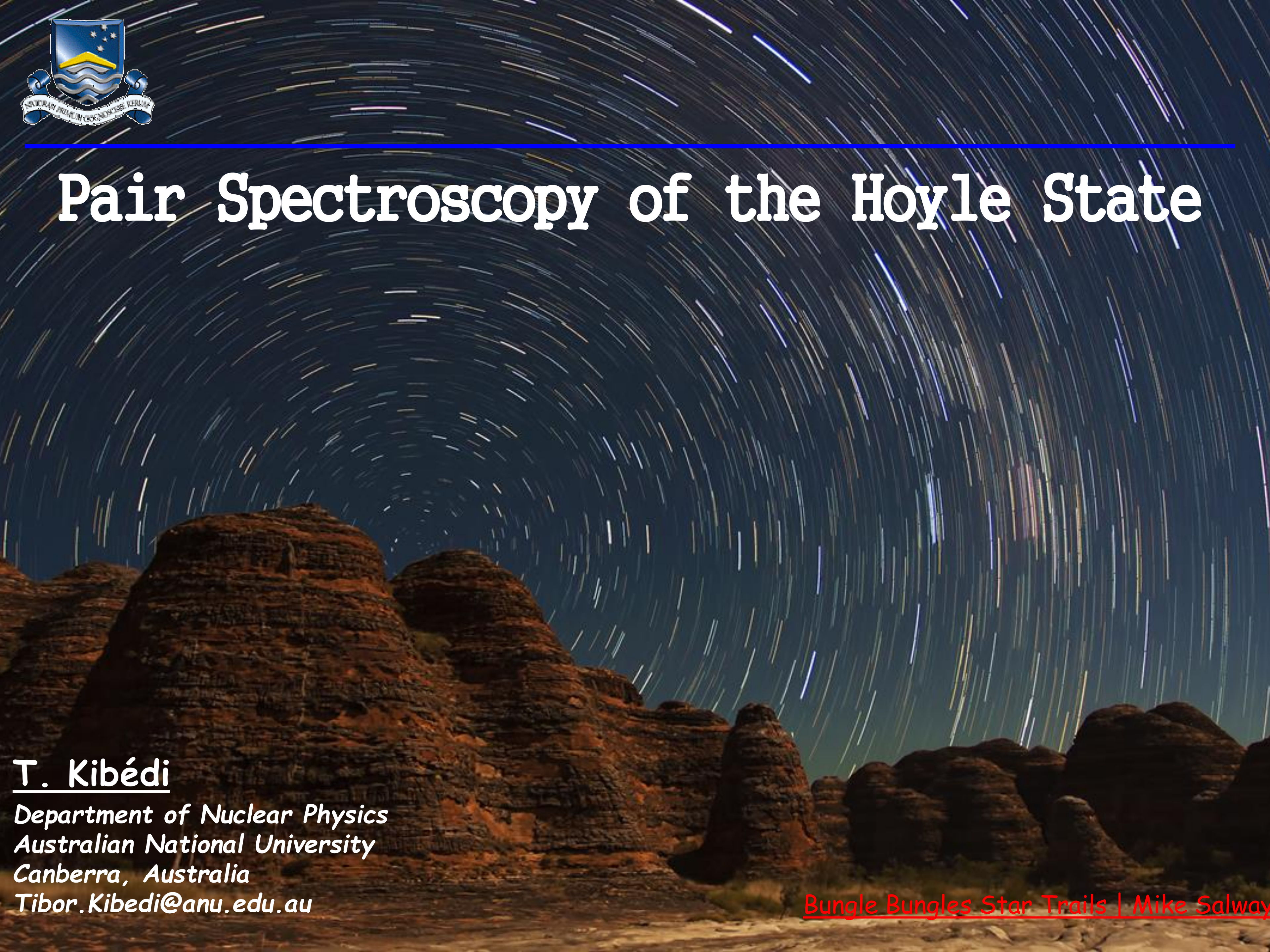
Pair Spectroscopy of the Hoyle State



T. Kibédi

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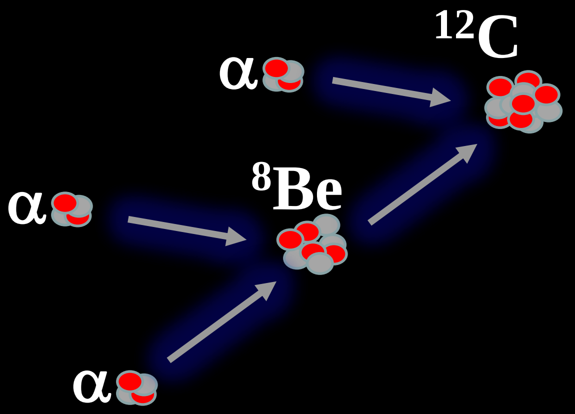
Bungle Bungles Star Trails | Mike Salway

