Direct determination of the radiative width of the Hoyle state from pair conversion

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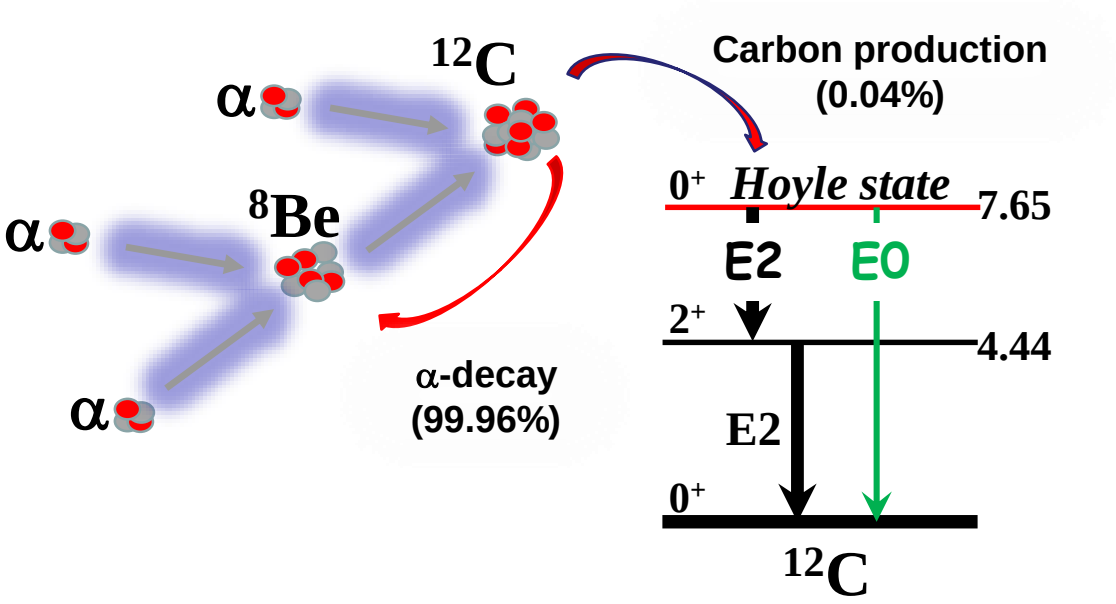
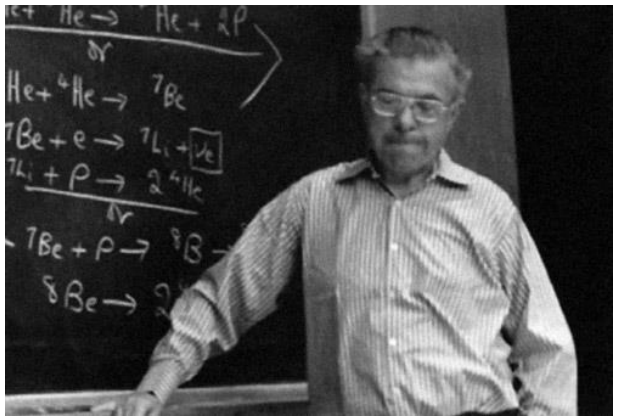
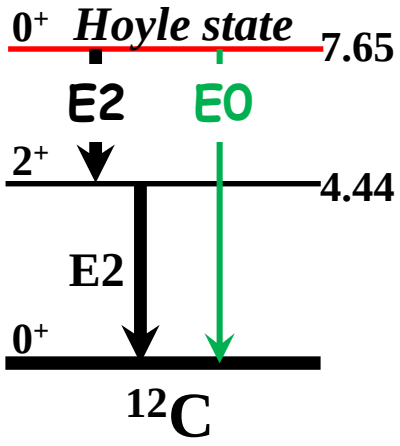
The triple-α process in stellar He burning

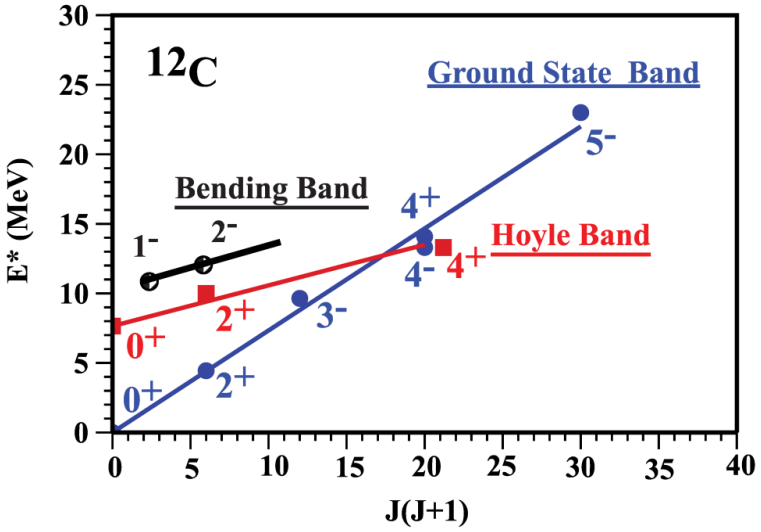




Sir Fred Hoyle (1915-2001)

The structure of the Hoyle state

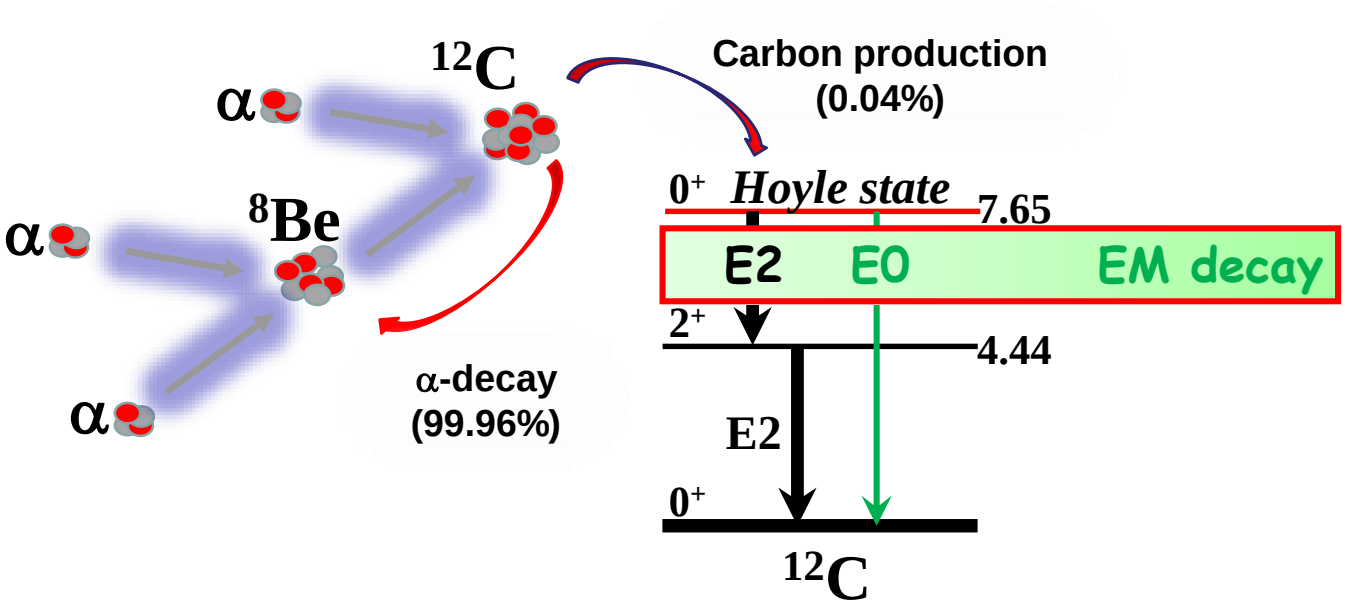




D.J. Marín-Lámbarri, et al., PRL **113** (2014) 012502

- $\Gamma(0_2)$=9.3(9) eV; $T_{1/2}(0_2)$=3.5(3) ×10^{-17} s
- "Extended object" (Brink 1966)
  RMS=2.89(4) fm = 1.2* RMS(g.s.)
  PRC ***80*** *(2009) 054603*
- ρ^2(E0)=500(81) ADNDT **89** (2005) 77
- 2^+ at 9.8 MeV
  Nucl. Phys. ***A738***, (2004) 268; Phys. Rev. ***C*** **84** (2011) 054308; **80** (2009) 041303(R); **84** (2011) 027304; **86** (2012) 034320; *PRL* ***113*** *(2014) 012502*
- 4^+ at 13.3 MeV
  Phys. Rev. ***C*****83** (2011) 034314
- 0_3^+ at 10.3 MeV; $\Gamma(0_3)$=2.7 MeV
  Nucl. Phys. ***A738***, (2004) 268
- Microscopic α-cluster model /exp
  $E(0_2)-E_{3\alpha}$=0.23 / 0.38 MeV
  $\Gamma(0_2)$=7.6 / 9.3(9) μeV
  M(E0)= 6.3 / 5.4(2) fm^2
  Yasuro Funaki, Phys. Rev. ***C*** **94 (2016) 024344**

