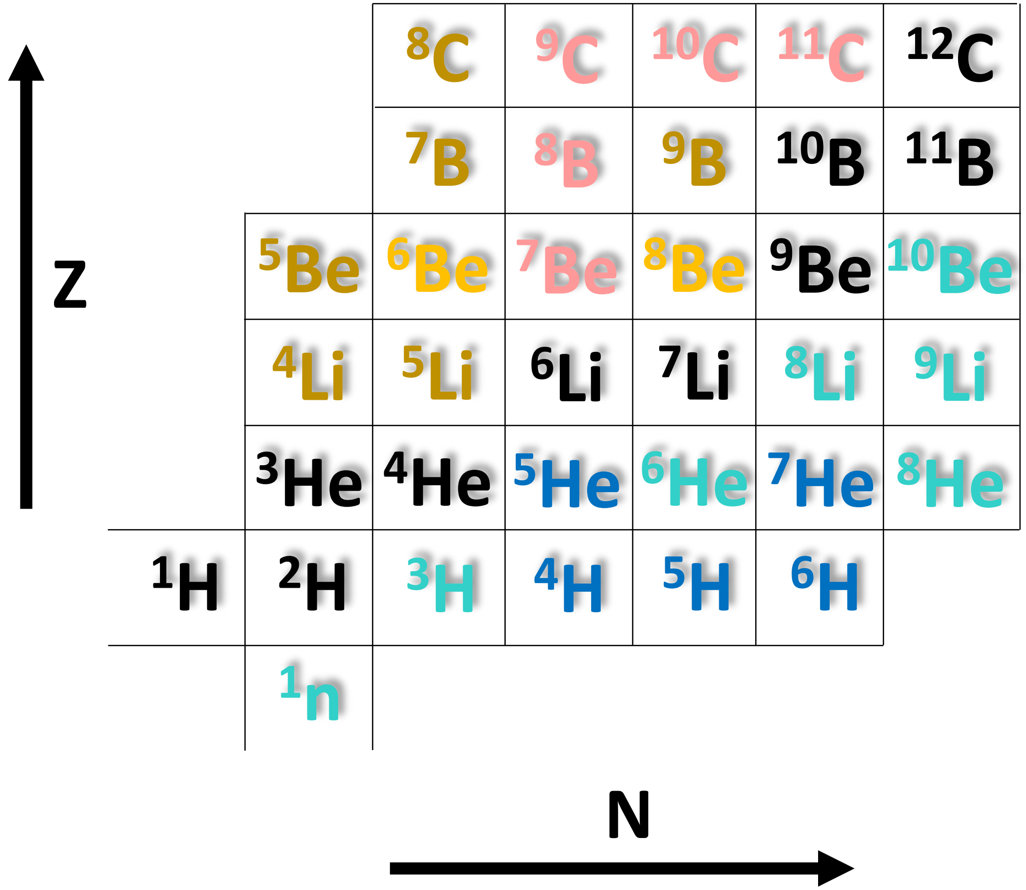
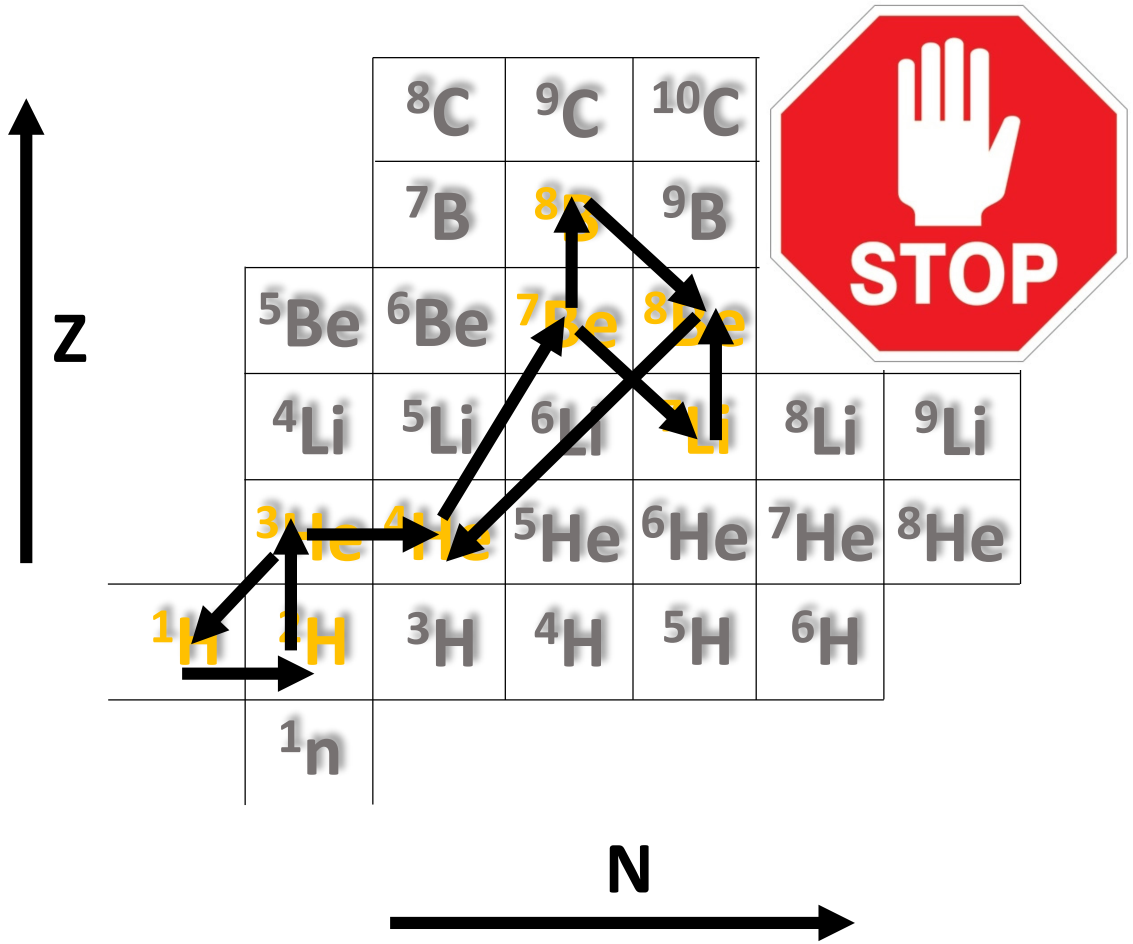
# The 3α process and pair decay from the Hoyle state

Tomas K. Eriksen
The Australian National University



8C 9C 10C 11C 12C
7B 8B 9B 10B 11B
5Be 6Be 7Be 8Be 9Be 10Be
4Li 5Li 6Li 7Li 8Li 9Li
3He 4He 5He 6He 7He 8He
1H 2H 3H 4H 5H 6H
1n
Z
N