The triple-α rate in stellar He burning

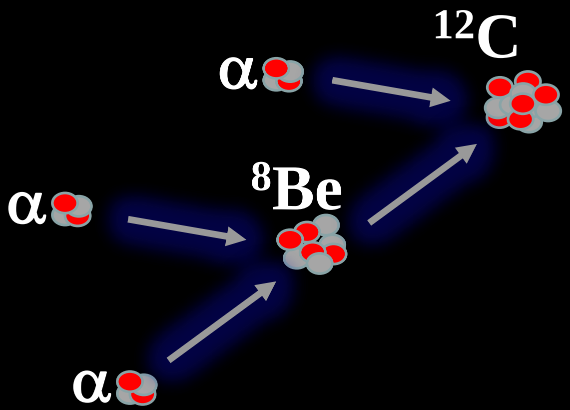


Hans A. Bethe (1906-2005)

1939: No stable A=5 to 8 elements

Triple-α process to bypass the gap; PR **55** (1939) 434

The triple-α rate in stellar He burning



Hans A. Bethe (1906-2005)

Edwin E. Salpeter (1924-2008)

1939: No stable *A*=5 to 8 elements

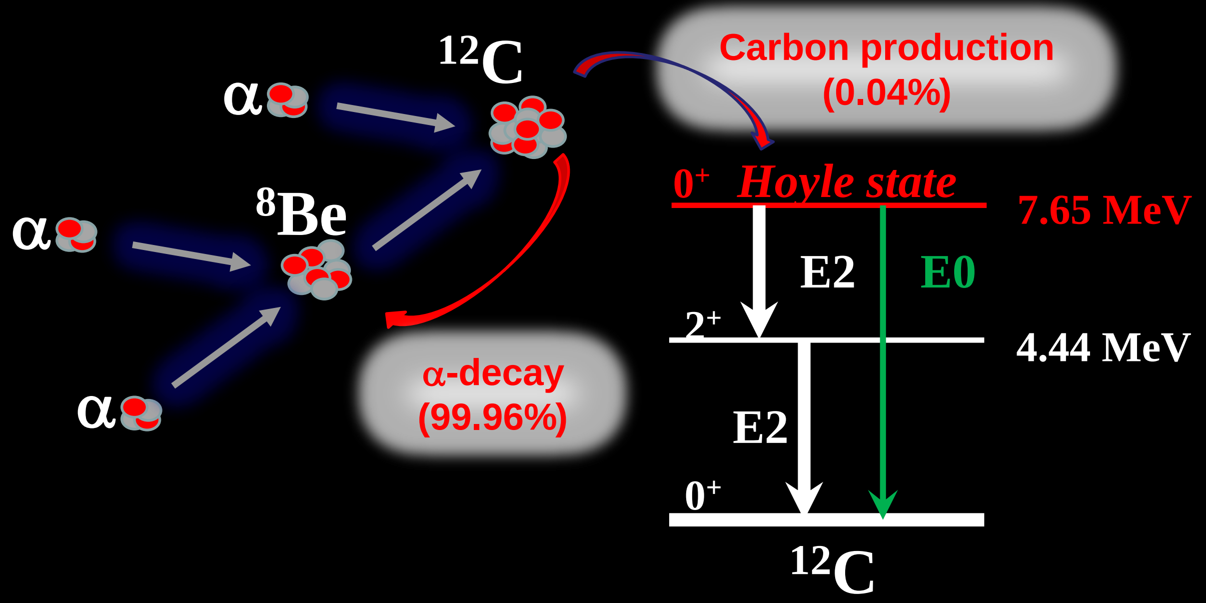
Triple-α process to bypass the gap; PR **55** (1939) 434