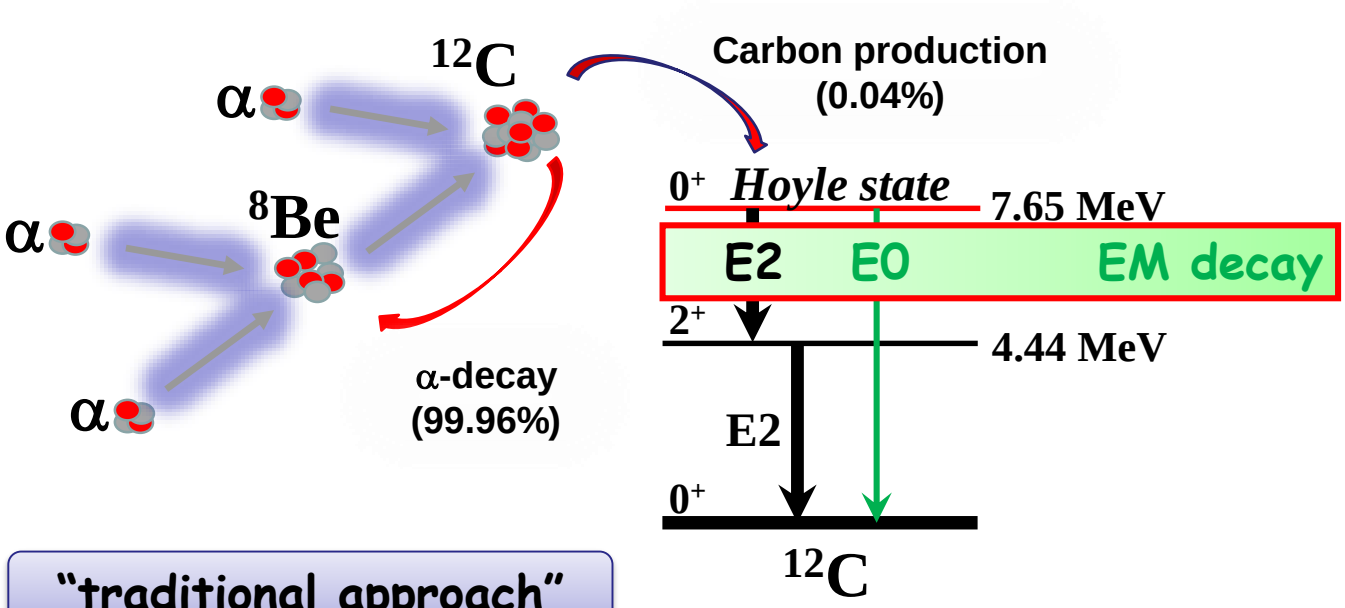
The triple-α rate in stellar He burning



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

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

Determining the triple-α rate



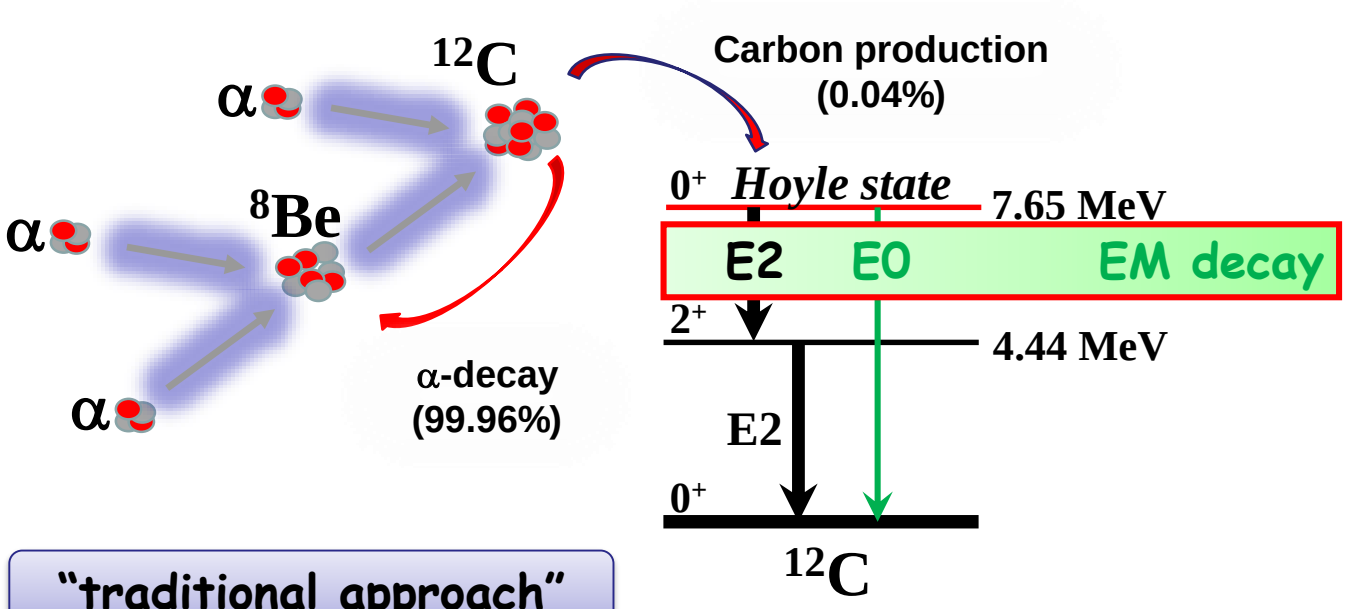
"traditional approach"

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

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

Γ_{rad} could not be measured directly!

Determining the triple-α rate



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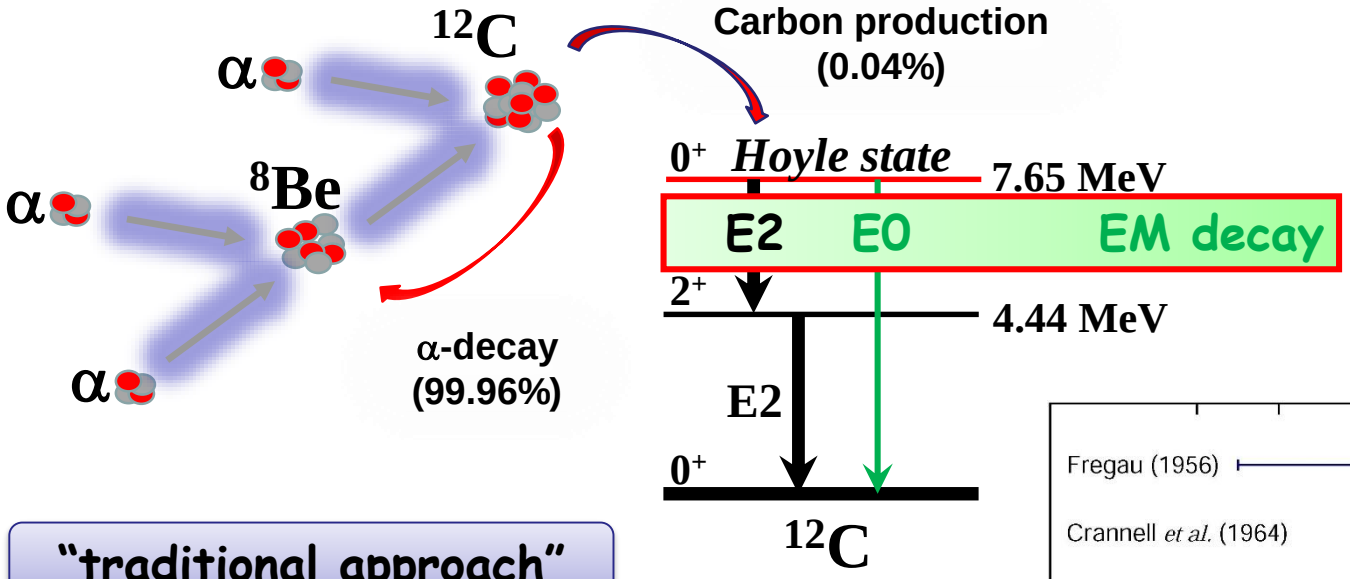
$$\Gamma_{rad} = \left[\frac{\Gamma_{rad}}{\Gamma}\right] \times \left[\frac{\Gamma}{\Gamma_{\pi}(E0)}\right] \times [\Gamma_{\pi}(E0)]$$

		Unc. [%]	# exp
Γ_{rad}/Γ ($\times 10^{-4}$)	4.19(11)	2.7	8
$\Gamma_{\pi}(E0)/\Gamma(\times 10^{-6})$	6.7(6)	8.9	4
$\Gamma_{\pi}(E0)$ (μeV)	62.3(20)	3.2	8

Γ_{rad}=3.9(4) ×10^{-3} eV
EM branching: 0.042%

Determining the triple-α rate



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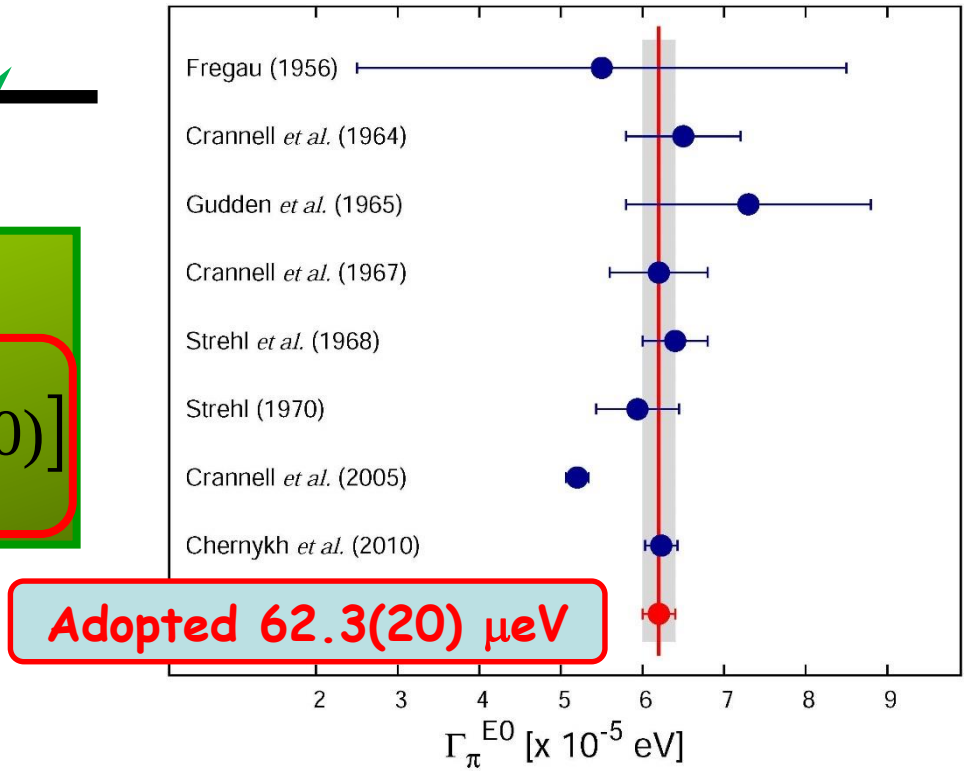
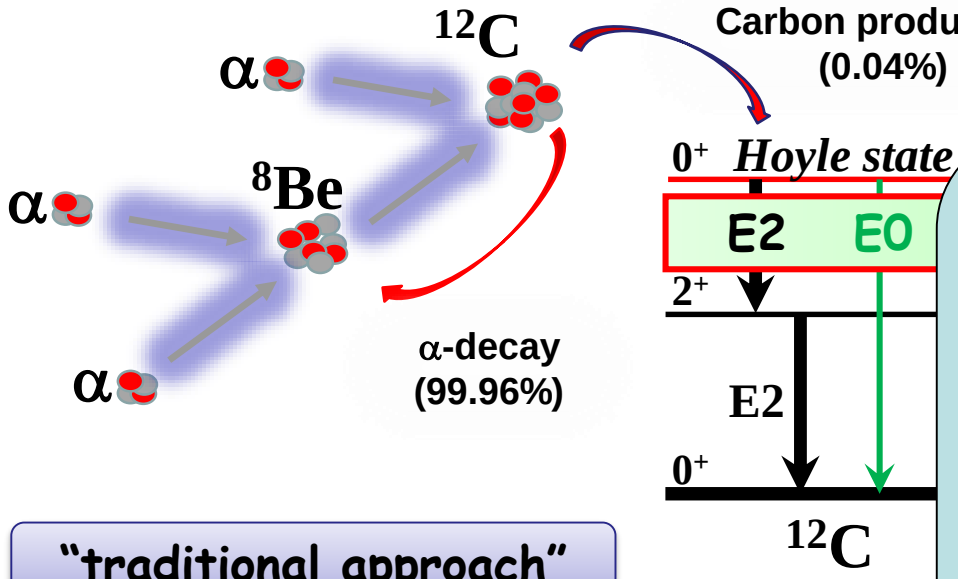


Adopted 62.3(20) μeV

Determining the triple-α rate



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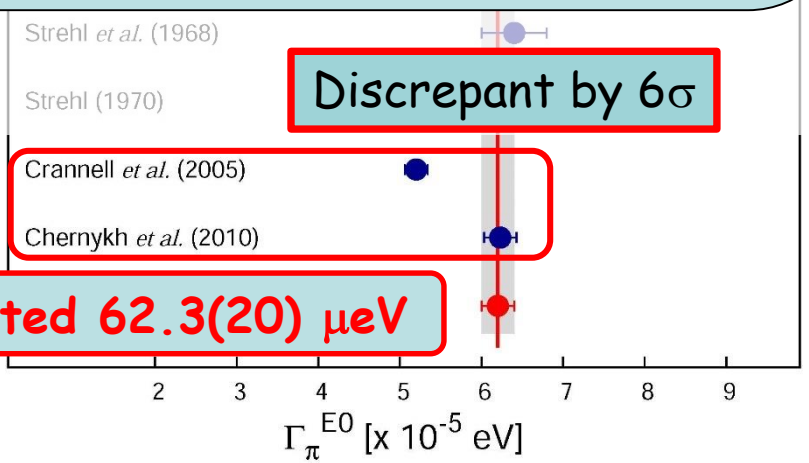
Crannel et al NP A785 (2005) 399c