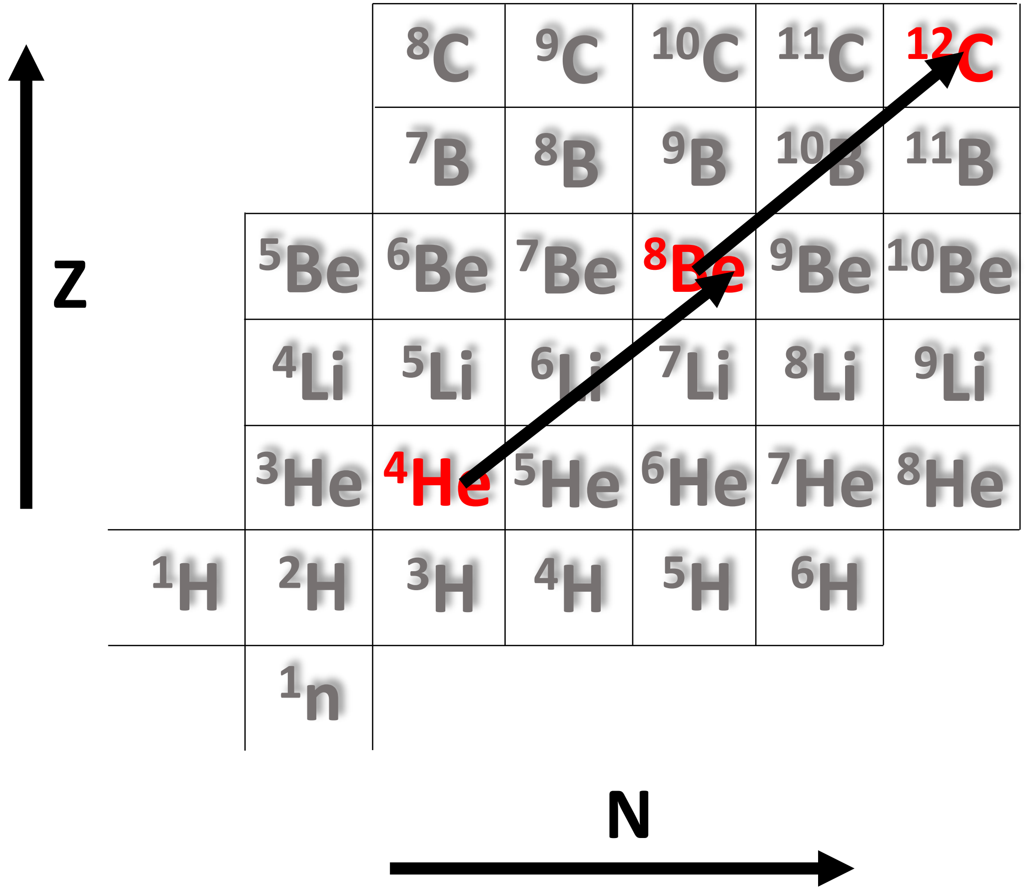
# The proton-proton chain

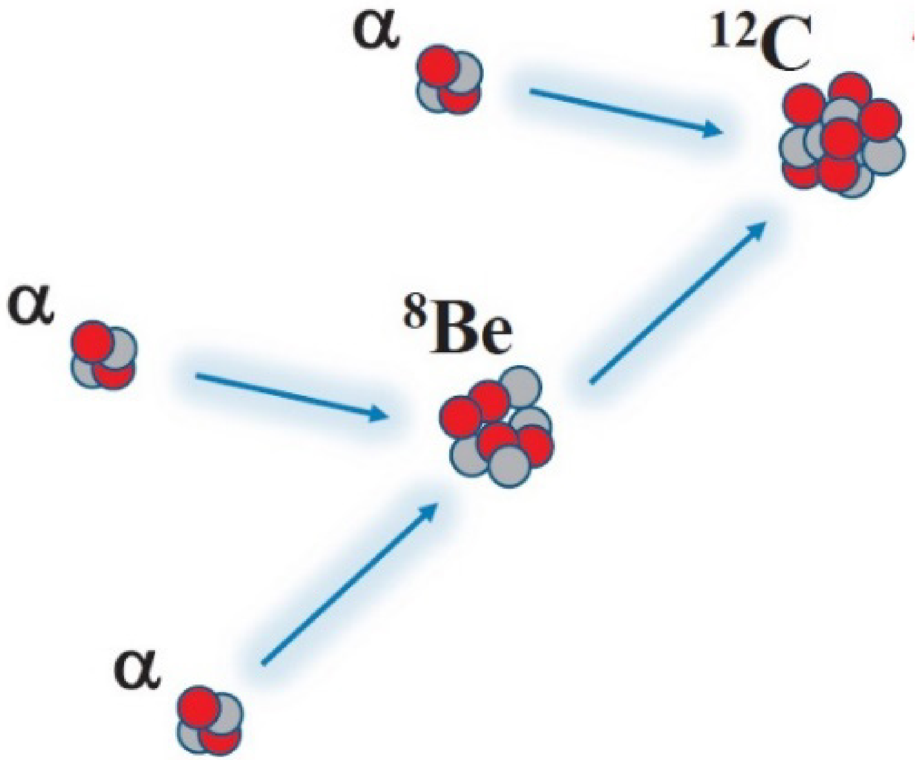



$^{8}Be \rightarrow 2\alpha$

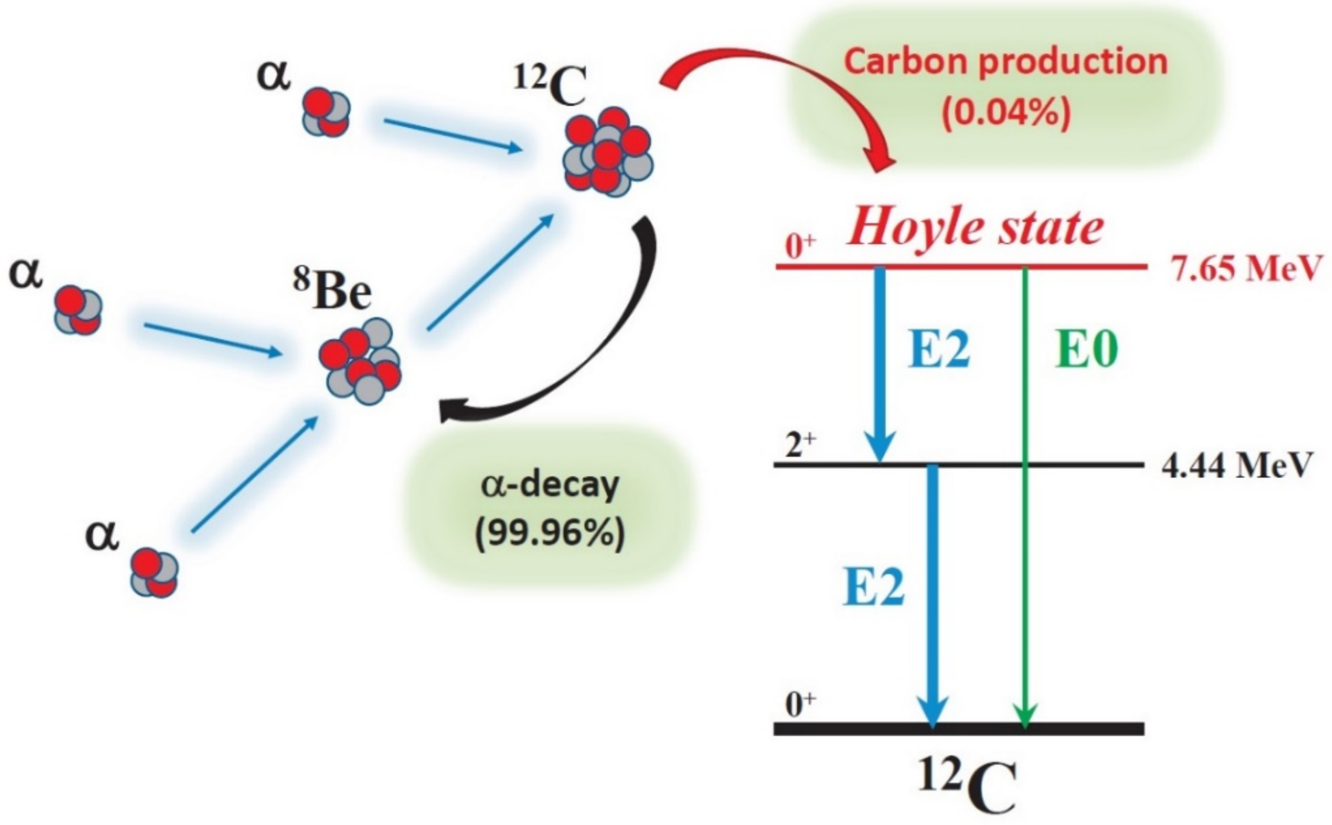
$T_{1/2} = 6.7 \cdot 10^{-17}$ s

# Stellar formation of carbon



# Stellar formation of carbon




- Stable carbon only formed following radiative decay
- The 3α reaction rate:

$$\boxed{r_{3\alpha} \propto \underline{\Gamma_{\mathrm{rad}}} \cdot \exp(-E_{3\alpha}/k_B T)}$$

(Rolfs and Rodney, 1988)

- Cannot be measured directly!

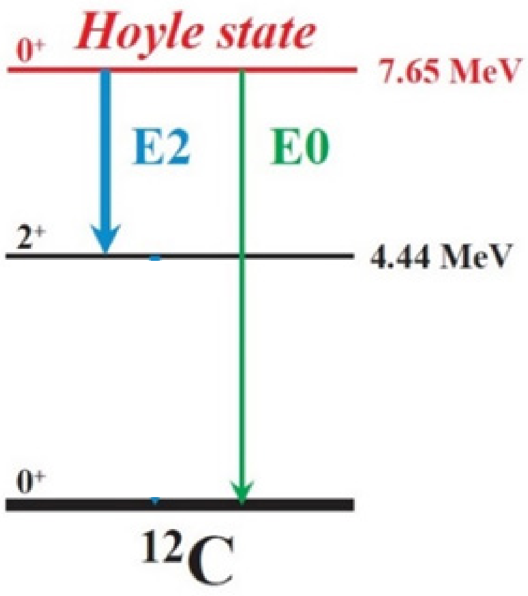
# Traditional method

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

Is there another way?

- Indirectly determined by 3 measurements
- Have to consider proton and γ angular distributions

# Proposed method




$$\Gamma_{\text{rad}} = \Gamma_{\gamma}(E2) + \Gamma_{\pi}(E2) + \Gamma_{\pi}(E0)$$

<u>Out of the ~0.04%</u>

$G_g(E2)$ = 98.5%

$G_p(E0)$ = 1.5%

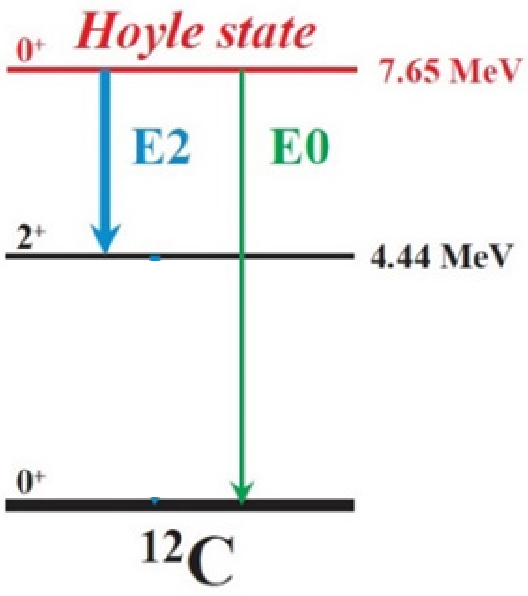
$G_p(E2)$ = 0.088%

$G_{CE}(E2)$ ~2.5E-5%

$G_{CE}(E0)$ ~1E-5%

Internal pair conversion

# Proposed method




$$\boxed{\Gamma_{\text{rad}} = \Gamma_{\gamma}(E2) + \Gamma_{\pi}(E2) + \Gamma_{\pi}(E0)}$$

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

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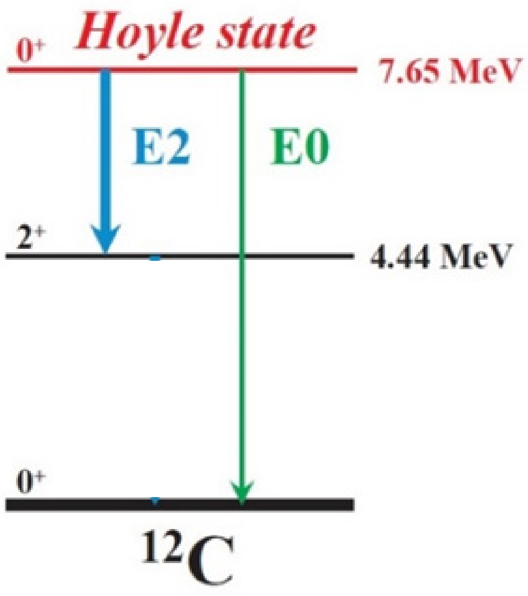


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$G_{CE}$(E0) ~1E-5%

Internal pair conversion

- Two direct measurements
- PCC known with ≈ 1 % uncertainty [1]
- No alignment, same experiment

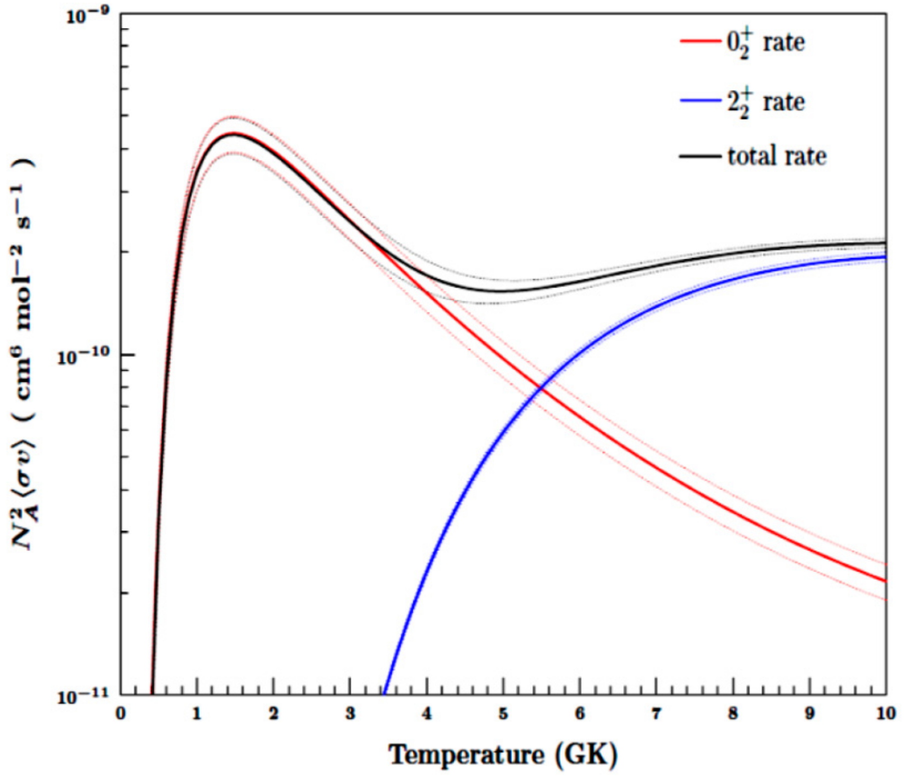
[1] P. Schlüter *et al.*, Phys. Rep. **75** (1981)

# Motivation

The 3α rate is significant for

- elemental abundances
- properties of supernova explosions
- dynamics of asymptotic giant branch (AGB) stars
- the *s*-process of heavy elements
- the weak *s*-process in massive stars

An accuracy of 5% is requested




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

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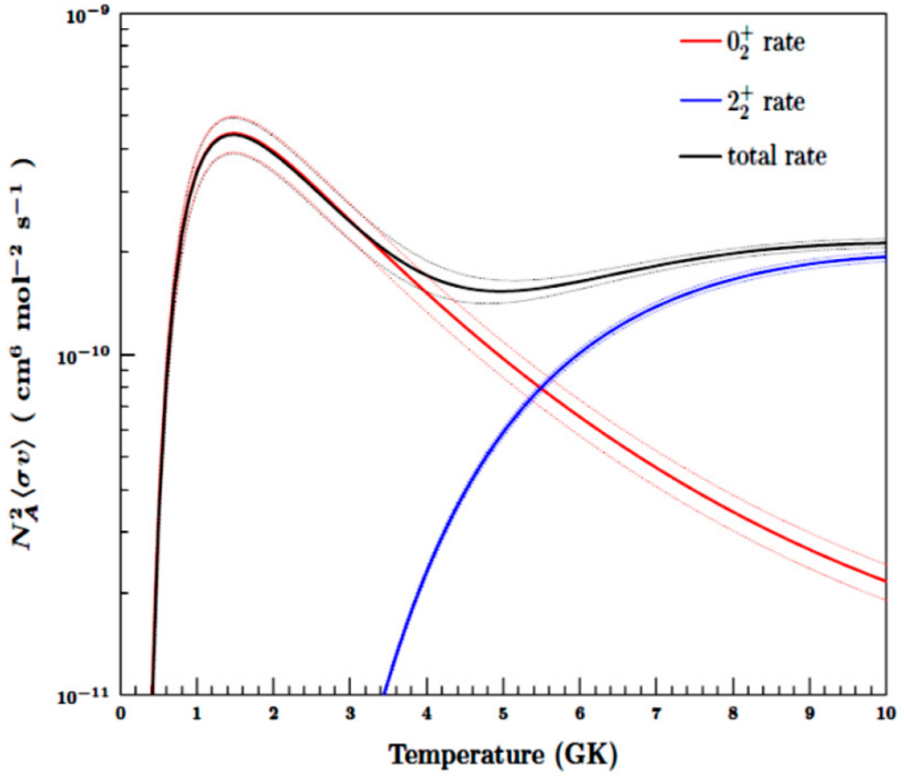
An accuracy of 5% is requested