1952: Carbon production rate calculated; *APJ* **115** (1952) 326

$^{4}He + {}^{4}He + 95\ keV \rightarrow {}^{8}Be + \gamma$ (^{8}Be *g.s. resonance*)

$^{4}He + {}^{8}Be \rightarrow {}^{12}C + \gamma$

The triple-α rate in stellar He burning



Hans A. Bethe (1906-2005)

Edwin E. Salpeter (1924-2008)

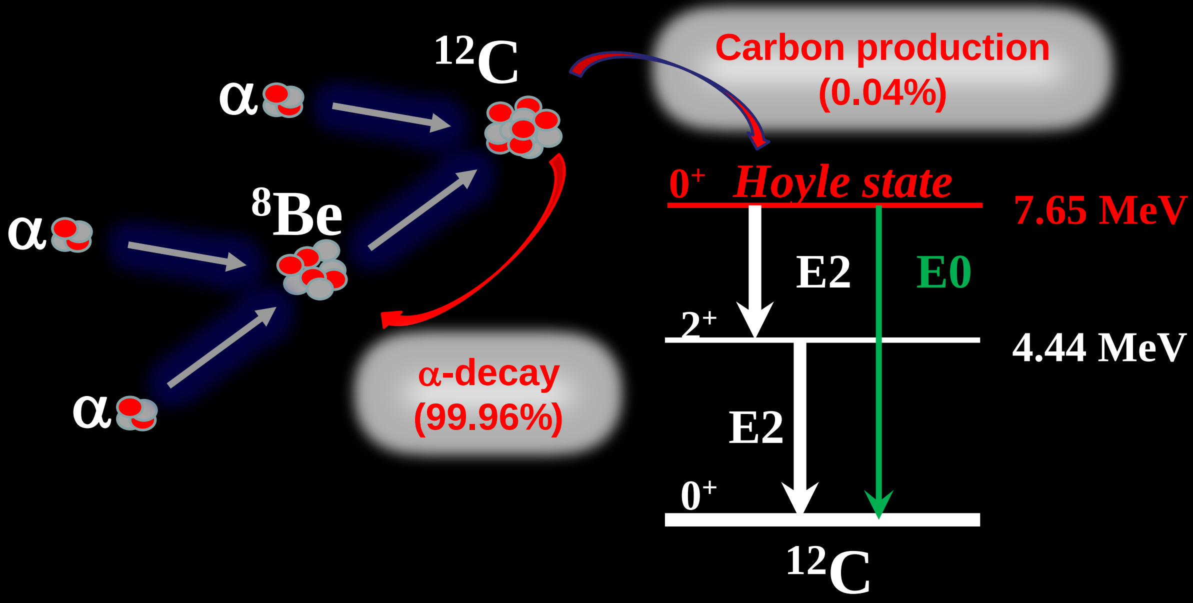
Sir Fred Hoyle (1915-2001)

1939: No stable A=5 to 8 elements
Triple-α process to bypass the gap; PR **55** (1939) 434

1952: Carbon production rate calculated; APJ **115** (1952) 326
^{4}He + ^{4}He + 95 keV → ^{8}Be + γ (^{8}Be g.s. resonance)
^{4}He + ^{8}Be → ^{12}C + γ

1953: ^{4}He + ^{8}Be + 310 keV→ ^{12}C + γ (resonance at 7.68 MeV)
PR 92 (1953) 1095