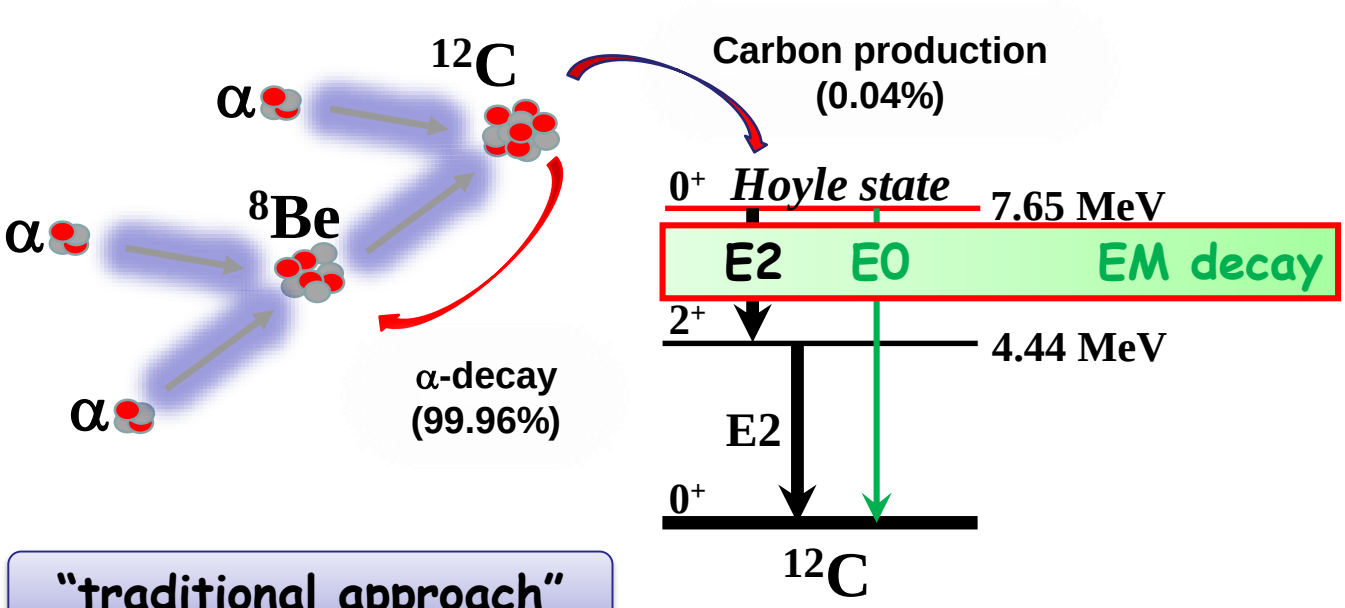
- 4 data sets from different labs (Darmstadt, Bates-CUA, NIKHEF-K, HEPL)

Chernykh et al. PRL 105 (2010) 022501

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



Determining the triple-α rate



"traditional approach"

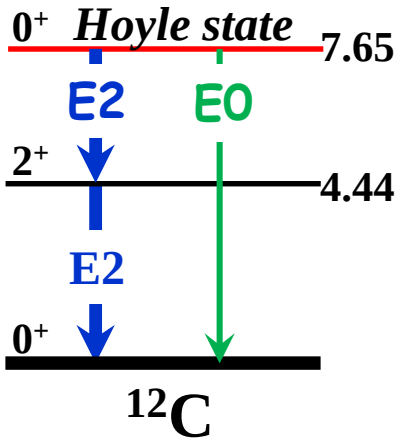
$$r_{3\alpha} \propto [\Gamma_{rad}]\exp(-[Q_{3\alpha}]/kT)$$

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

$\Gamma_{rad}/\Gamma = 4.19(11) \times 10^{-4}$
(8 experiments)

Γ_{rad}/Γ from p-γ-γ coincidences

Badriah Alshahrani (PhD)



$^{12}C(p,p'\gamma\gamma)$ @ 10.7 MeV
Oslo cyclotron lab. CACTUS & SiRi
talks by A-C. Larsen & M. Guttormsen
12 days run, 6E+9 events
N_p = 2.56(5)E+8
$N_{p\gamma\gamma}$ = 529(23)

Γ_{rad}/Γ from p-γ-γ coincidences

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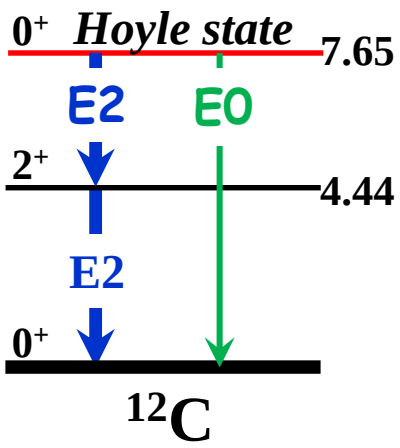

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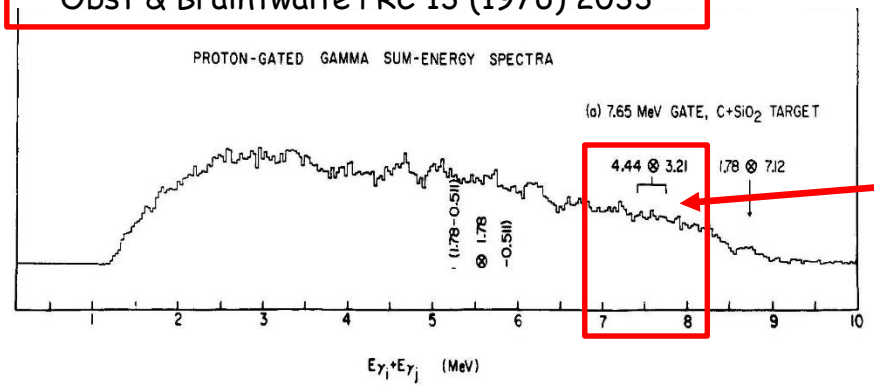
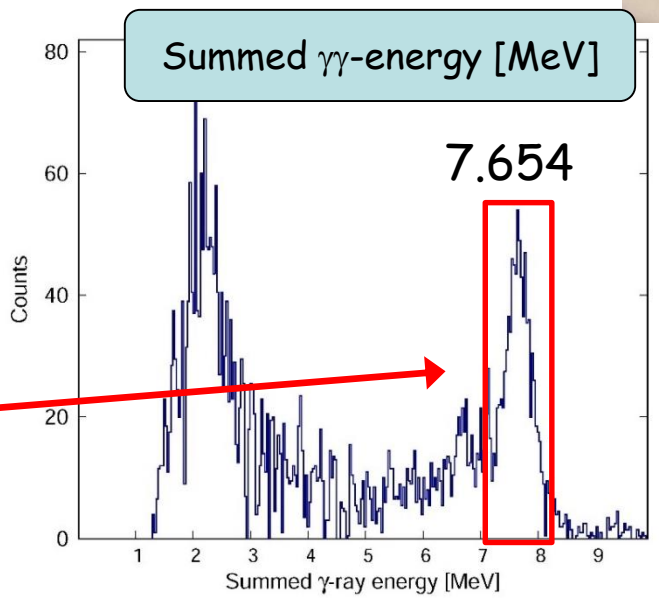
Obst & Braihtwaite PRC 13 (1976) 2033



Summed γγ-energy [MeV]



Γ_{rad}/Γ from p-γ-γ coincidences

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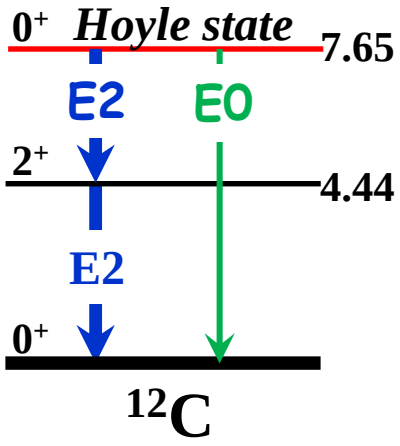
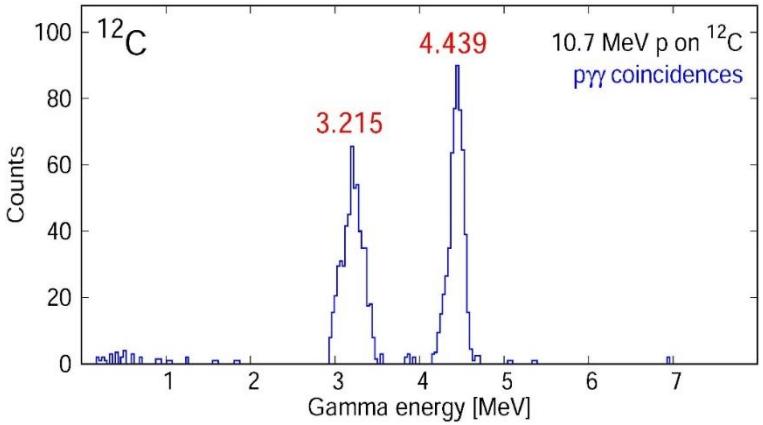
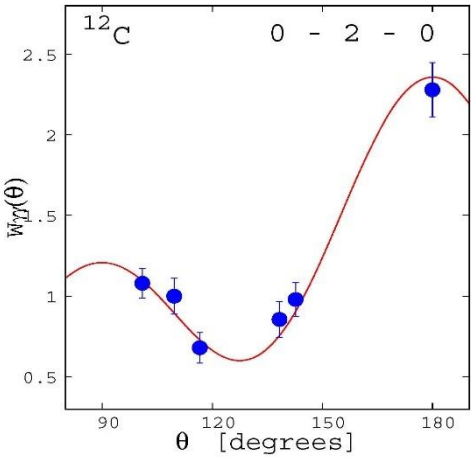


ANU-Oslo (2016)
$^{12}C(p,p')\,p\gamma\gamma$

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





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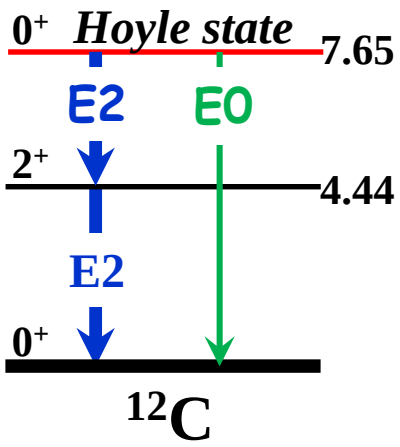
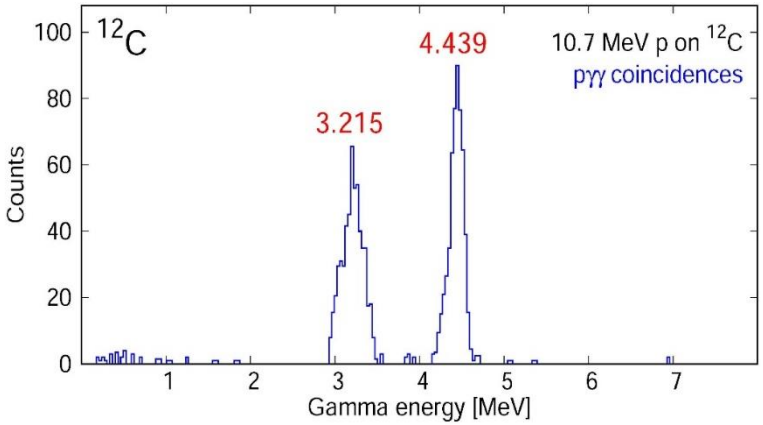
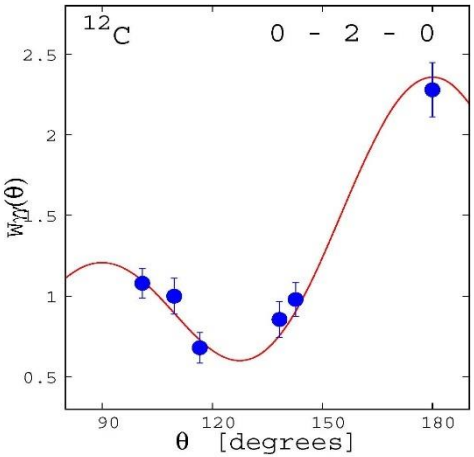