Current uncertainty: ~10 %

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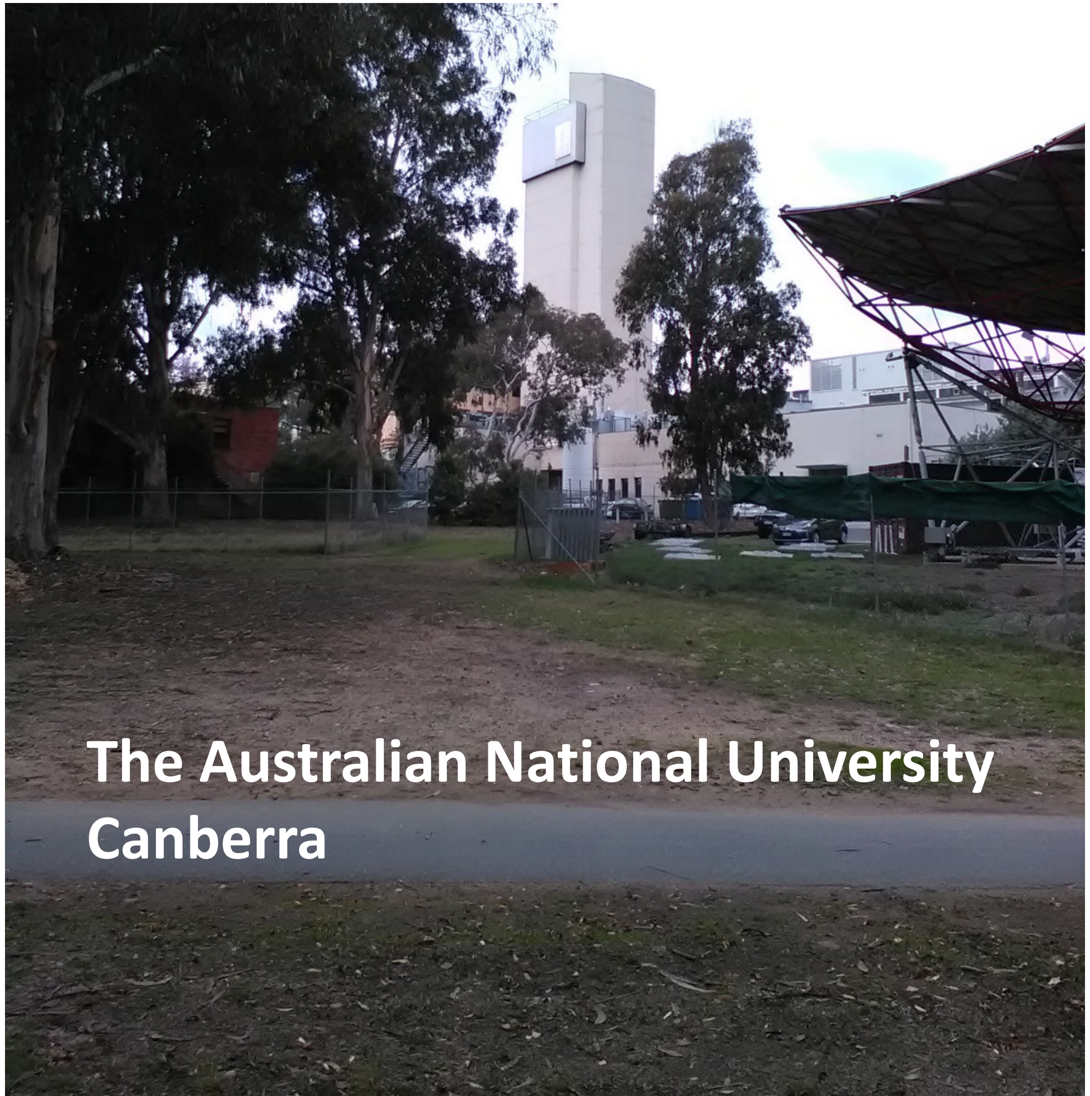
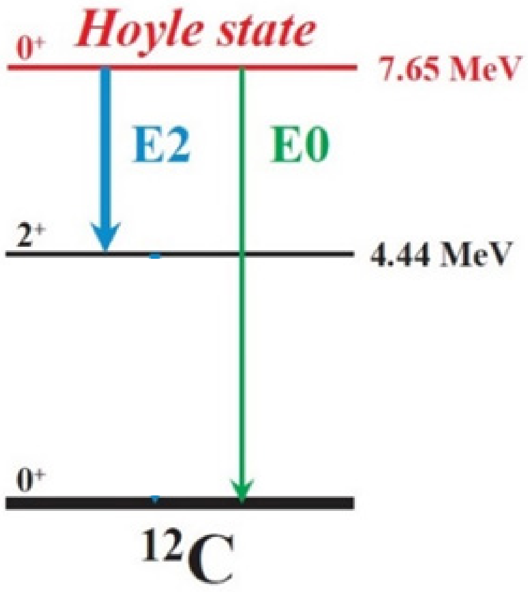
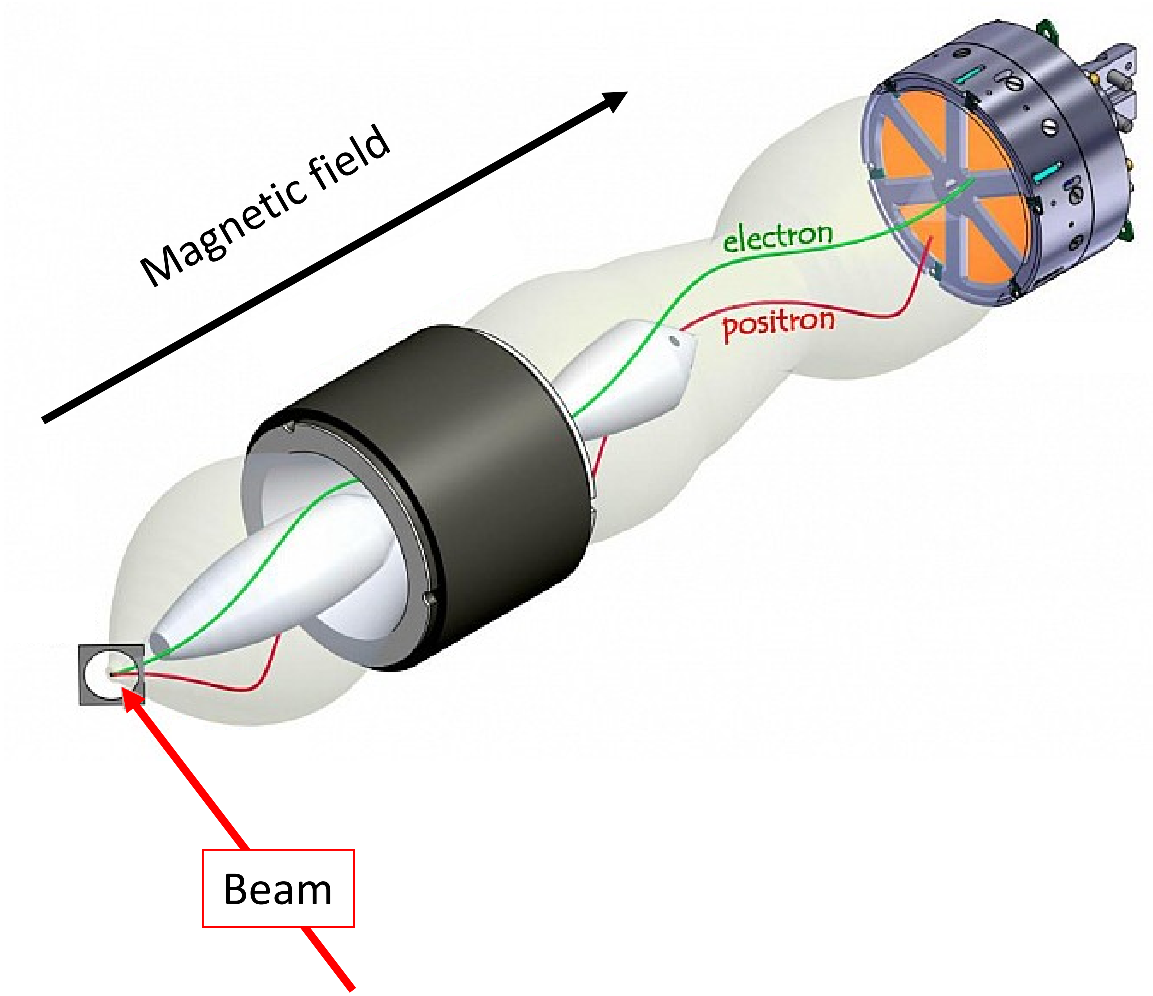
# Experiment




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

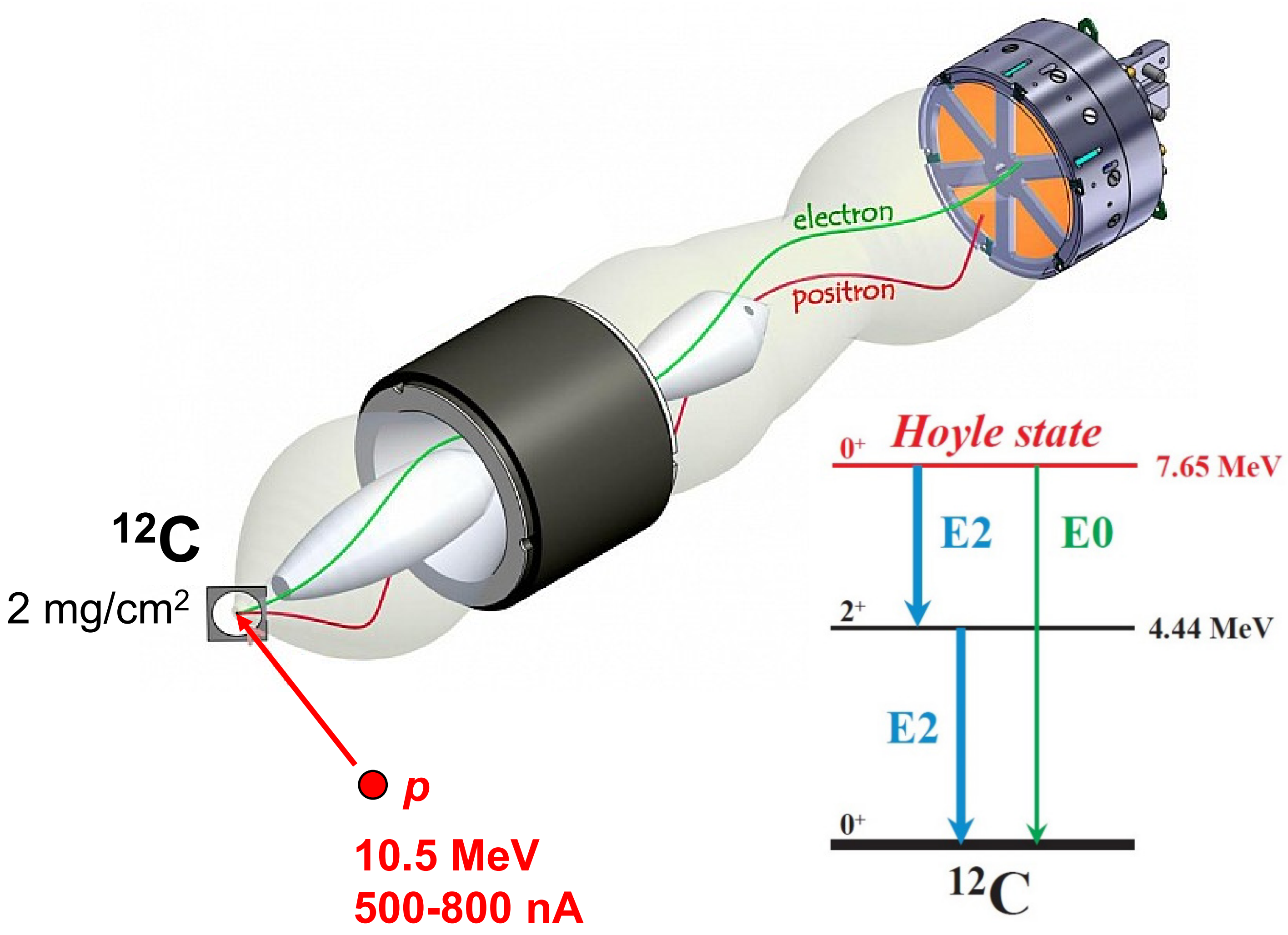


# Super-e

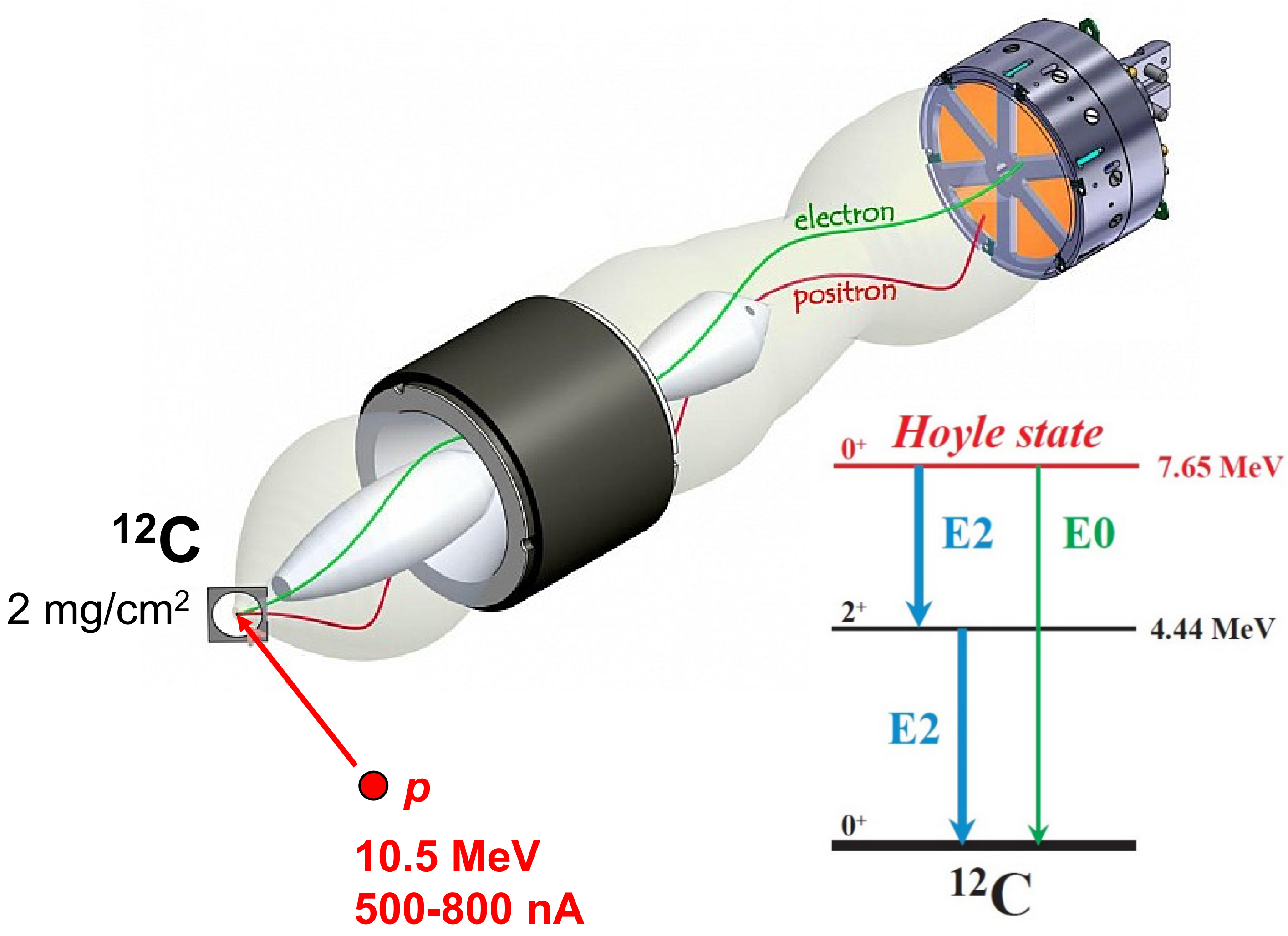



- Six 9 mm thick Si(Li) segments
  Stops electrons up to 3.5 MeV
- Baffle system shields against γ rays
- Charged particles transported by the magnetic field
- Gammas monitored by a HPGe detector