The triple-α rate in stellar He burning

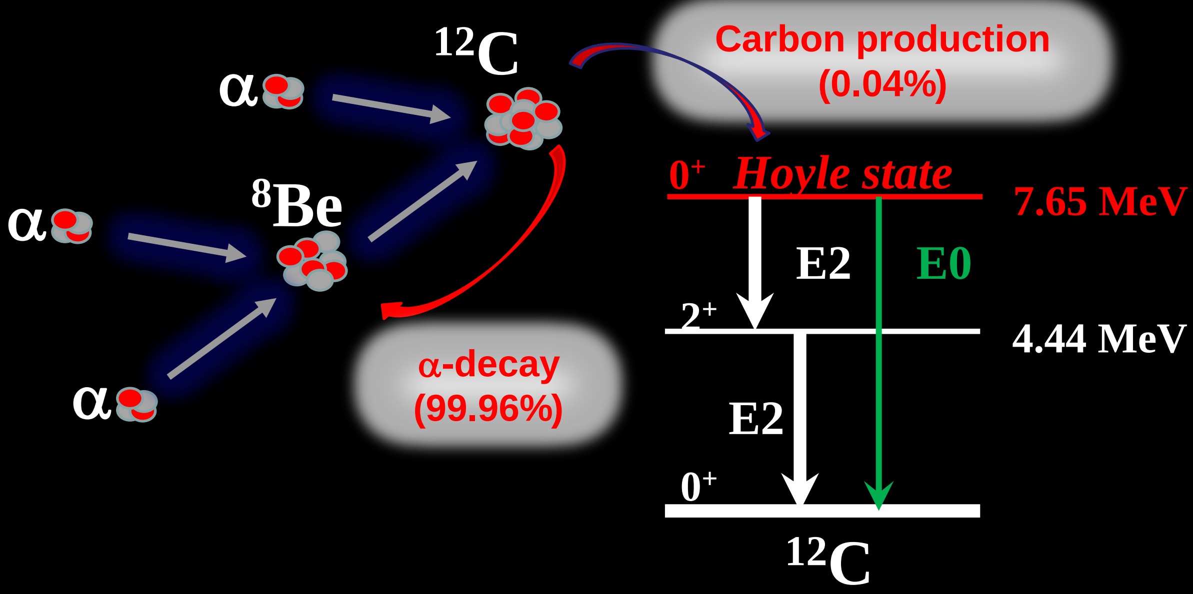


Edwin E. Salpeter (1924-2008)

Sir Fred Hoyle (1915-2001)

The Crafoord Prize 1997 in Astronomy: *"for their pioneering contributions to the study of nuclear processes in stars and stellar evolution"*

The triple-α rate in stellar He burning



Hans A. Bethe (1906-2005)

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Sir Fred Hoyle (1915-2001)

Noel Dunbar (1922-2011)

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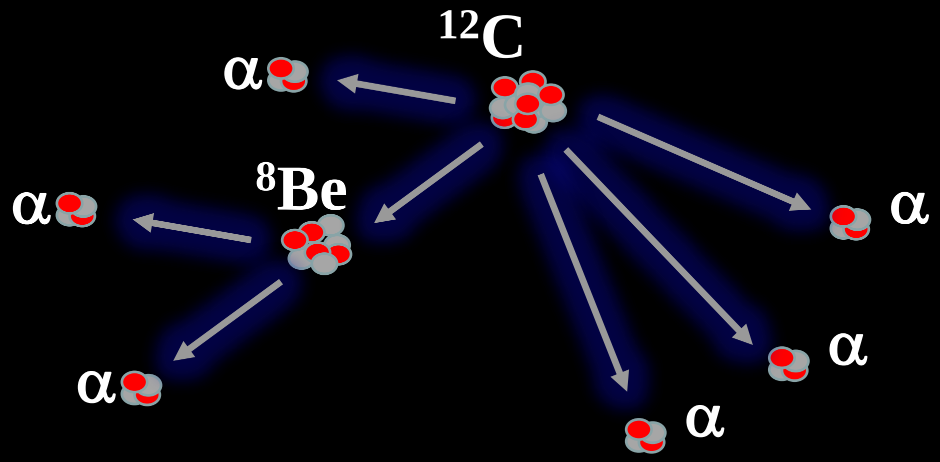
^{4}He + ^{8}Be $\rightarrow$ ^{12}C + γ

1953: ^{4}He + ^{8}Be + 310 keV$\rightarrow$ ^{12}C + γ (resonance at 7.68 MeV)
PR 92 (1953) 1095