ANU-Oslo (2016)
^{12}C(p,p') pγγ

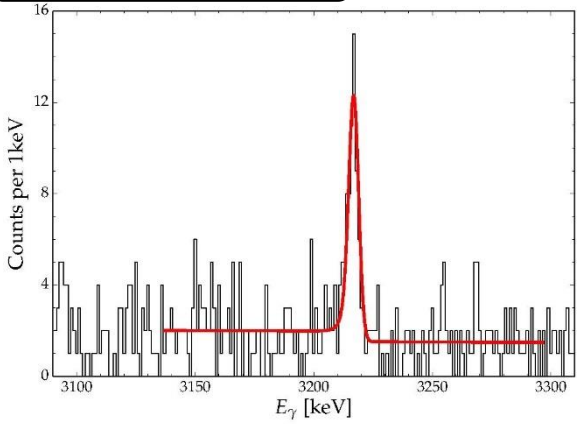
$N_{pγγ}$=529(23) cts

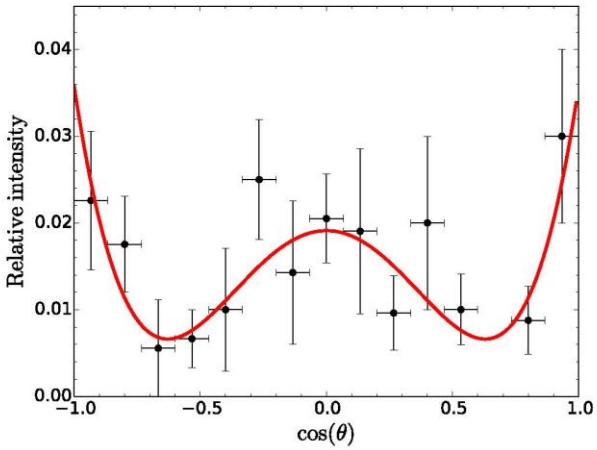




Munich et al., PRC **93** (2016) 065803
^{12}B β^- decay, γγ with GAMMASPHERE

$N_{γγ}$=58(9) cts





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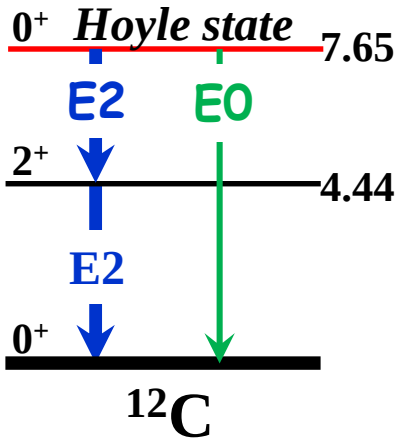

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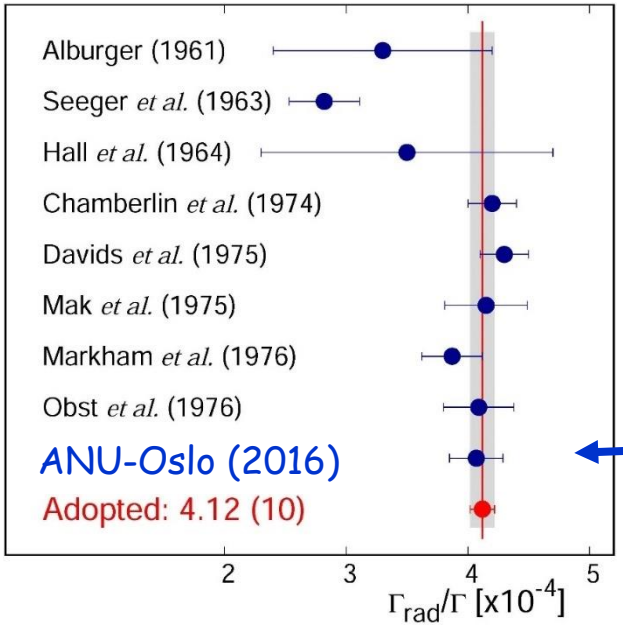


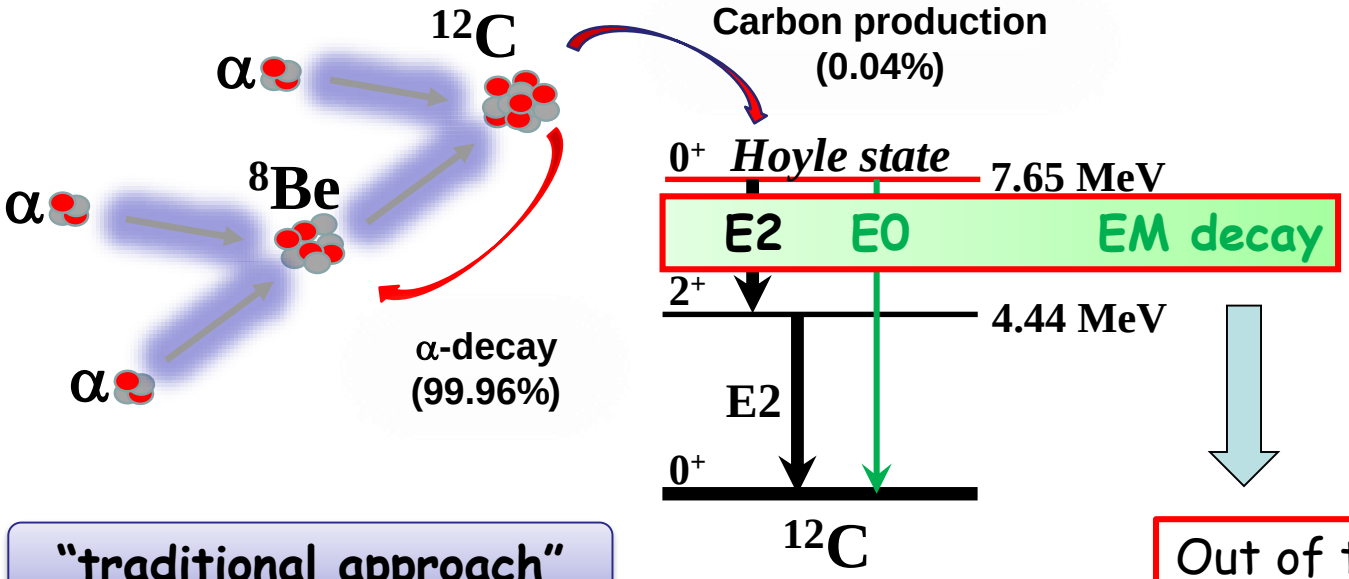
preliminary

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

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

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

New approach to determine the triple-α rate



"traditional approach"

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

From direct measurement of the E0 and E2 transitions

α_π(E2, BrIcc)=8.765E-4

Out of the ~0.04%

Γ_γ(E2) = 98.5%

Γ_π(E0) = 1.5%

Γ_π(E2) = 0.088%

Γ_{CE}(E2) ~2.5E-5%

Γ_{CE}(E0) ~1E-5%

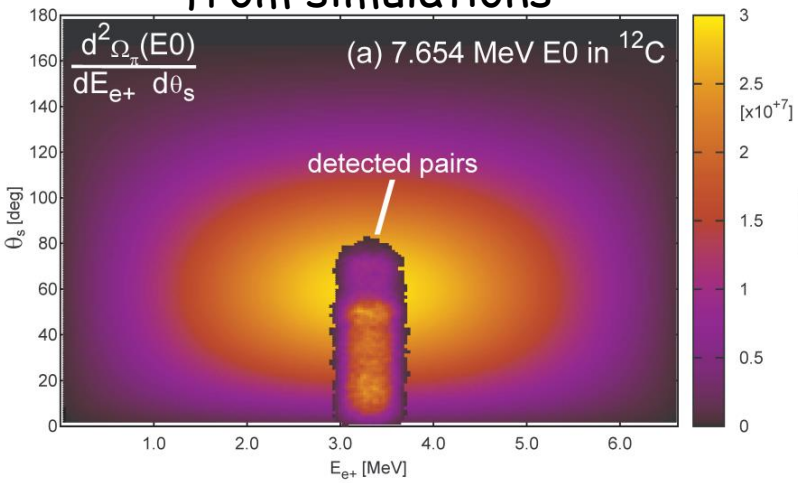
Internal pair conversion

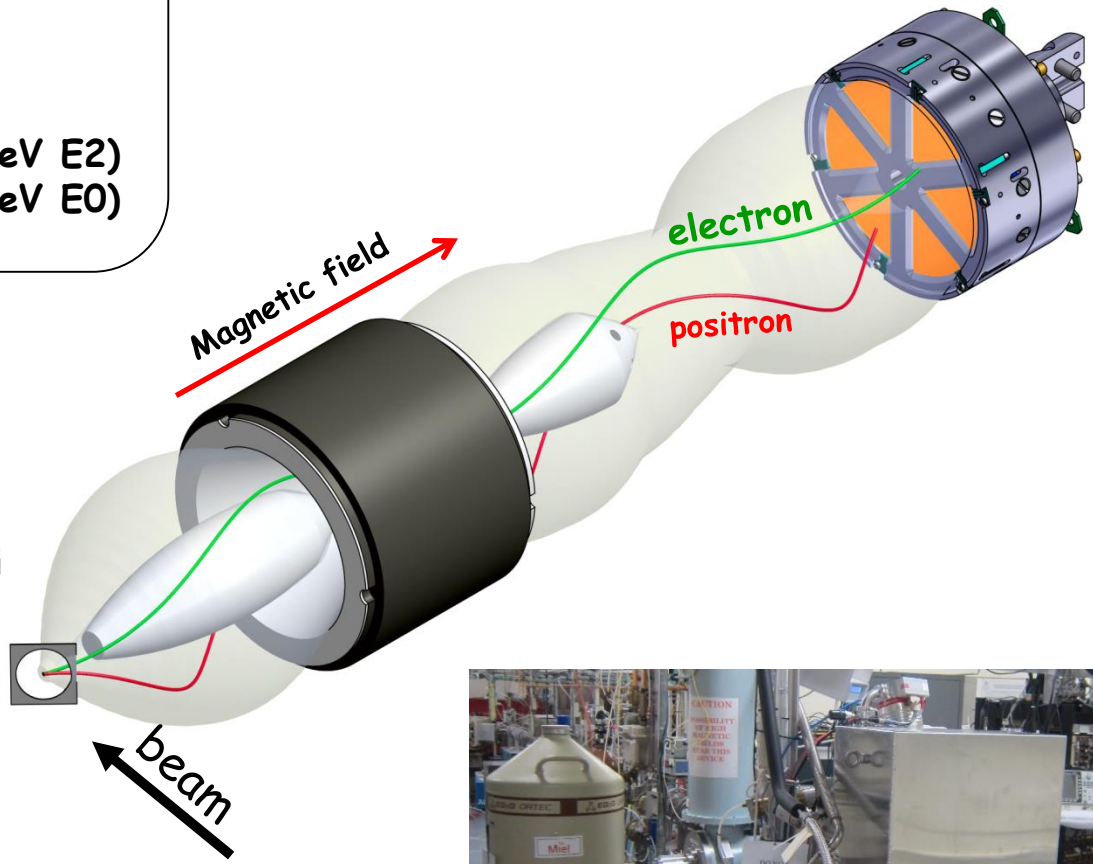
$^{12}C(p,p')^{12}C^*$ pair measurements

(Tomas K. Eriksen, PhD)

$^{12}C(p,p'\pi)$ @ 10.5 MeV; 500-900 nA
ANU HIAF & Super-e
talks by A.E. Stuchbery & T.K. Eriksen
Acceptance angles: 15.9°- 46.9 °
Efficiency – singles (swept): 0.5%
- singles (fixed): 3.0%
Efficiency – pairs: 0.0935% (3.21 MeV E2)
0.0618% (7.65 MeV E0)