# Experimental details



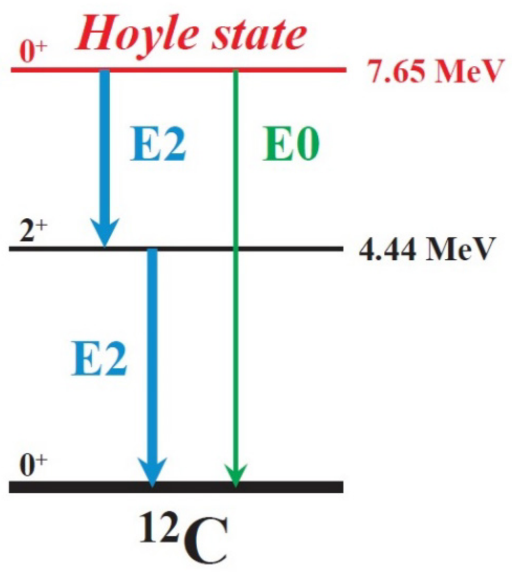
# Experimental details




$$E_{e^+} = E_{e^-} = \frac{E_{\text{tr}} - 2m_0c^2}{2}$$

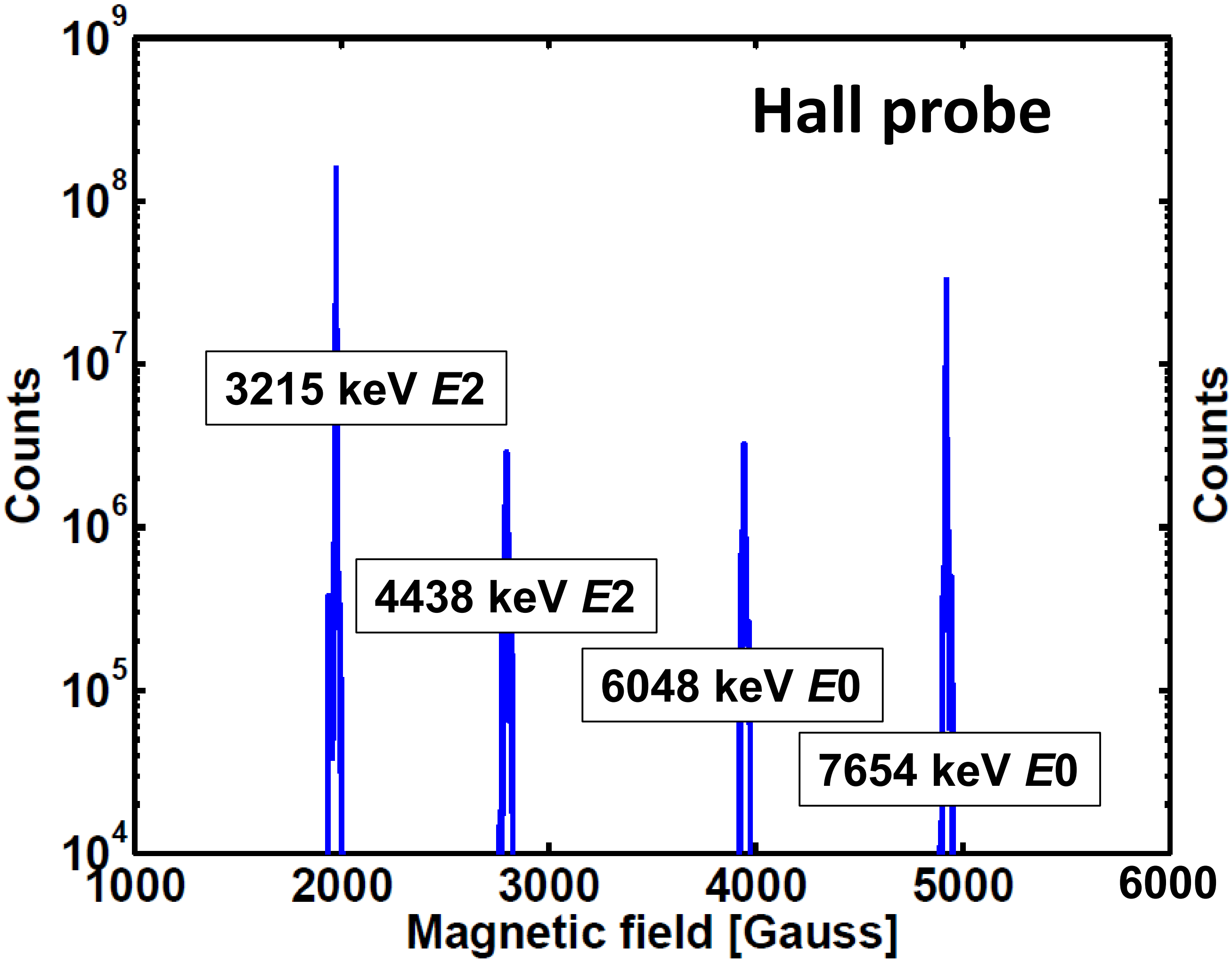
| Transitions | Sampling time |
|---|---|
| 3215 keV *E*2 | 40x |
| 4438 keV *E*2 | 1x |
| 6048 keV *E*0 ($^{16}$O) | 2x |
| 7654 keV *E*0 | 10x |

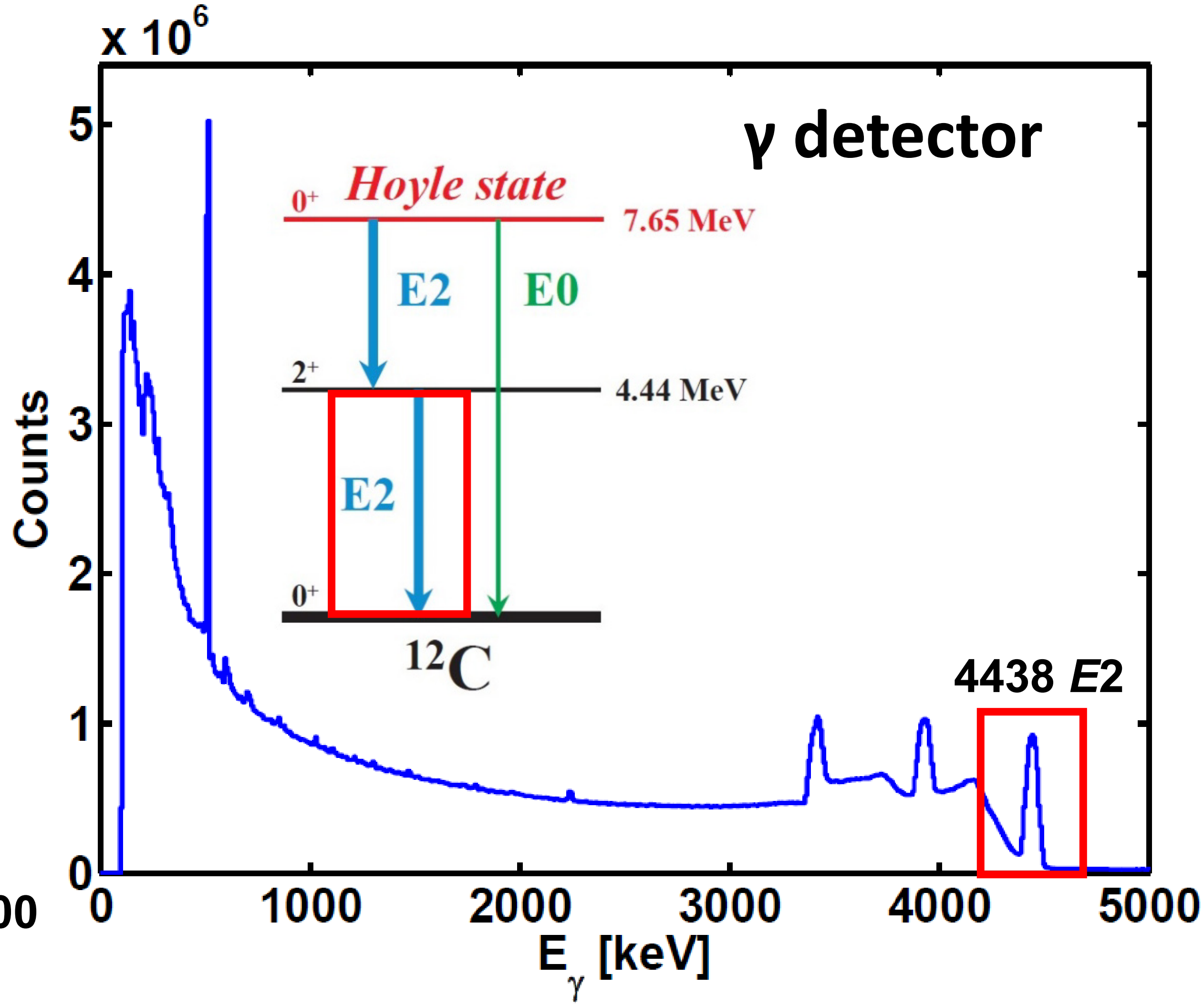
# Experimental details


- Require coincidence:
  Segment energies + times
- γ energy
- Magnetic field
- Extract:
  ΣE gated on ΔT and magnetic rigidity

# Sampling

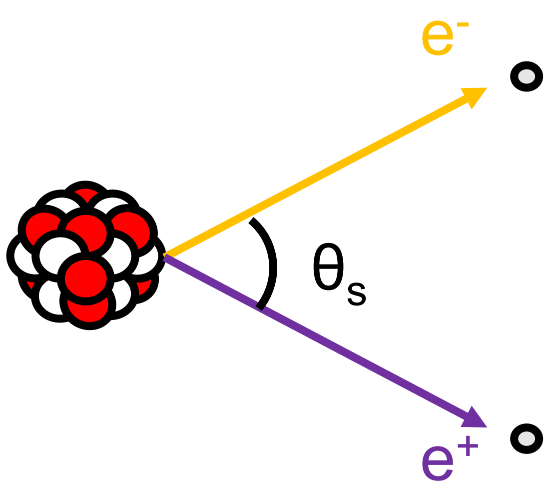

Hall probe
Counts
Magnetic field [Gauss]
3215 keV E2
4438 keV E2
6048 keV E0
7654 keV E0
1000
2000
3000
4000
5000
6000


γ detector
x 10^6
Counts
E_γ [keV]
0+ Hoyle state 7.65 MeV
E2
E0
2+ 4.44 MeV
E2
0+
12C
4438 E2
0
1000
2000
3000
4000
5000

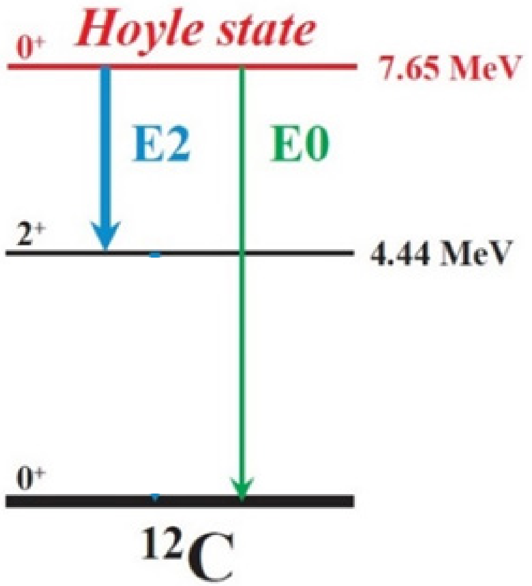
# Relative pair efficiency

No practical sources, have to rely on theory and simulation:

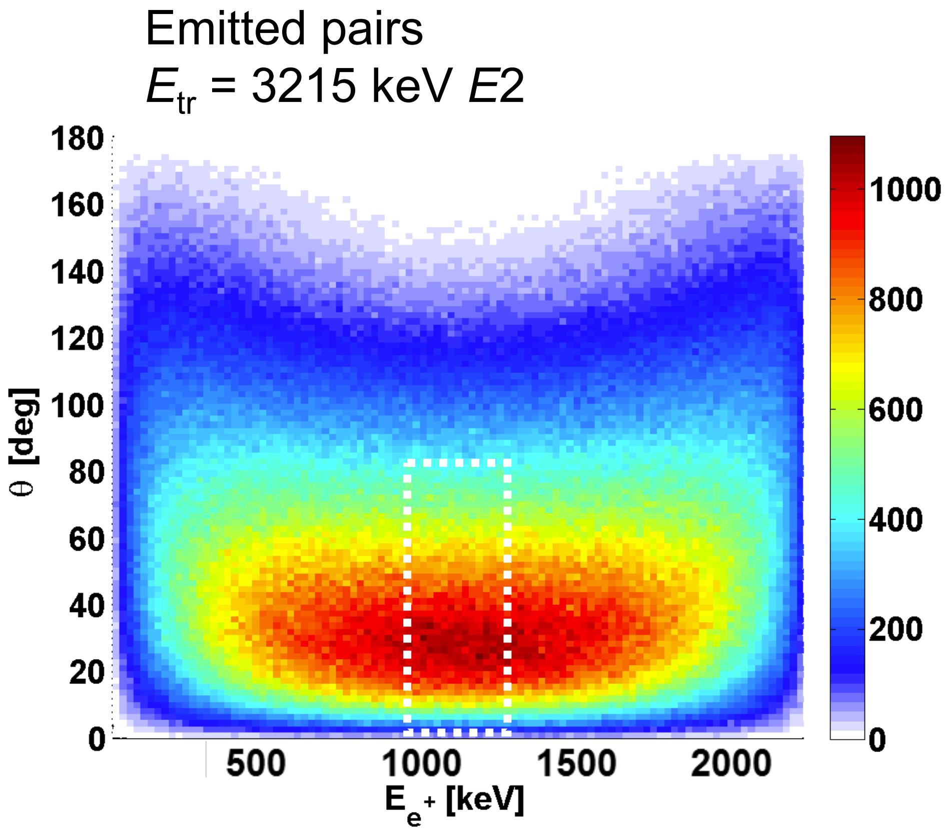
- Born approximation with Coulomb correction
- Depends on multipolarity, positron energy, separation angle

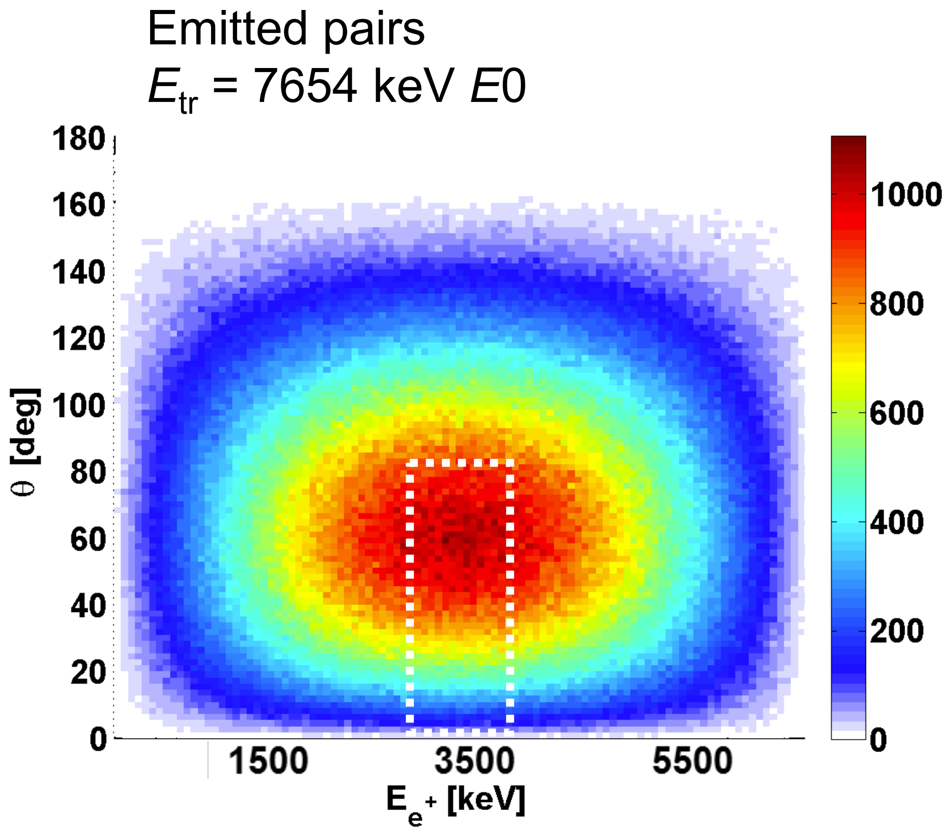



$$\frac{d^2 P_\pi(XL)}{dE_{e^+} d\theta_s}$$

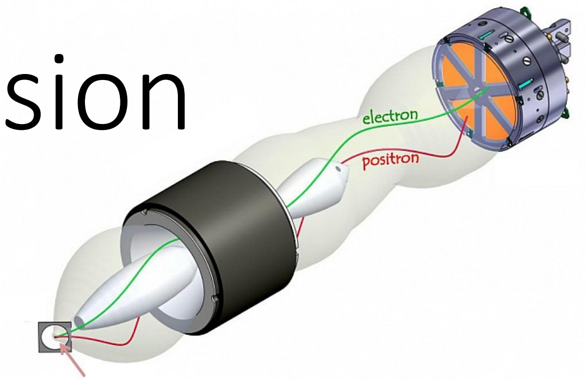


# Relative efficiency – Step 1: Emission

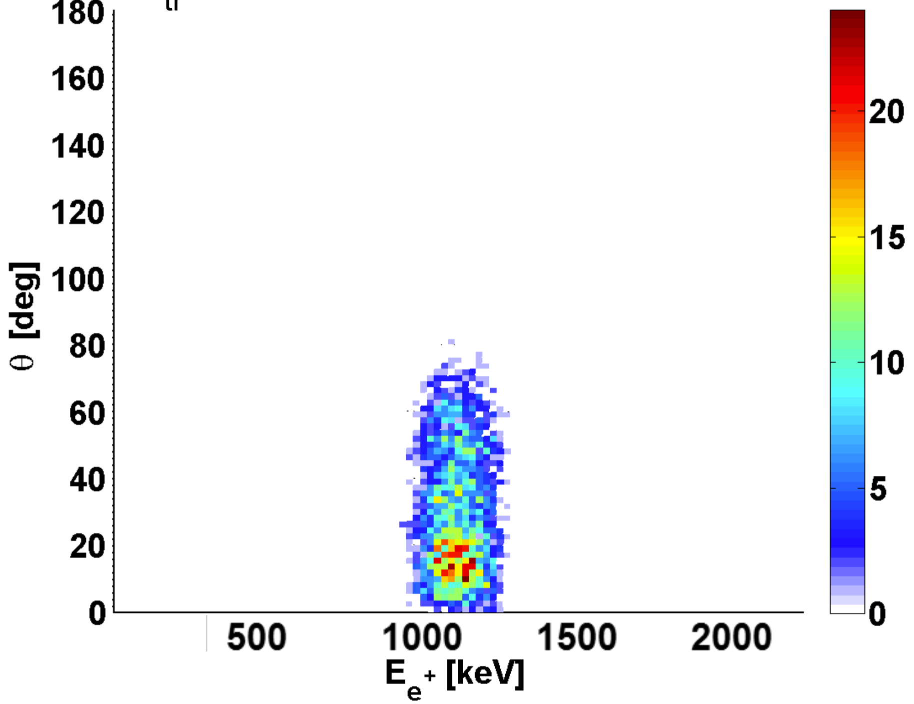


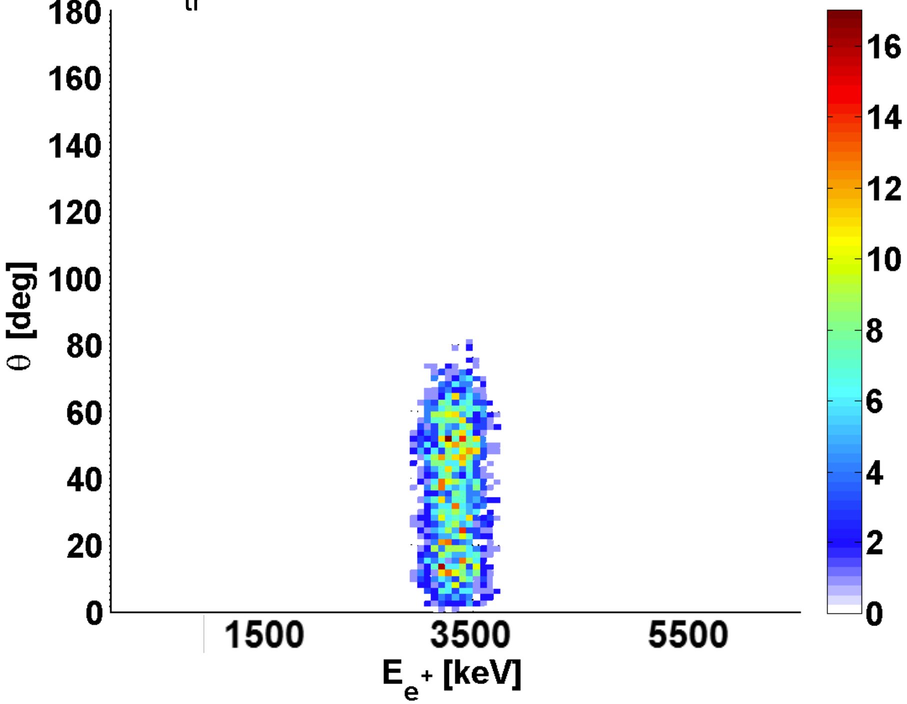
# Relative efficiency – Step 2: Transmission