1953: The 7.68 MeV state identified from ^{14}N(d,α)^{12}C
PR 92 (1953) 649

New experimental results for the triple-α rate



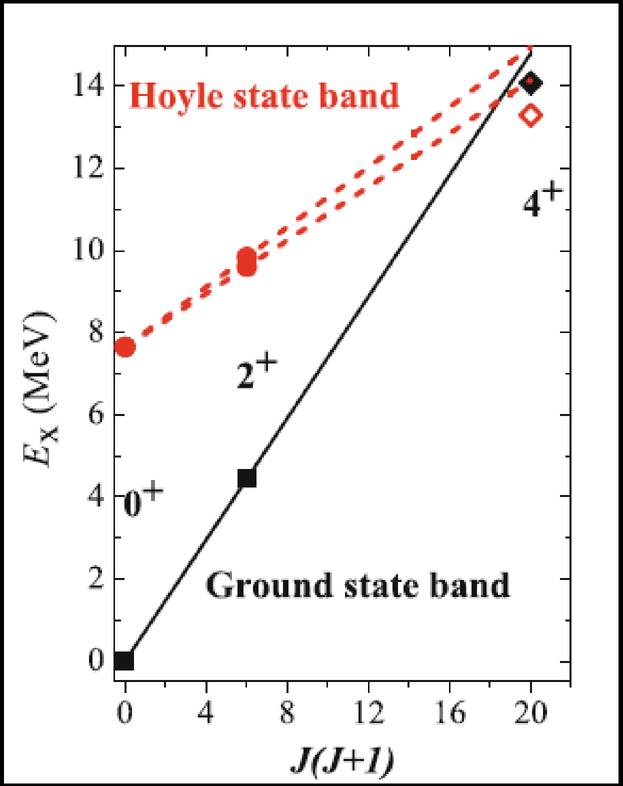
- Observation of a 16% alpha-decay branch bypassing the ground state of ^{8}Be ($T_{1/2}=10^{-16}$ s; Raduta et al. PRL B705 (2011) 65)

- New upper limit: 0.1% (Kiresebom et al. PRL 108 (2012) 202501; Manfredi et al. PRC (2012) 037603)

New experimental results for the triple-α rate

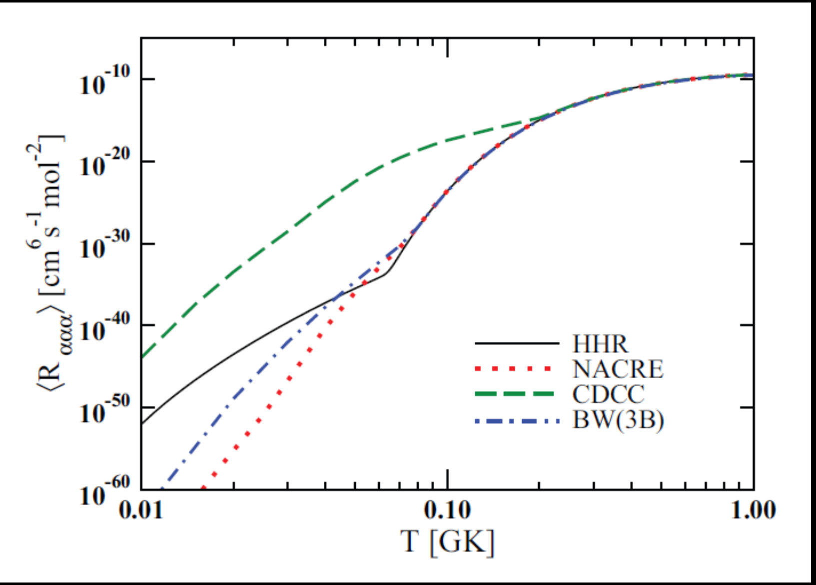
- 2^+ excitation of the Hoyle state: E=9.75(10) MeV, Γ=750(150) keV (Freer et al. PRC86 (2012) 034320)

- R(2+)=3.07(13) fm, similar to the Hoyle state (Ogloblin et al. Eur. Phys. J. A49 (2013) 46)



New theoretical results for the triple-α rate

Controversy over calculated reaction rates at low (10^7 K) temperatures



HHR - Hyperspherical Harmonic R-matrix method
NACRE - Nuclear Astrophysics Compilation of REaction rates
CDCC – Continuum Discretized Coupled Channel
BW(3B) - three-body Breit Wigner