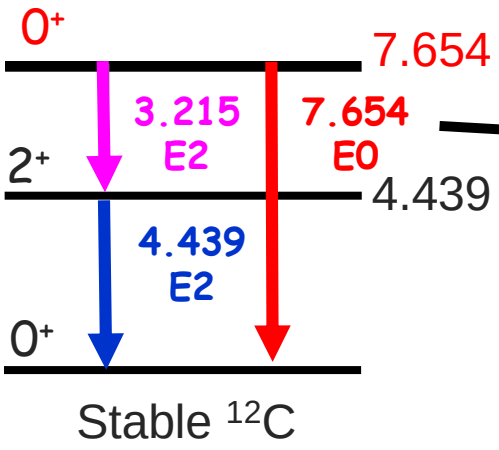
Spectrometer response from simulations



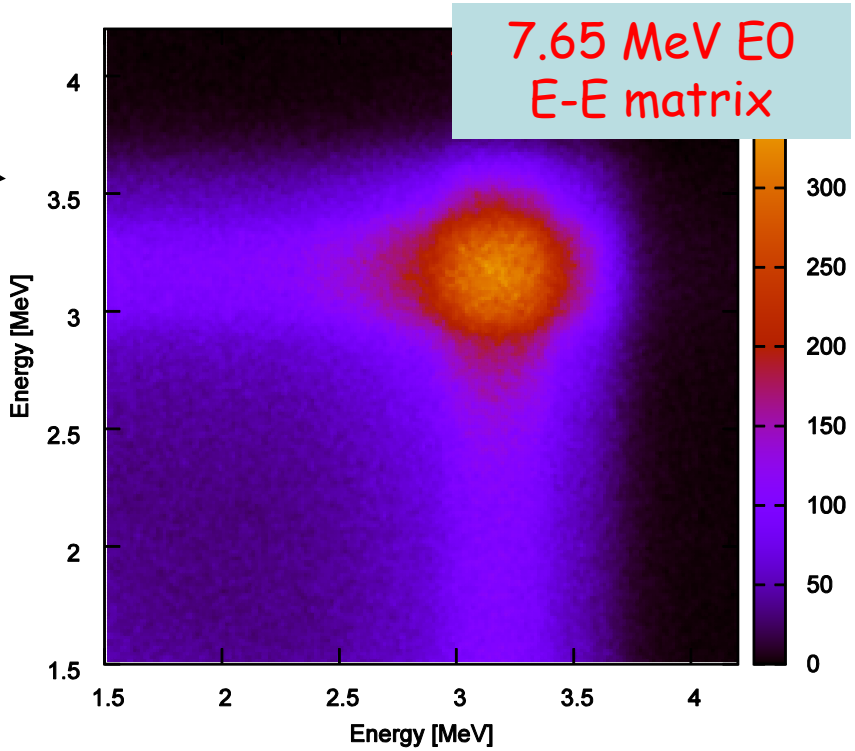


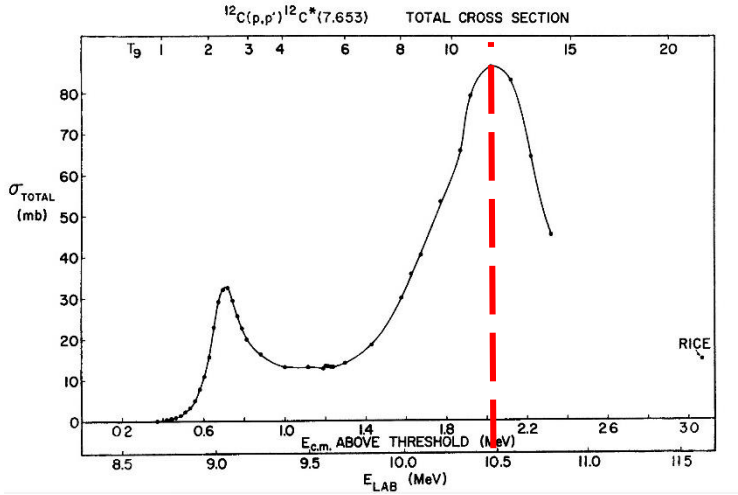
$^{12}C(p,p')^{12}C^*$ pair measurements

(Tomas K. Eriksen, PhD)

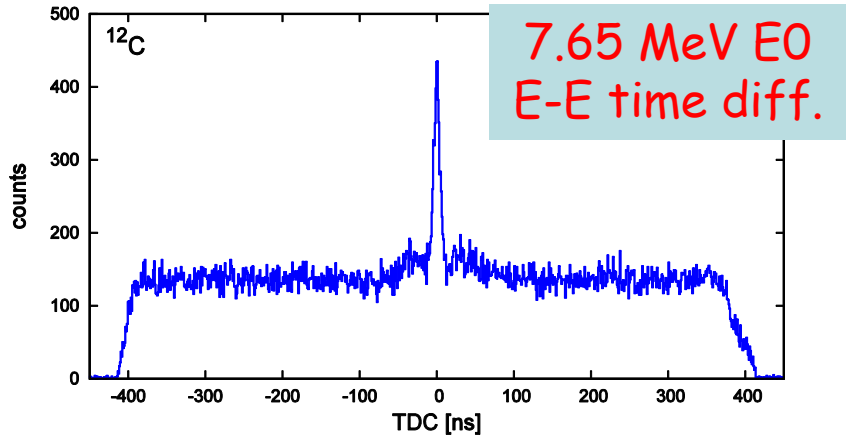


6.7E-6 decay branch





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



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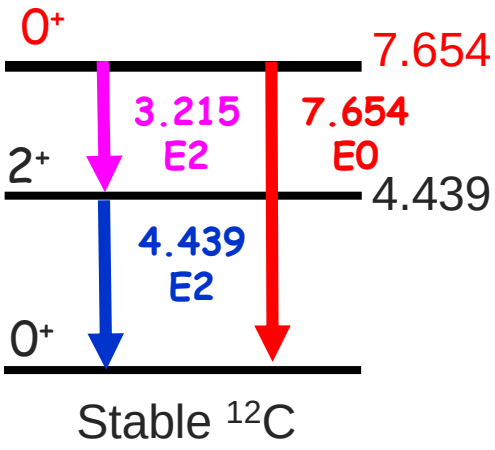

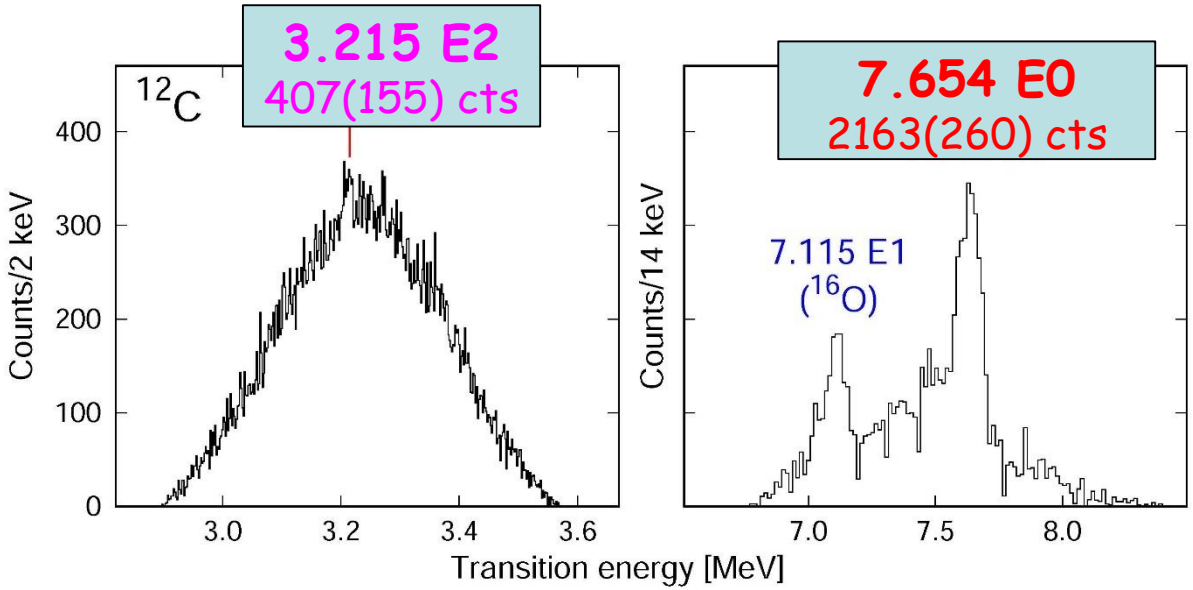

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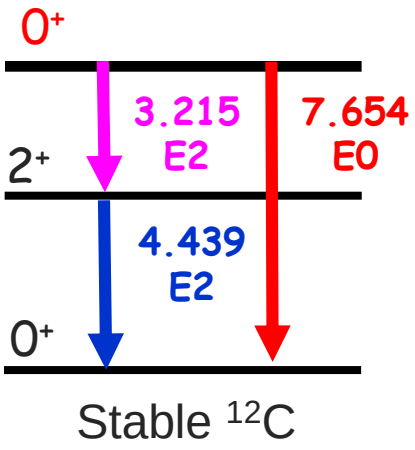
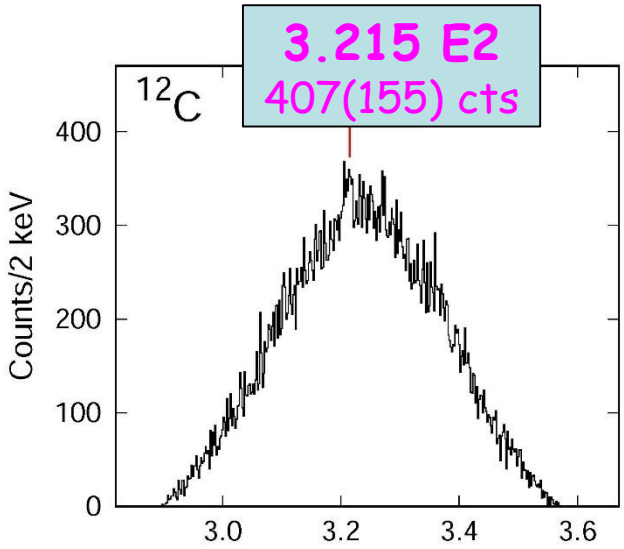
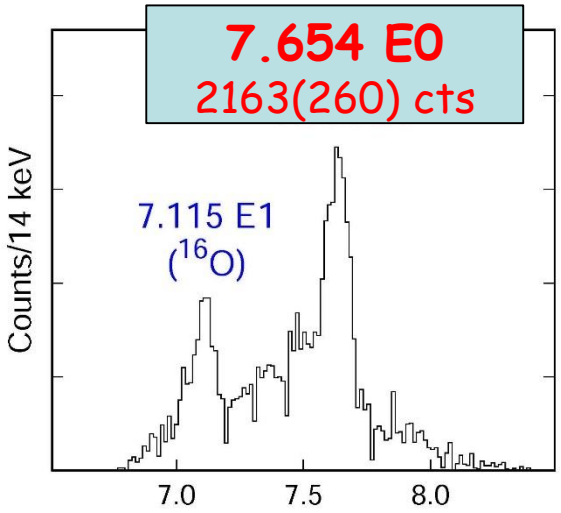
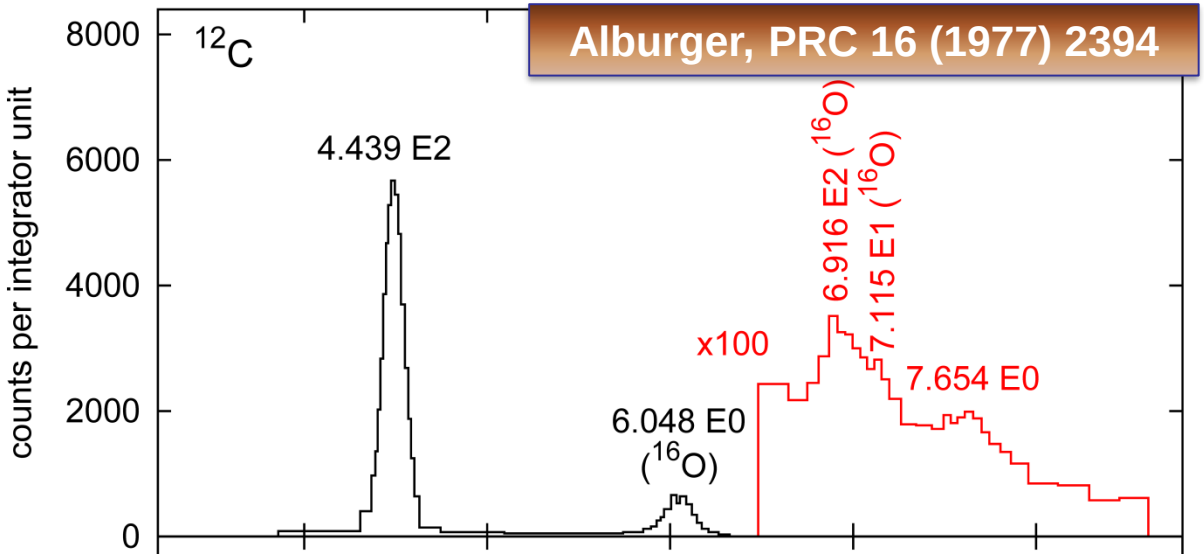
(Tomas K. Eriksen, PhD)