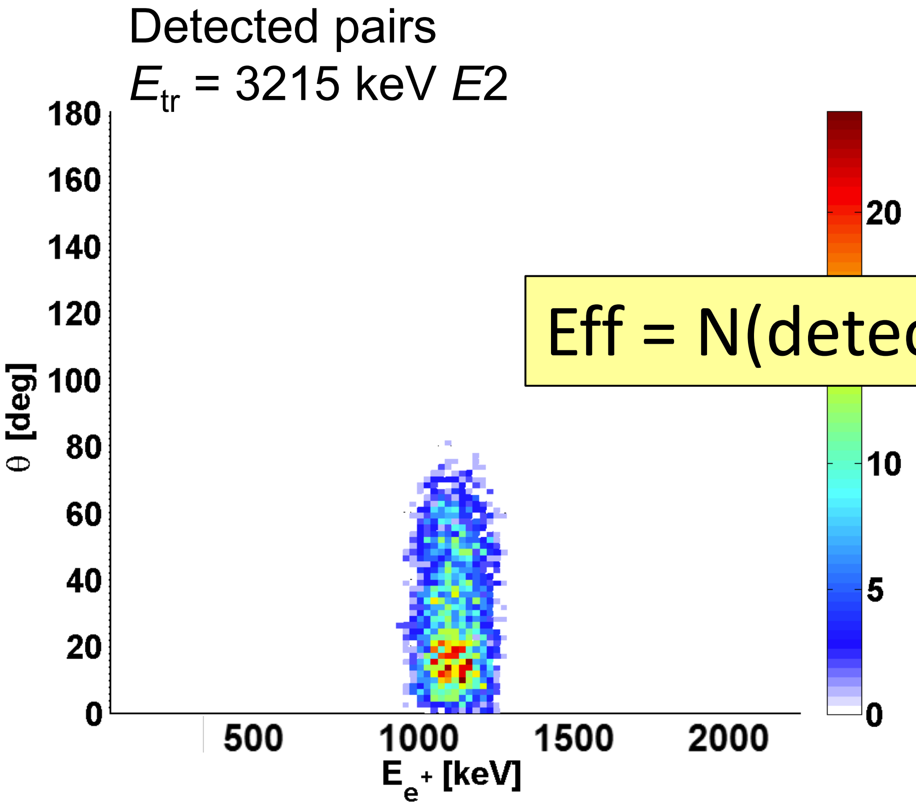

Detected pairs
$E_{tr}$ = 3215 keV $E2$

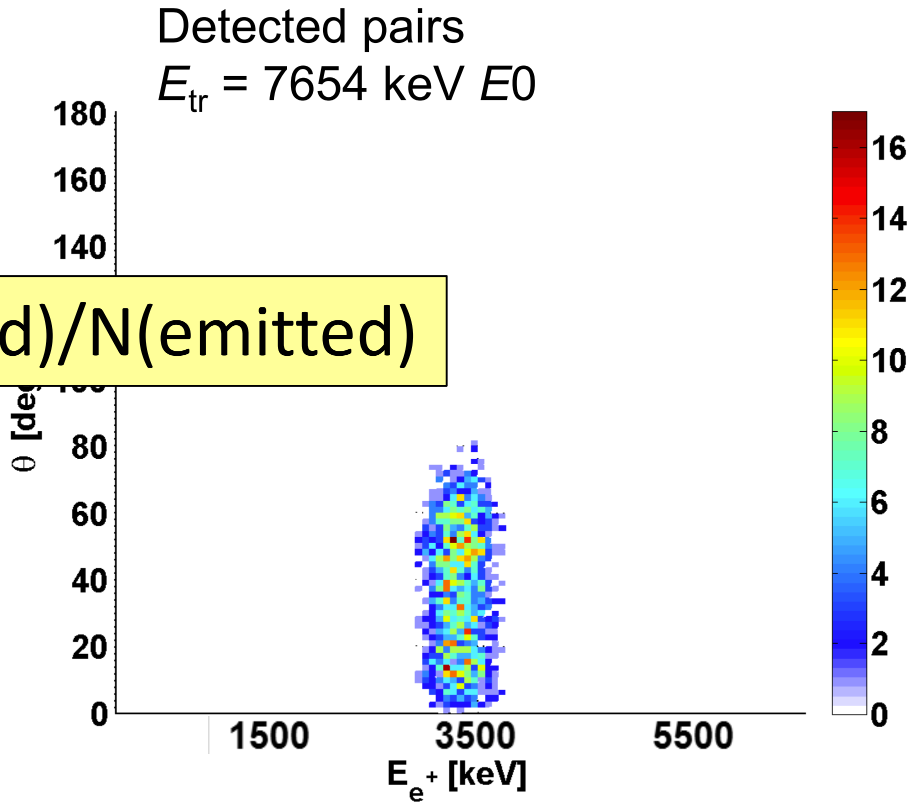



Detected pairs
$E_{tr}$ = 7654 keV $E0$



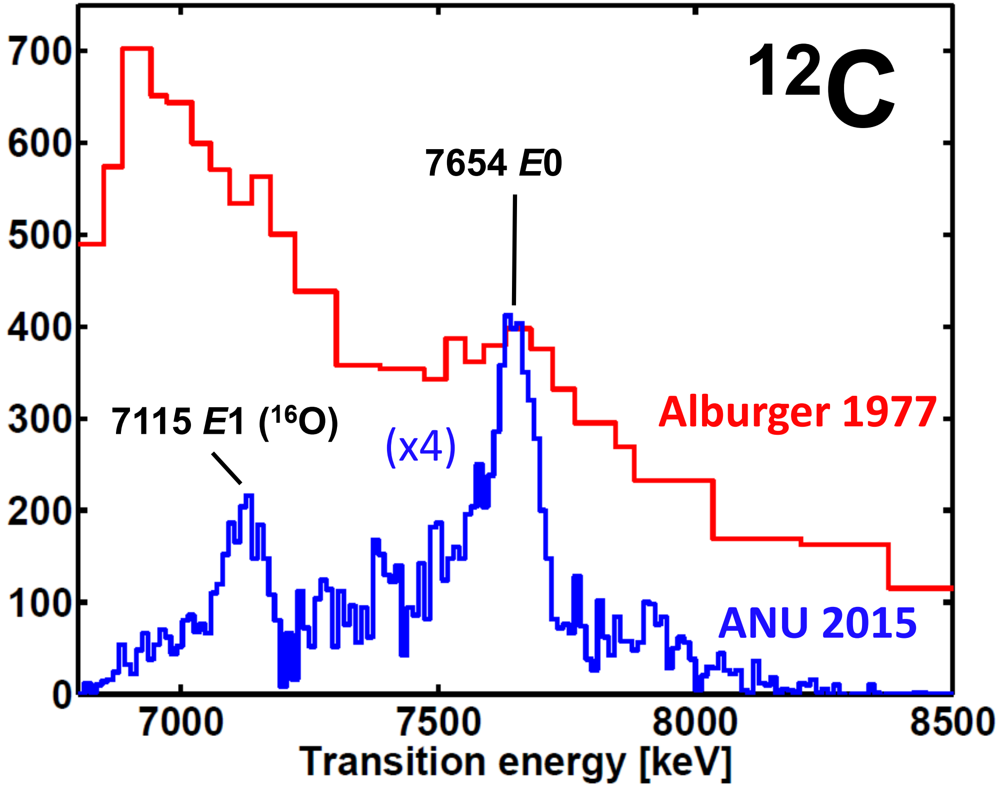
# Relative efficiency – Step 2: Transmission



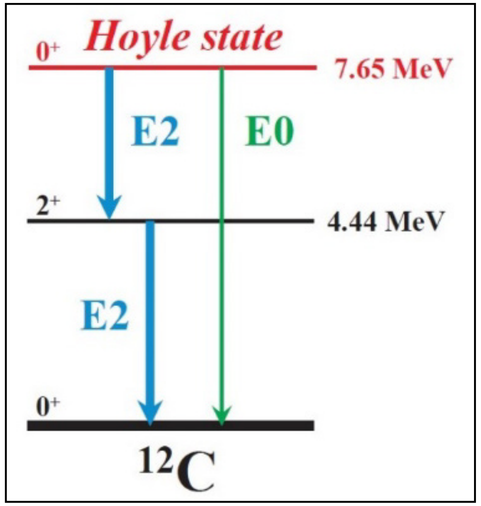




Eff = N(detected)/N(emitted)

# Experiments

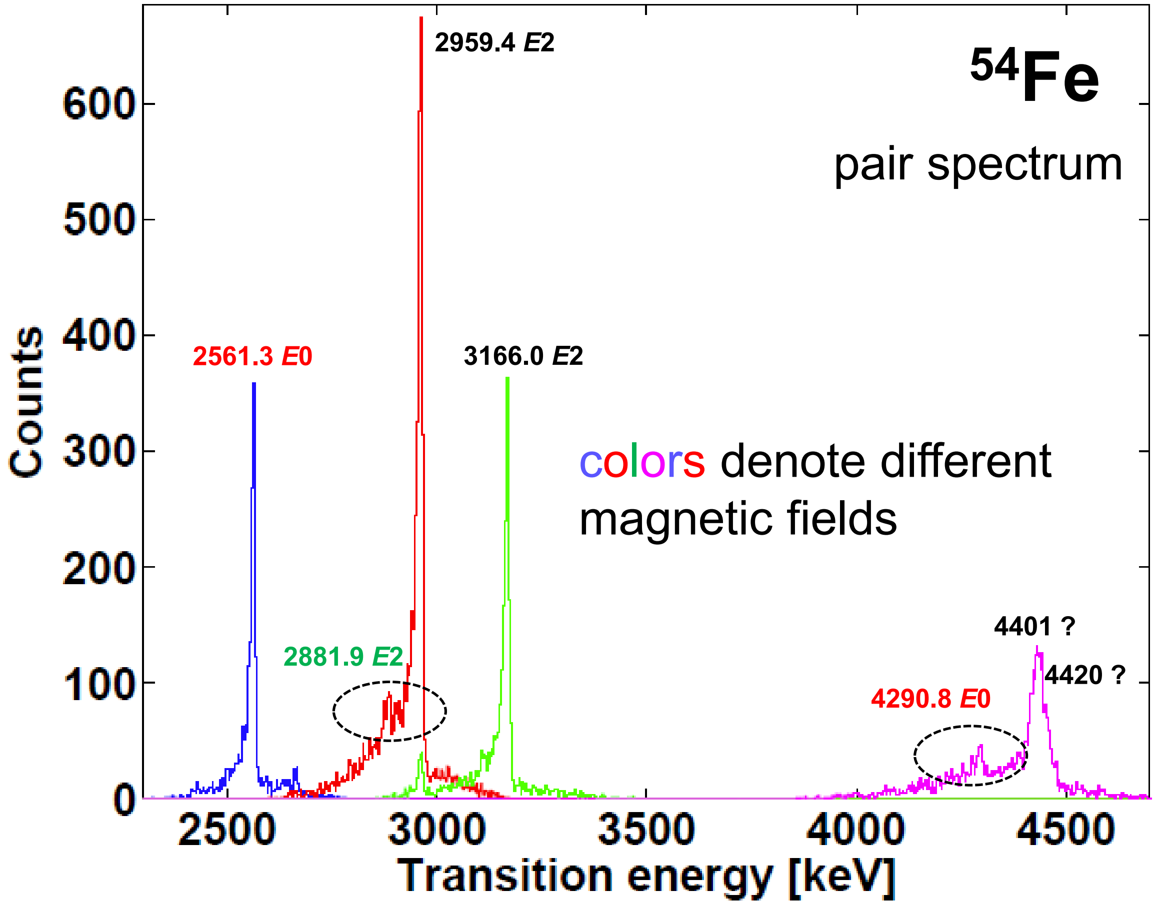


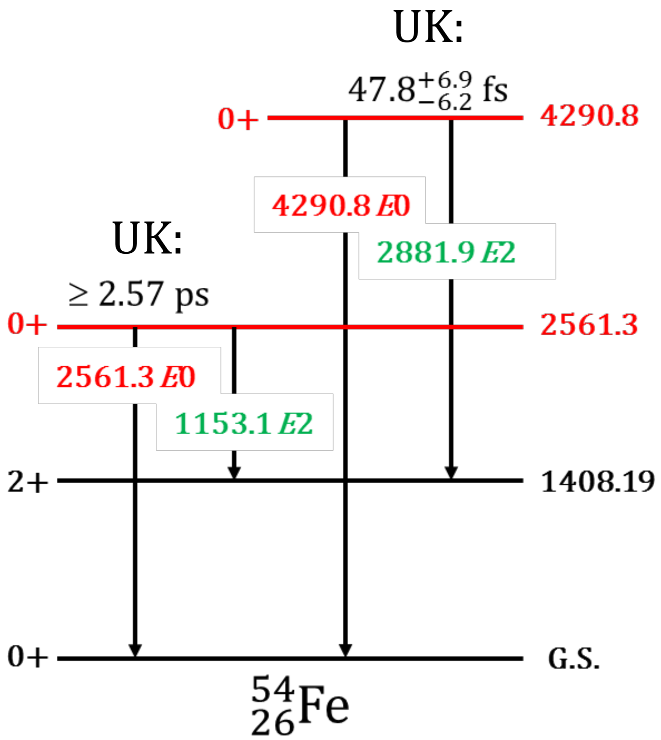

- 5 experiments since 2014
- Focussed on the 7.65 MeV *E*0
  First success in 2015
- In 2016: more sampling of the 3.2 MeV *E*2
- Several improvements to the electronics and setup