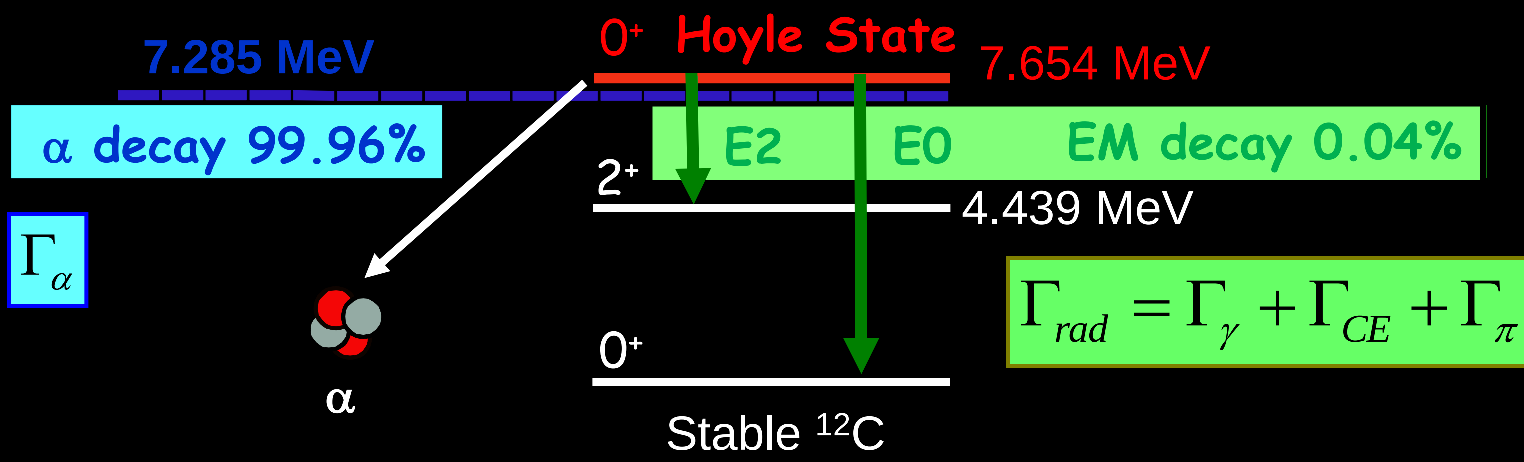
- 20 order of magnitude difference to NACRE compilation (Ogata et al. Prog. Theor. Phys. 122 (2009) 1055)
- New calculated rates are only few order of magnitude larger (Garido et al. Eur. Phys. J. A47 (2011) 102; Nguyen et al. PRL 109 (2012) 141101, PRC 87 (2013) 054615)

New theoretical results for the triple-α rate

- New ab initio calculations using lattice simulations effective field theory reproduce excitation energy (Epelbaum et al. PRL 106 (2011) 192501; PRL 109 (2012) 252501)
- 3-alpha microscopic cluster model (Vasilevsky et al., PRC 85 (2012) 034318)

		E, MeV		Γ, keV	
		Exp	Theor	Exp	Theor
0^+	Bound	-7.2746	−11.372		
	Resonance	0.3796	0.684	0.0085(10)	2.78
2^+	Bound	-2.8357	−8.931		
	Resonance	3.89	2.775	430(80)	9.95

Calculation of the triple-α



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

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

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

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

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

Triple-α rate – how well it is known now

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

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

"traditional approach"

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"traditional approach"

	Value	Unc. [%]	
$Q_{3\alpha}$	379.35(20) keV	0.05	
Γ_{rad}/Γ	$4.13(11)\times10^{-4}$	2.7	8
$\Gamma_{\pi}(E0)/\Gamma$	$6.75(60)\times10^{-6}$	8.9	4
$\Gamma_{\pi}(E0)$	$57(5)\times10^{-6}$ eV	8.8	8