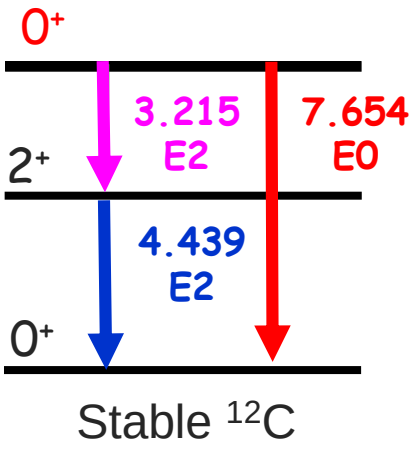


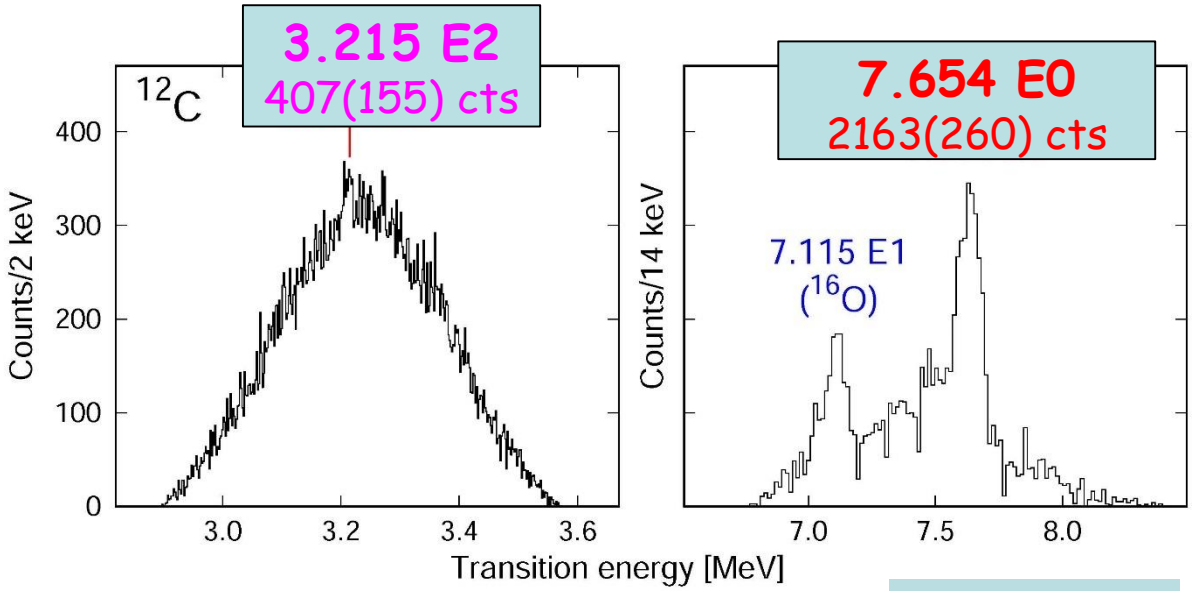






The radiative width of the Hoyle state from pair measurements





preliminary

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

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

E0 to E2 ratio: 33(13)
expected: ~18

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

$\Gamma_\pi(E0)$: 62.3(20) μeV (adopted)

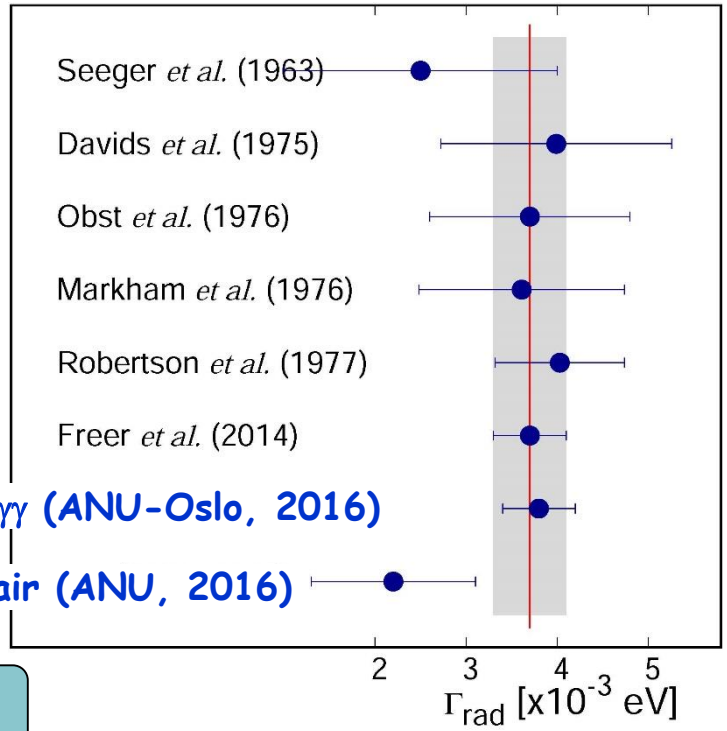
Γ_{rad} : 0.0022(9) eV

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

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

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

Preliminary results

From pγγ measurements:

- 529(23) pγγ triple coinc.
- Γ_{rad}/Γ: 4.07(22) E-4
- Γ_{rad}: 0.0038(4) eV

From pair measurements:

- 2163(26) 7.654 MeV E0 pairs
- 407(155) 3.215 MeV E2 pairs
- $\Gamma_\pi(E2)/\Gamma_\pi(E0)$: 0.030(12)
- Γ_{rad} : 0.0022(9) eV

- Recommended
  (Freer and Fynbo, Prog. in Part. and Nucl. Phys. 78 (2014) 1)
  Γ_{rad}: 0.0037(4) eV

Need more data (Nov-2016)

- ^{28}Si(p,p') @10.5 MeV
  4.98 MeV E0 & 3.20 MeV E2

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- S.S. Hota
- G.J. Lane
- A.J. Mitchell
- T.G. Tornyi

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- L.J. Evitts
- M. Moukaddam
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- C. Gudu
- J. Heighway
- A. Muirhead
- D. Tsifakis
- T. Tunningley

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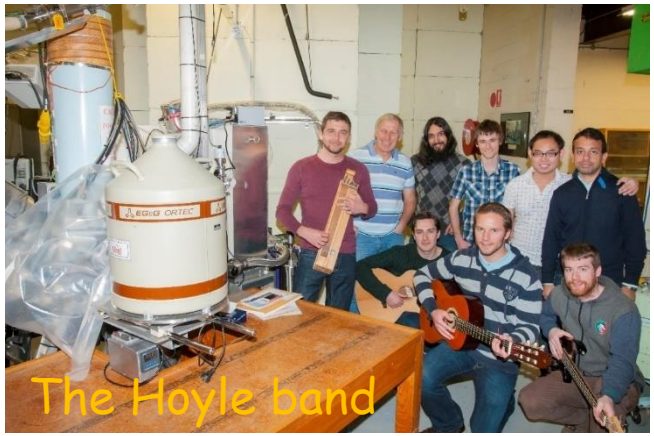
- B. Alshahrani
- A. Akber
- J. Dowie
- M. Gerathy
- B.Q. Lee
- M. de Vries
- T. Palazzo


The Hoyle band

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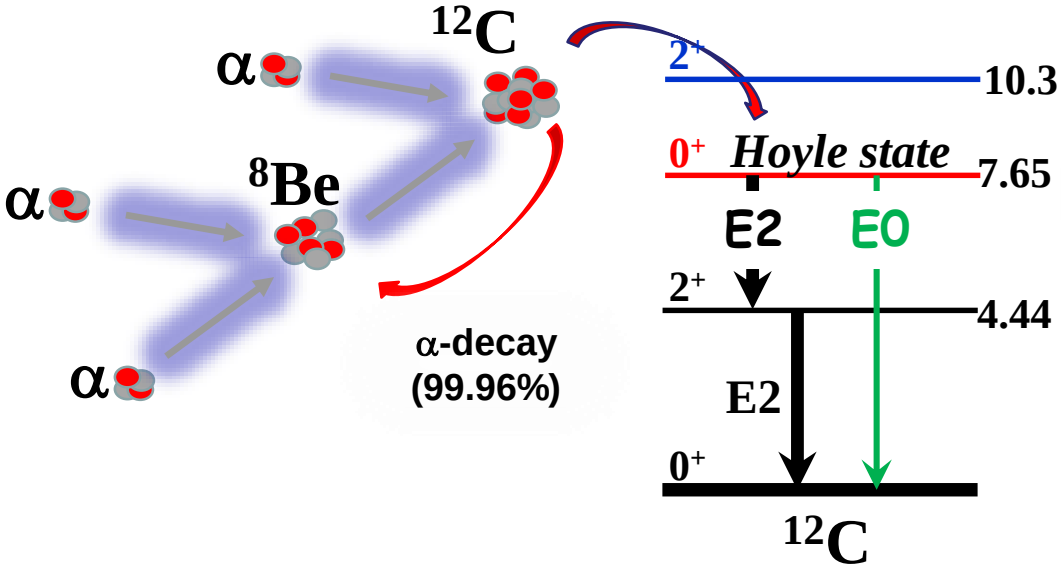
- A. Görgen
- A.C. Larsen
- S. Siem
- F. Giacoppo
- A. Morales Lopez
- E. Sahin
- G.M. Tveten
- F.L. Bello Garrote
- L.C. Campo
- M. Klintefjord
- S. Maharramova
- H-T. Nyhus
- T. Renstrøm


OCL, Jan-2014

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


NATURAM PRIMUM COGNOSCERE RERUM

The triple-α rate in stellar He burning

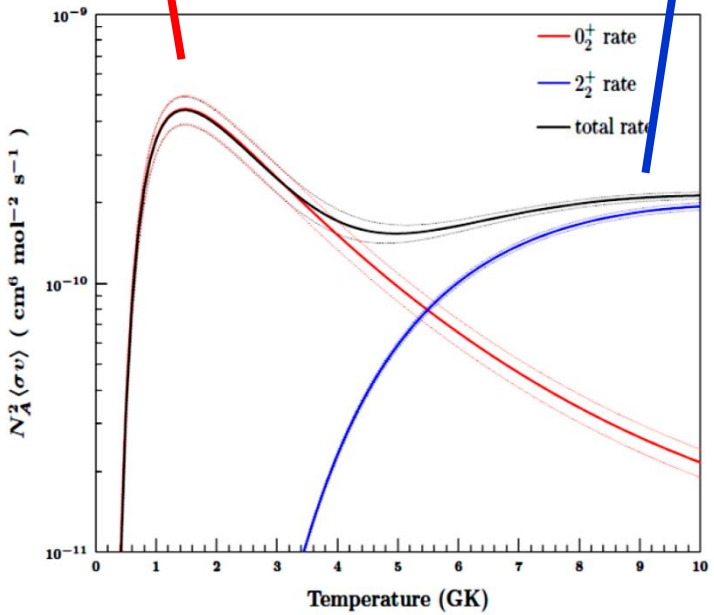


$^{8}Be+\alpha \Rightarrow {}^{12}C(2_2^+) \Rightarrow {}^{12}C(0_2^+) \Rightarrow {}^{12}C(g.s.)$