D.E. Alburger, Phys. Rev. **C16** (1977) 2394

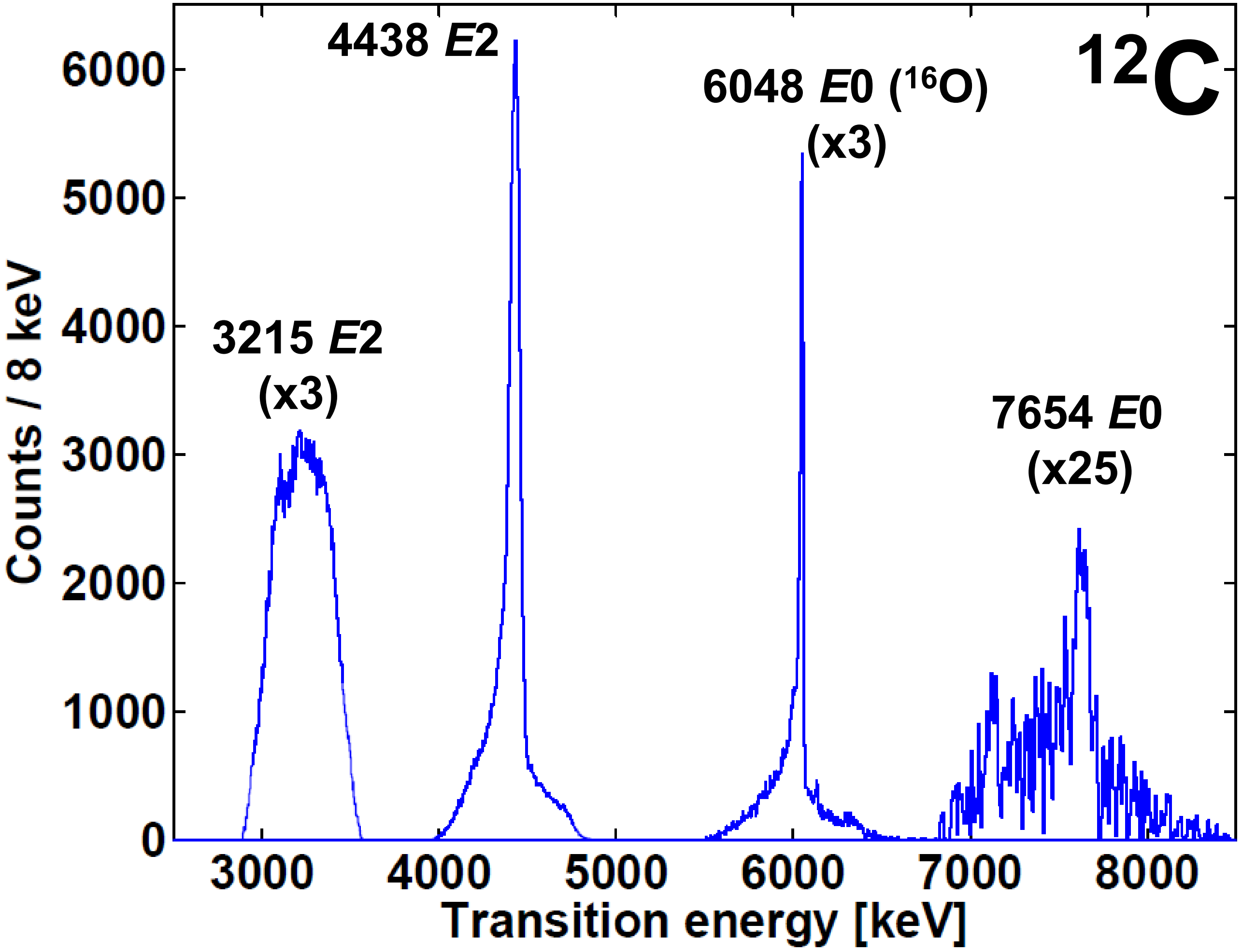
# $^{54}$Fe(p,p') @ 6.9 MeV



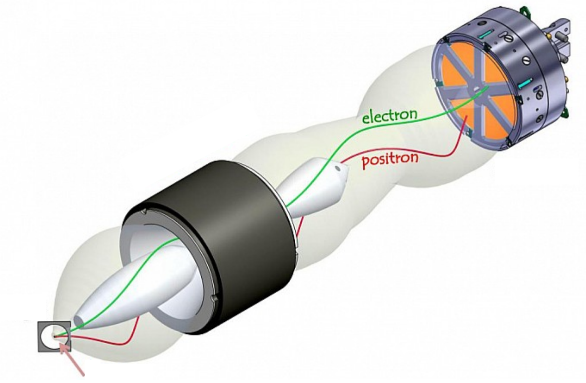



# Preliminary results
# April 2016

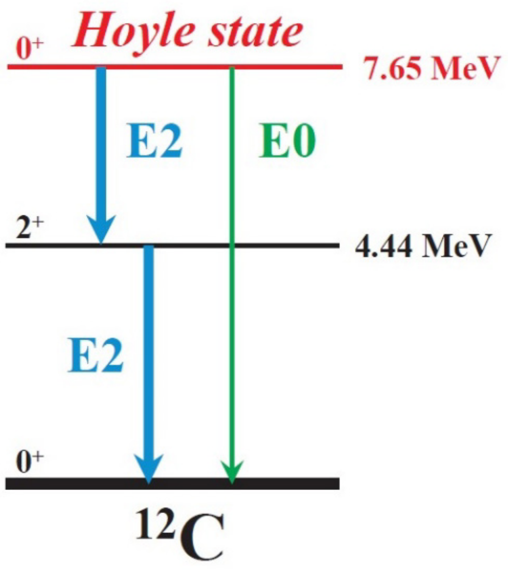
# April 2016



4438 E2
6048 E0 (16O)
(x3)
12C
3215 E2
(x3)
7654 E0
(x25)
Counts / 8 keV
Transition energy [keV]
0
1000
2000
3000
4000
5000
6000
3000
4000
5000
6000
7000
8000

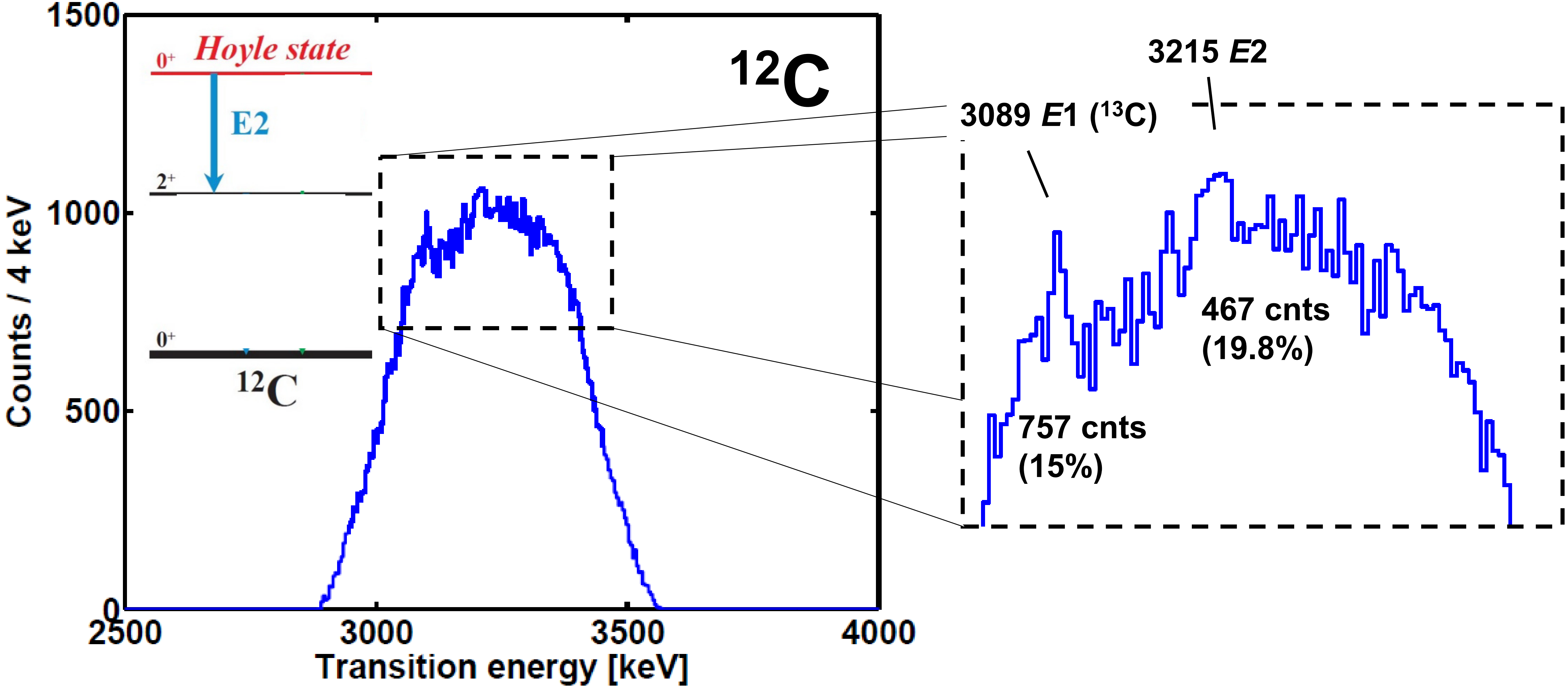



electron
positron

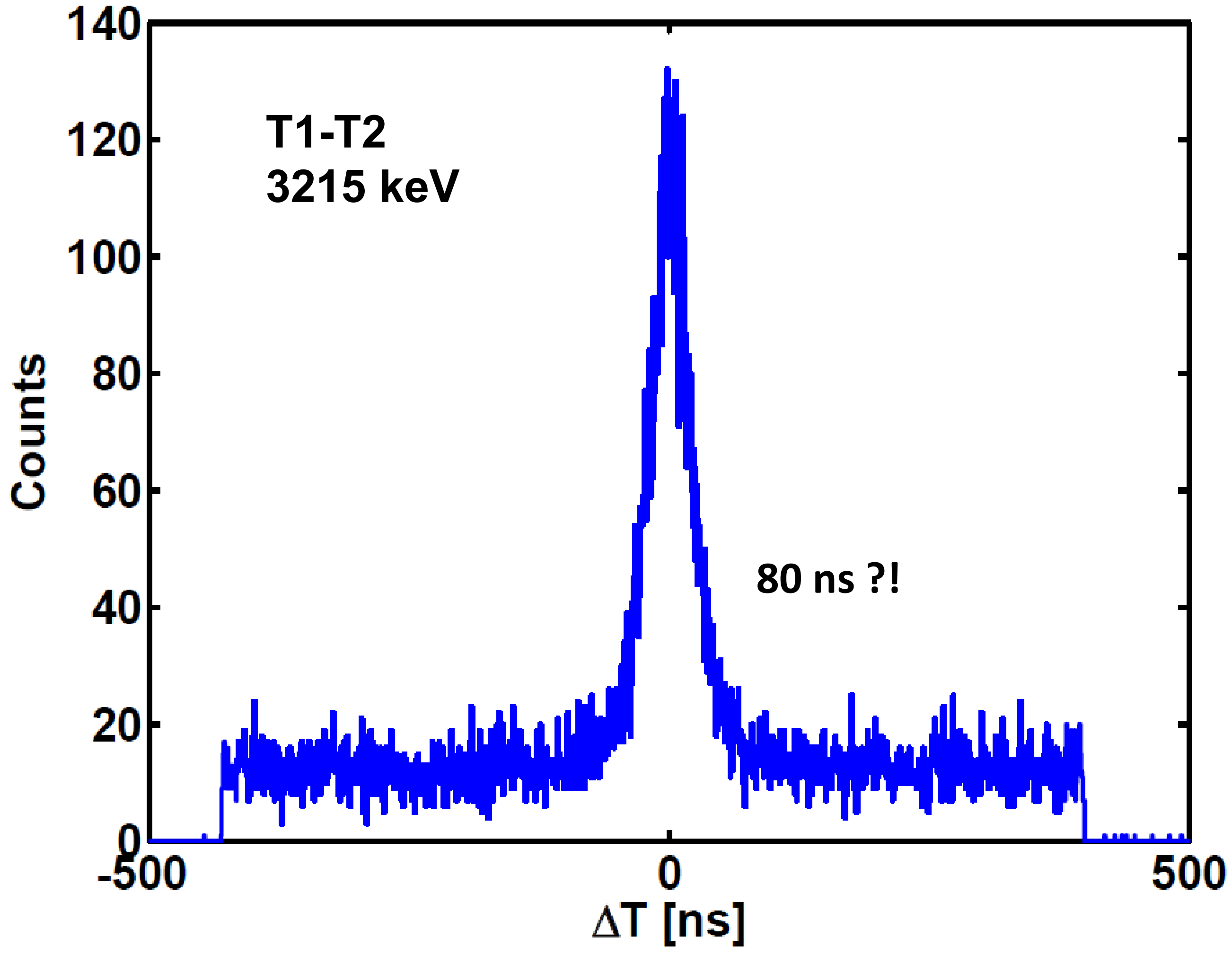
0+ Hoyle state
7.65 MeV
E2
E0
2+
4.44 MeV
E2
0+
12C

