{[\alpha_{\pi}(E2)]}\right) + 1\right) \times \left[\Gamma_{\pi}(E0)\right]$$

Preliminary results

- 529(23) pgg triple coinc.
- From pgg measurements:
  - G_{rad}/G: 4.07(22) E-4
  - G_{rad} : 0.0038(4) eV
- 2163(26) 7.654 MeV E0 pairs
- 407(155) 3.215 MeV E2 pairs
- From pair measurements:
  - $G_p(E2)/G_p(E2)$: 33(13)
  - G_{rad} : 0.0022(9) eV
- Recommended
  (Freer and Fynbo, Prog. in Part. and Nucl. Phys. 78 (2014) 1)
  G_{rad} : 0.0037(4) eV
- "Traditional" vs. "Direct" method
- $\Gamma/\Gamma_{\pi}(E0)$ 8.9% uncertainty

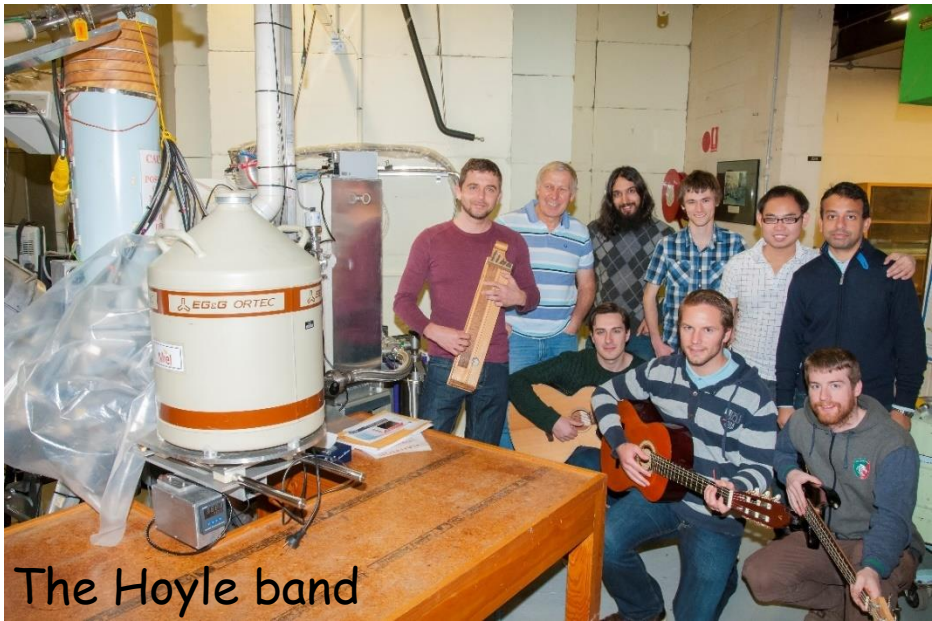
Collaborators (ANU)
- A.E. Stuchbery
- M.W. Reed
- S.S. Hota
- G.J. Lane
- A.J. Mitchell
- T.G. Tornyi

Collaborators (TRIUMF)
- A. Garnsworthy
- L.J. Evitts
- M. Moukaddam
- J. Smallcombe

ANU technical staff
- A. Cooper
- C. Gudu
- J. Heighway
- A. Muirhead
- D. Tsifakis
- T. Tunningley

Collaborators (Oslo)
- M. Guttormsen
- A. Görgen
- S. Siem
- A.C. Larsen
- F. Giacoppo
- A. Morales Lopez
- E. Sahin
- G.M. Tveten
- F.L. Bello Garrote
- L.C. Campo
- M. Klintefjord
- S. Maharramova
- H-T. Nyhus
- T. Renstrm

Students
- T.K. Eriksen
- B. Alshahrani
- A. Akber
- J. Dowie
- M. Gerathy
- B.Q. Lee
- M. de Vries
- T. Palazzo



The Hoyle band

ANU Major Equipment Grans 2011
ARC Discovery (2014-2016)
DP140102986