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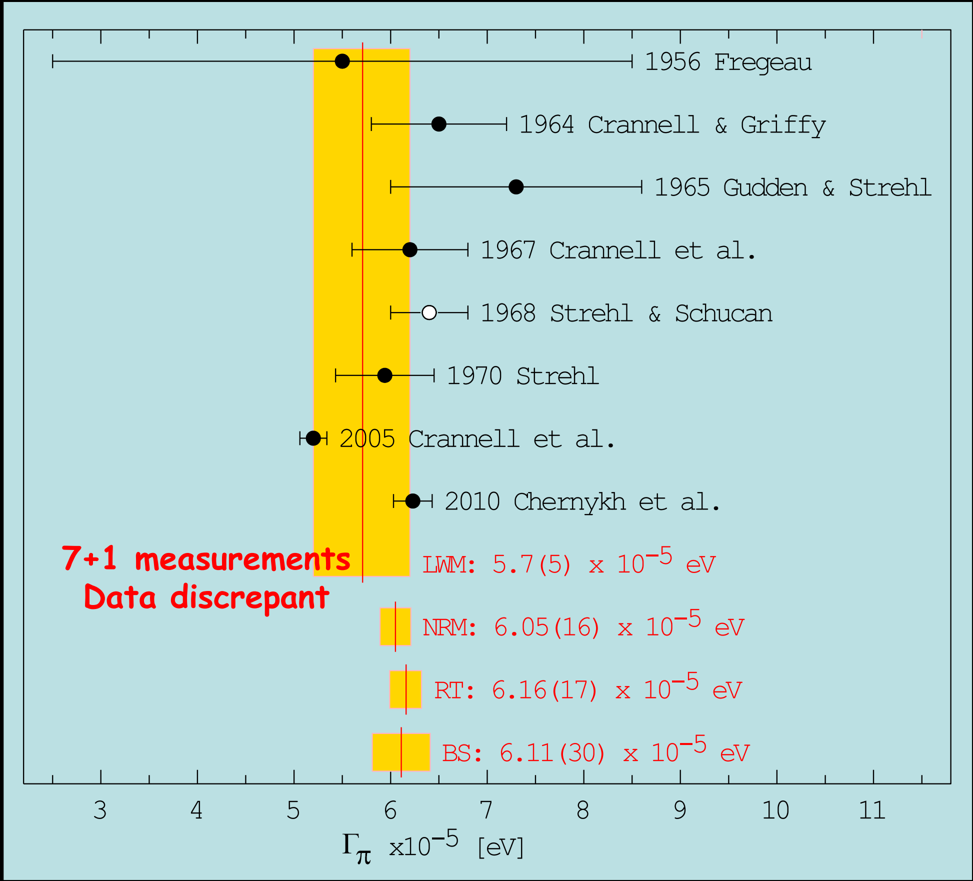
2005 Crannell at al: $\Gamma_{\pi}(E0)$=52.0(14) μeV; q=0.27-3.04 fm^{-1}; Extensive data from Darmstadt, Bates-CUA, NIKHEF-K & HEPL

2010 Chernykh et al: $\Gamma_{\pi}(E0)$=62.3(20) μeV; q=0.21-0.67 fm^{-1}; Darmstadt S-DALINAC



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

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Largest known E0 strength!

in "Wilkinson units"
$S_{wi,u.} = |M_{exp}|^2 / |M_{s.p.}|^2 = 2.3(2)$ s.p.u.

Triple-α rate – how well it is known now

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

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

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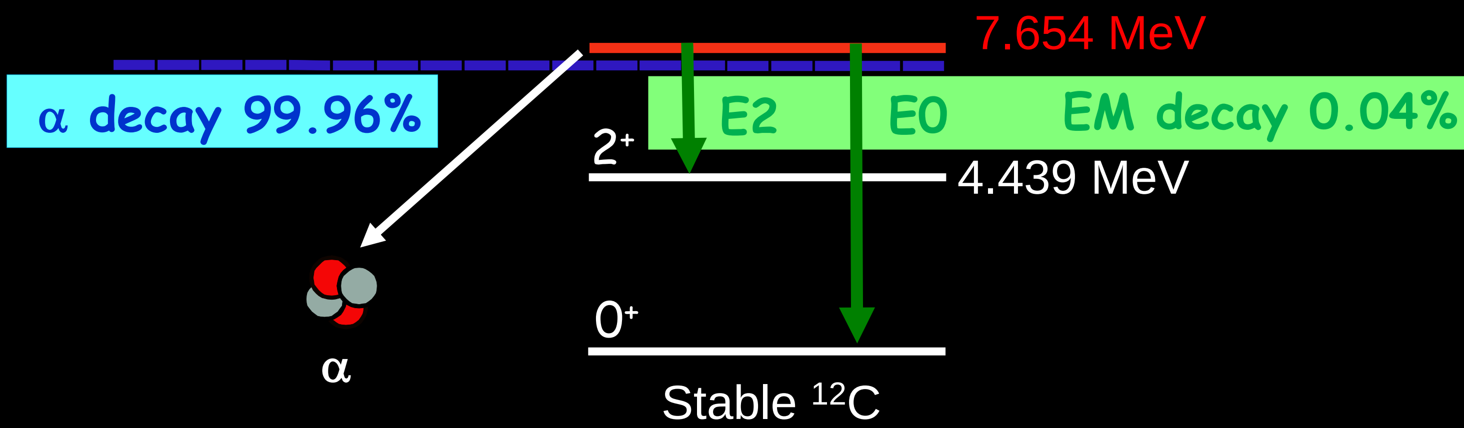
$\Gamma_{\pi}(E0)$	$57(5)\times10^{-6}$ eV	8.8	8
Γ_{rad}	$3.49(45)\times10^{-3}$ eV	12.9	