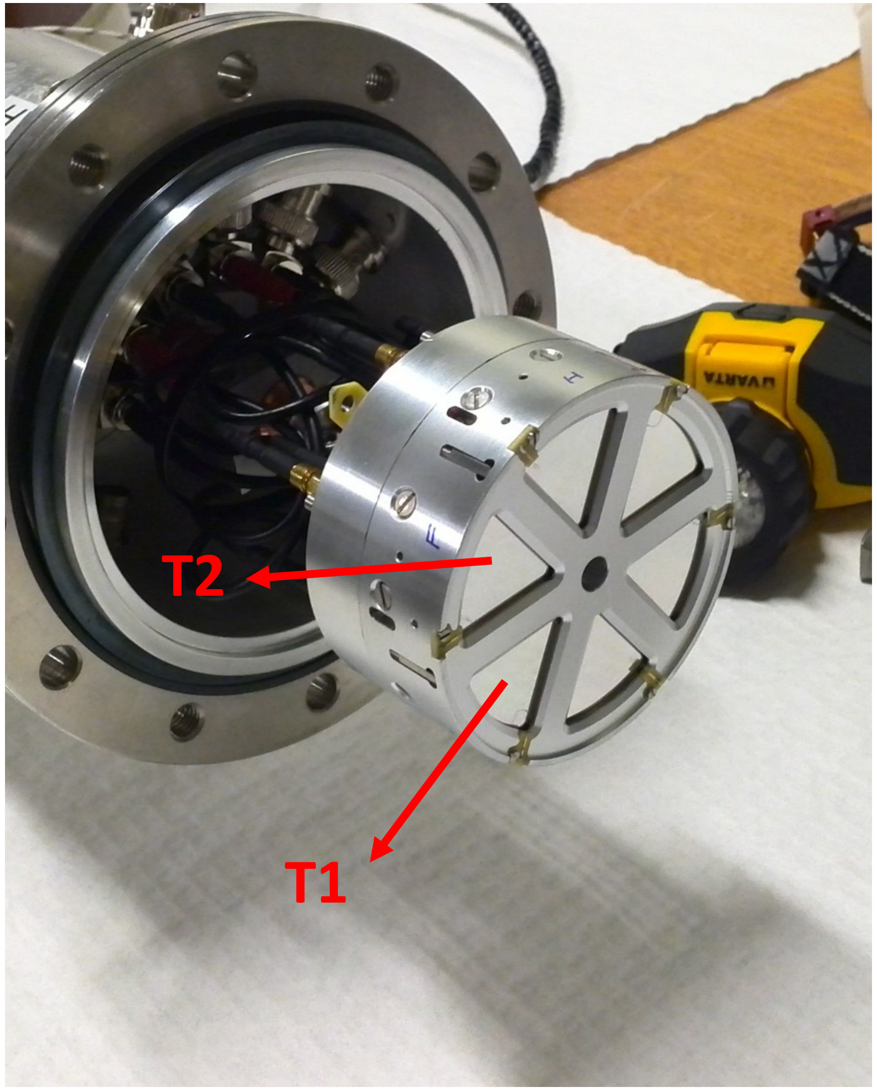
# April 2016



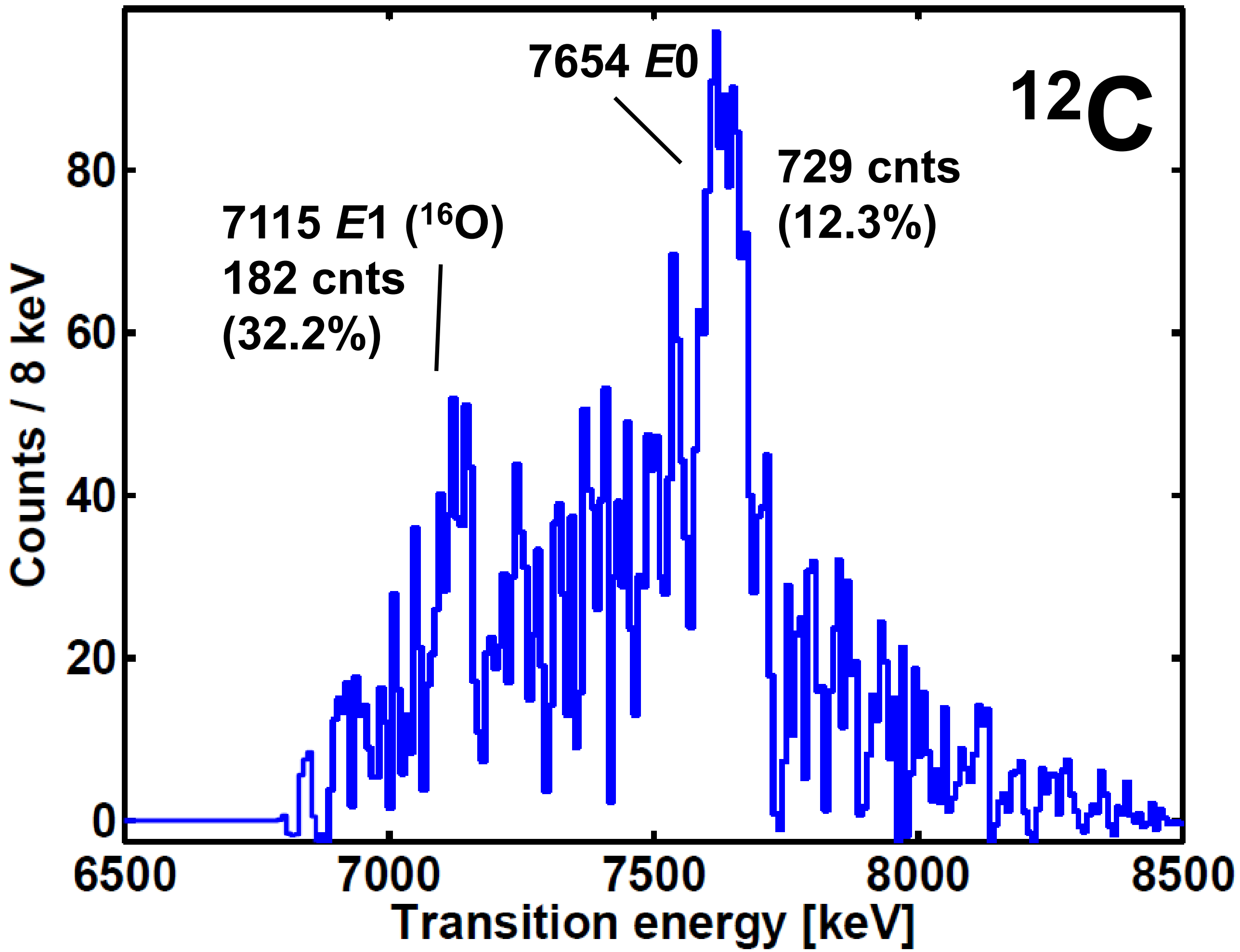
12C
Hoyle state
0+
E2
2+
0+
12C
1500
1000
500
0
Counts / 4 keV
2500
3000
3500
4000
Transition energy [keV]
3215 E2
3089 E1 (13C)
467 cnts
(19.8%)
757 cnts
(15%)

# Time differences

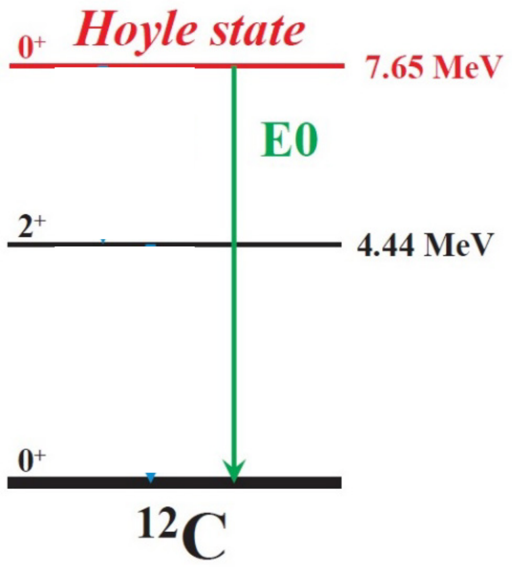


# April 2016



7654 E0
729 cnts
(12.3%)
12C
7115 E1 (16O)
182 cnts
(32.2%)
Counts / 8 keV
0
20
40
60
80
6500
7000
7500
8000
8500
Transition energy [keV]

0+
Hoyle state
7.65 MeV
E0
2+
4.44 MeV
0+
12C

# Results

$$\boxed{\frac{\Gamma_\pi(E2)}{\Gamma_\pi(E0)} = \frac{467(93)}{729(90)} \times \frac{5.5891 \cdot 10^{-4}}{8.3121 \cdot 10^{-4}} \times \frac{12.6}{34.3} = 0.158(37)}$$

# Results

$$\boxed{\frac{\Gamma_\pi(E2)}{\Gamma_\pi(E0)} = \frac{467(93)}{729(90)} \times \frac{5.5891 \cdot 10^{-4}}{8.3121 \cdot 10^{-4}} \times \frac{12.6}{34.3} = 0.158(37)}$$

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

$\boxed{6.2(2) \cdot 10^{-5}\mathrm{eV}}$

$\boxed{8.77(13) \cdot 10^{-4}}$

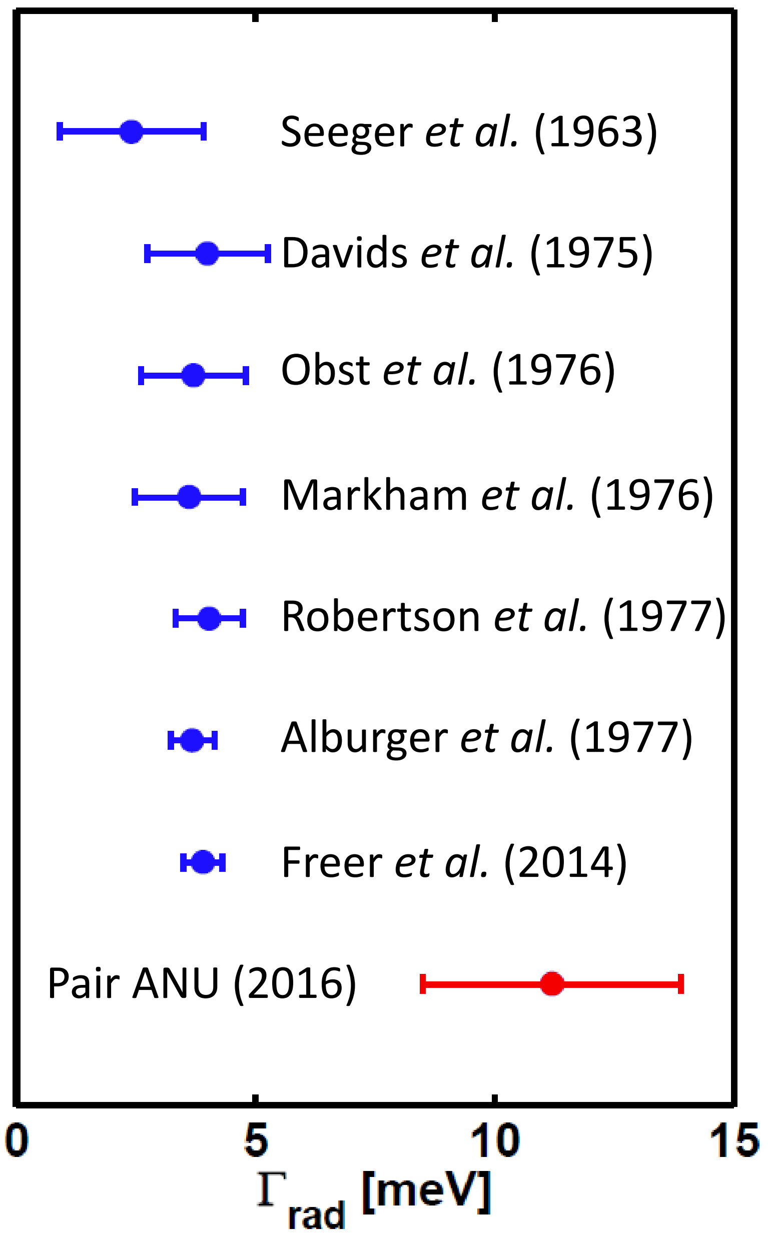
Freer and Fynbo, Prog. in Part. and Nucl. Phys. **78** (2014) 1

BrICC:
T. Kibédi *et al.*, Nucl. Instr. and Meth. A **589** (2008)

# Results

$$\Gamma_{\text{rad}} = 11.2(27) \cdot 10^{-3}\ \text{eV}$$

24.1 % uncertainty



# Summary

- Both pair transitions from the Hoyle state measured for the first time!
  $\Gamma_\pi(E0)$ and $\Gamma_\pi(E2)$ are 65 and 1100 times smaller than $\Gamma_\gamma(E2)$

- Large background around the 3.2 MeV *E*2
  Scattering or timing issues?

- The deduced $\Gamma_{rad}$ is ~3 times larger than previous values

# Outlook

- Improve the time resolution, hopefully reduce the background
- Simulations to investigate scattering and secondary radiation, improve baffle system
- Another experiment this fall

# Thanks!

<u>Australian National University</u>
T. Kibédi
M.W. Reed
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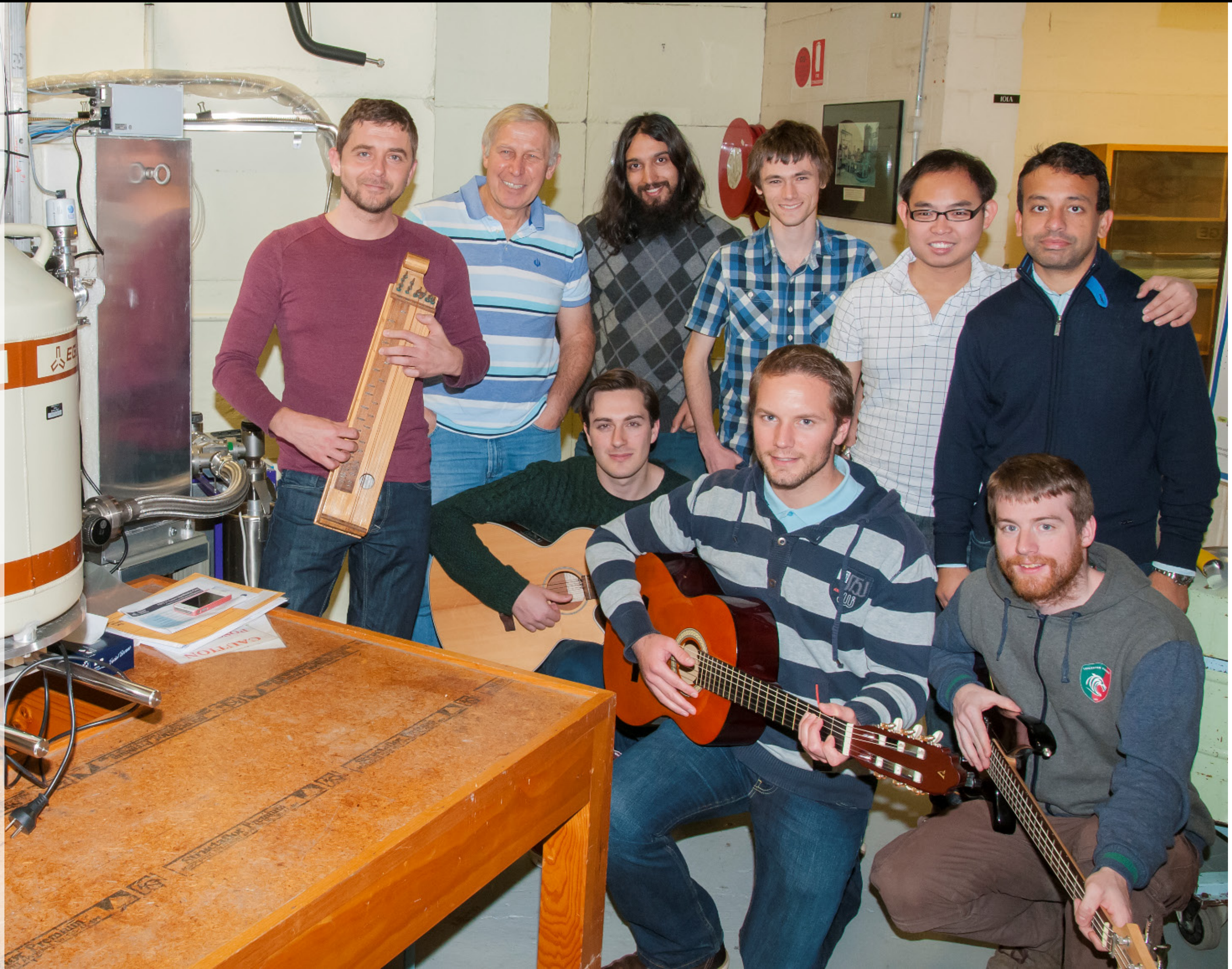
G. J. Lane
B.Q. Lee
A.J. Mitchell
T. Palazzo
T.G. Tornyi
M. de Vries

<u>TRIUMF</u>
L.J. Evitts
A.B. Garnsworthy
J. Smallcombe



# Extra slides