$^{8}Be+\alpha \Rightarrow {}^{12}C(0_2^+) \Rightarrow {}^{12}C(g.s.)$

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

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

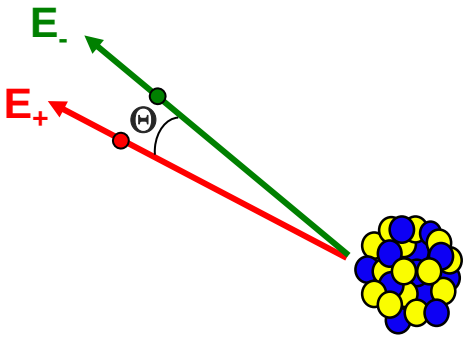


W.R. Zimmerman, PhD (2013) Univ. Connecticut

Measuring electron-positron pairs

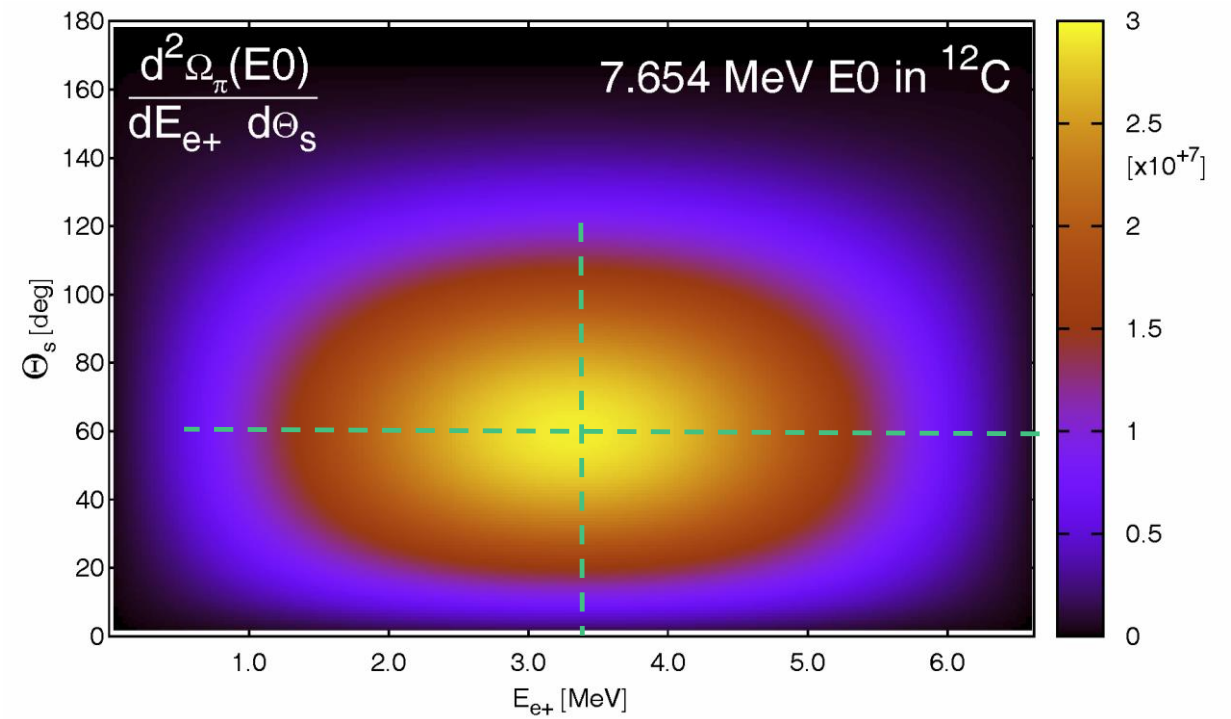
- e^- - e^+ particles share the available kinetic energy:

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



Need to observe both particles

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



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

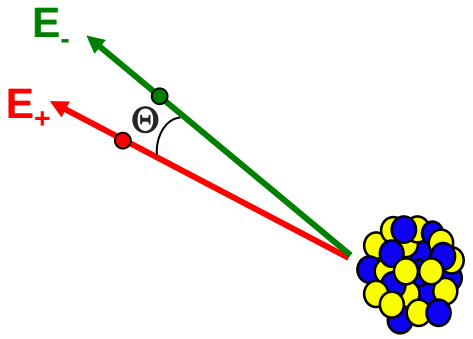
$$E_+ \approx E_-$$

$$\theta_{sep} \approx 60°$$

Measuring electron-positron pairs

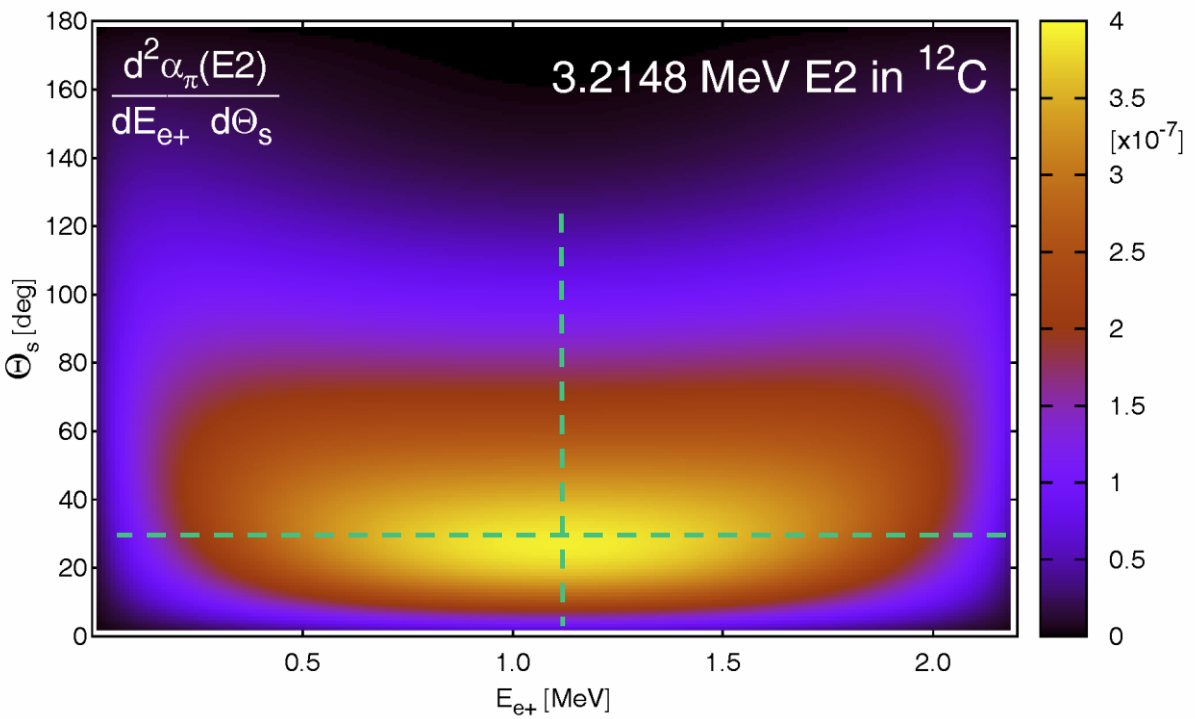
- e^- - e^+ particles share the available kinetic energy:

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



Need to observe both particles

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



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

$E_+ \approx E_-$

$\theta_{sep} \approx 30°$

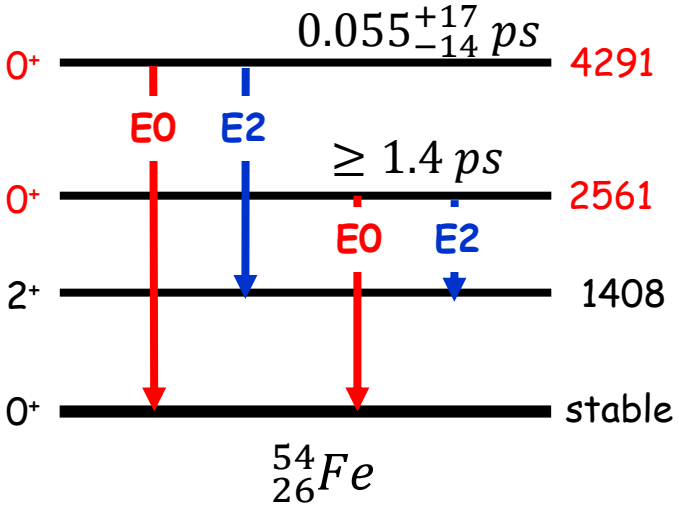
$W_\pi(E0) \sim \rho^2(E0) \times \Omega_\pi(E0)$

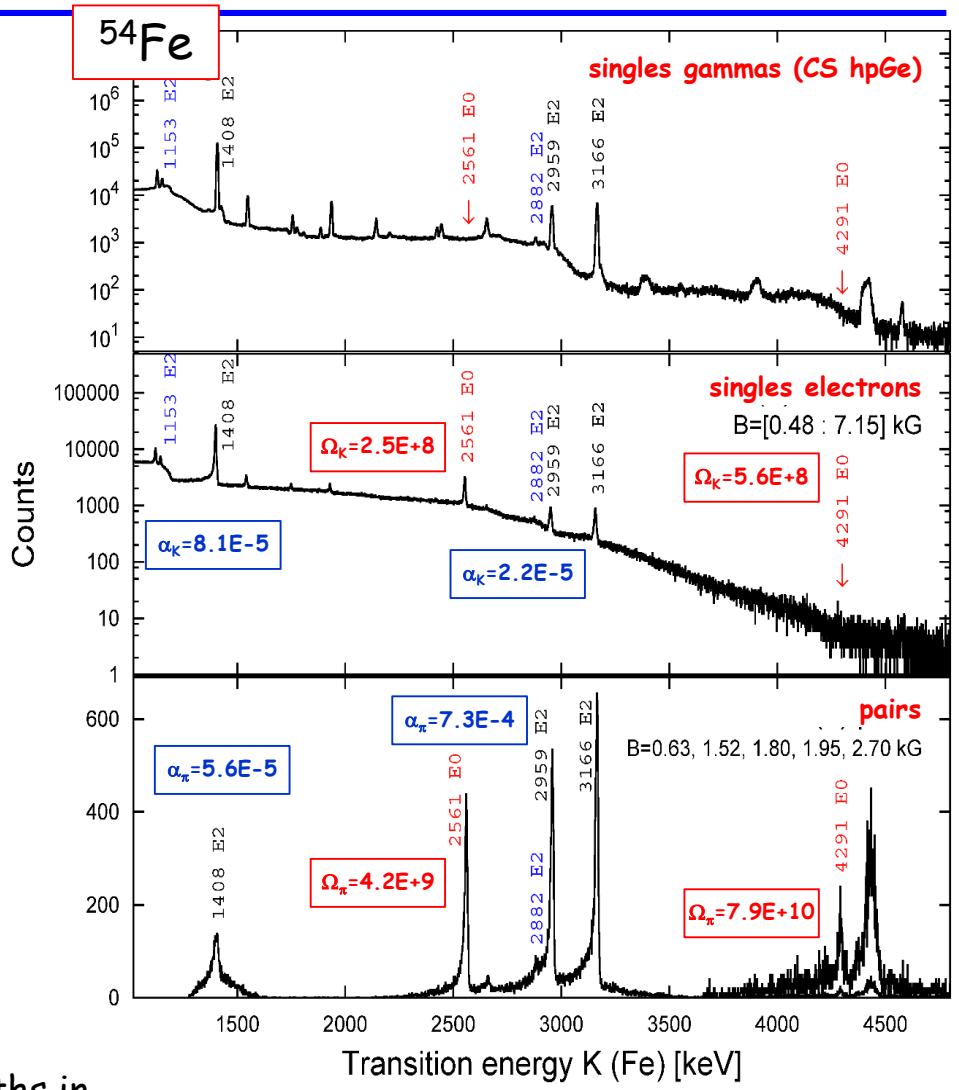
$W_\pi(E2) = \Gamma_\gamma(E2) \times \alpha_\pi(E2)$

ICC

^{54}Fe(p,p'γ) @ 6.9 MeV

Tomas Eriksen PhD





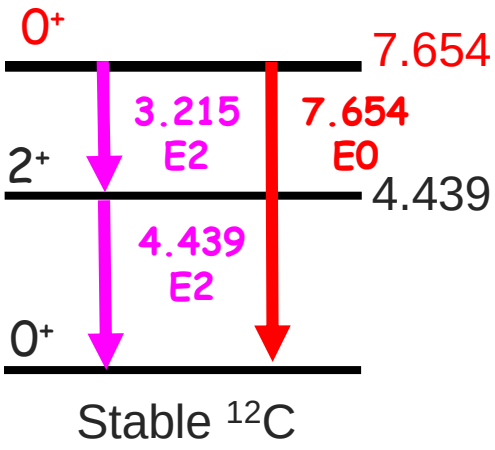
Lee Evits, Electric monopole transition strengths in stable Nickel Isotopes (talk on Wednesday)

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

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

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

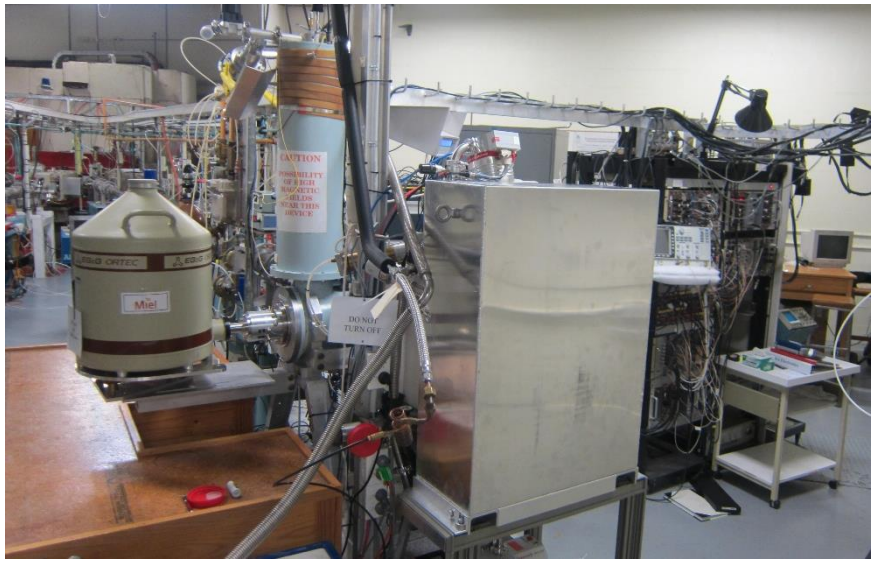
(2015-2016)



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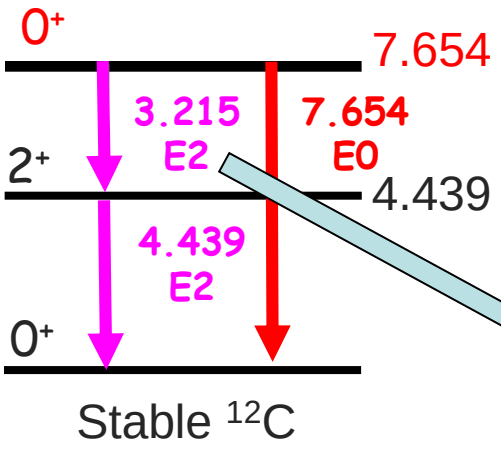
$^{12}C(p,p`\gamma)^{12}C^*$ pair measurements

(2015-2016)



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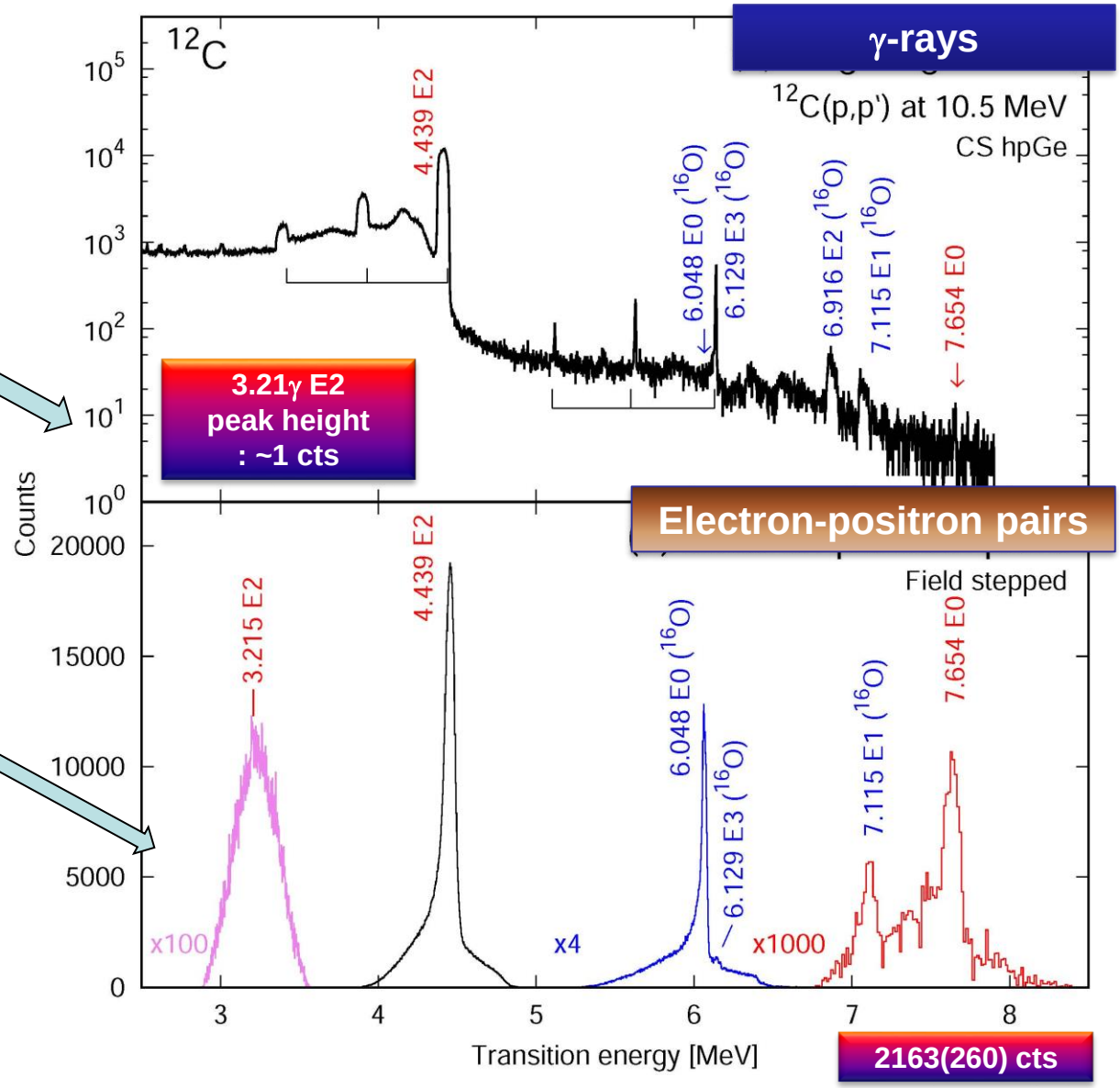

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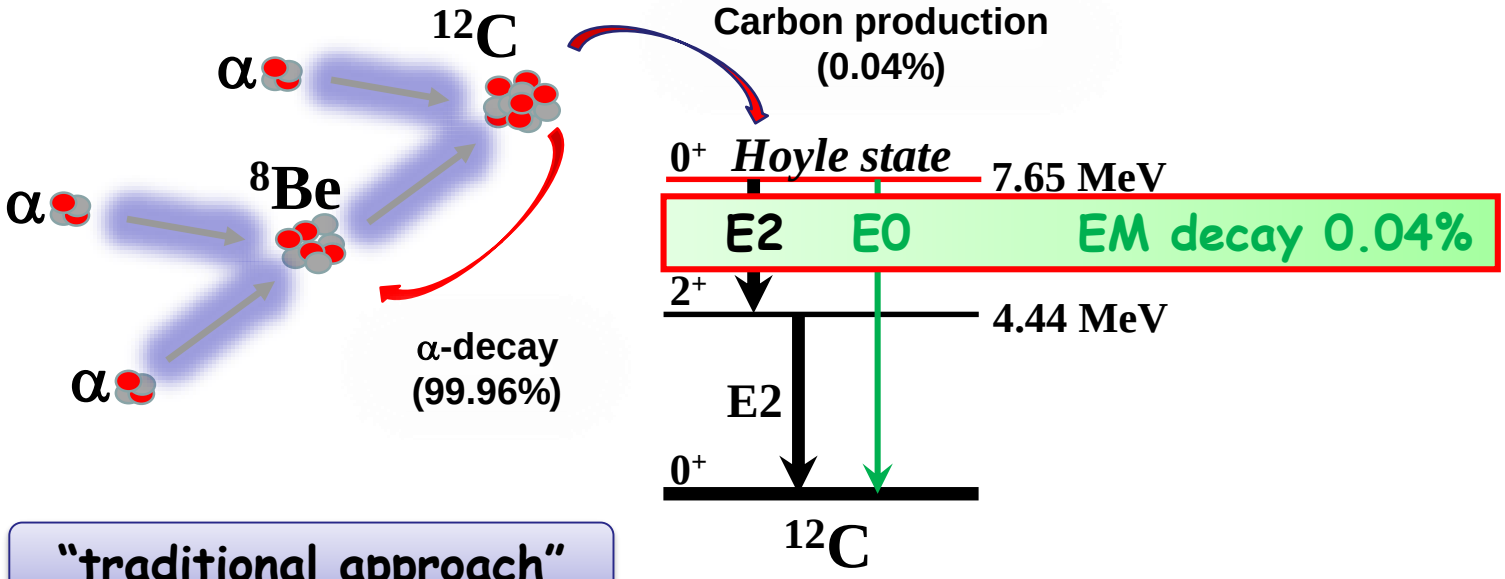
Determining the triple-α rate

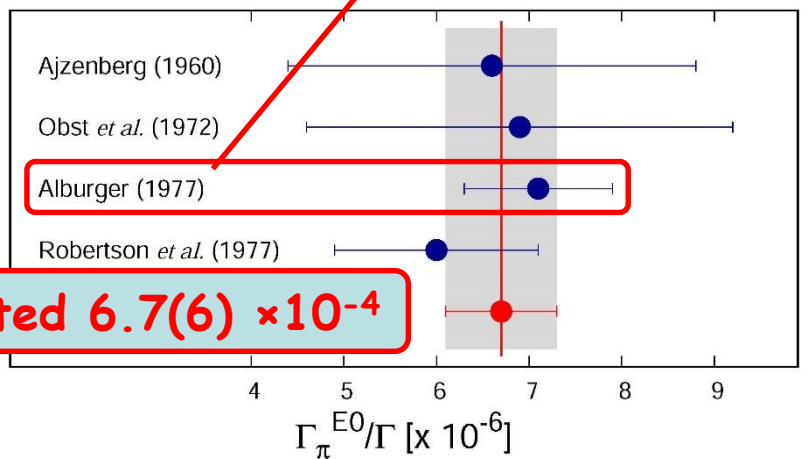


"traditional approach"

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

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

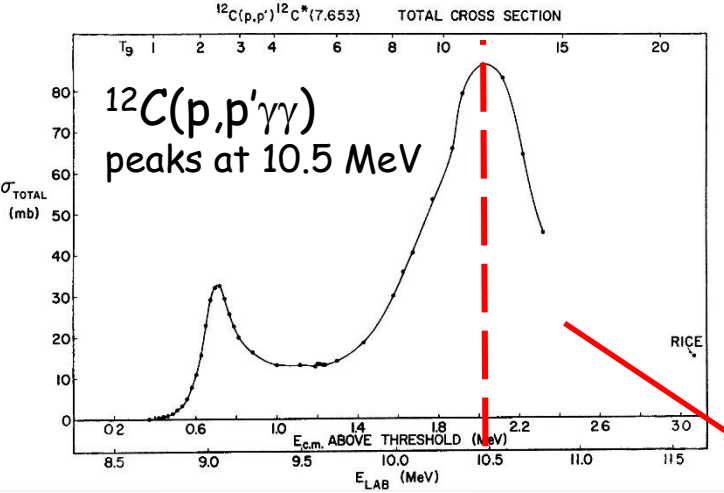
Only experiment using magnetic spectrometer



Adopted 6.7(6) ×10^{-4}

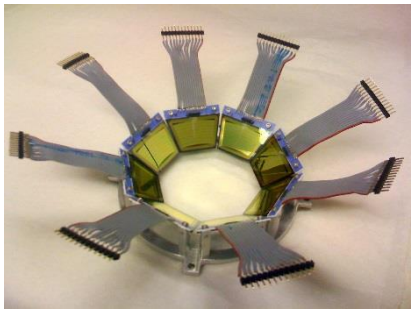
pγγ Measurements to determine Γ_{rad}/Γ

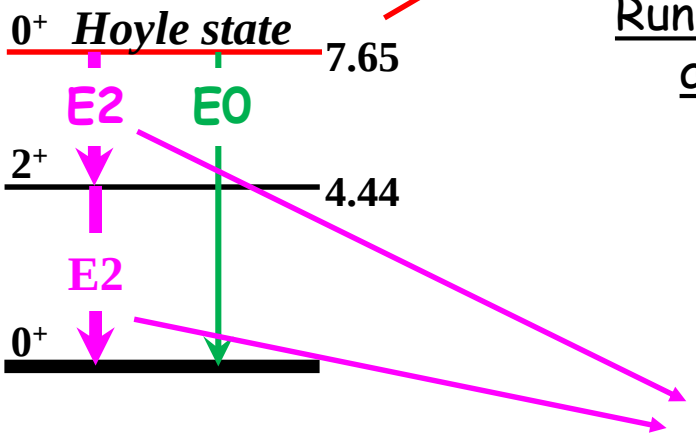
Badriah Alshahrani`s thesis (ANU)



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'γγ) for calibration

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