Need 5% accuracy

New approach to determine Γ_{rad}



Observe both EM transitions in the same experiment to determine relative intensities

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

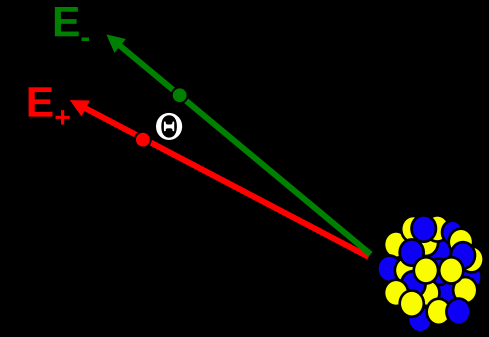
~98.5% ~1.5% ~0.088% ~9×10^{-6}% ~3×10^{-5}%

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

Measuring electron-positron pairs

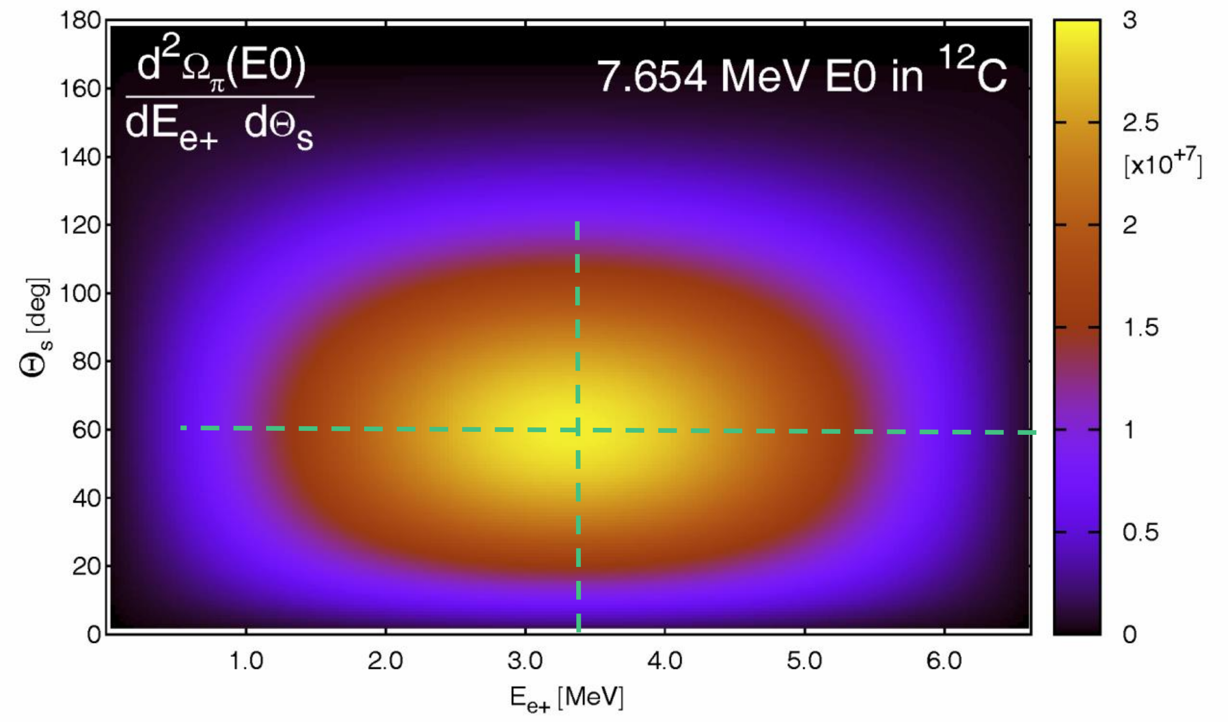
- e^- - e^+ particles share the available kinetic energy:

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



Need to observe both particles

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



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

$E_+ \approx E_-$

$\theta_{sep} \approx 60°$

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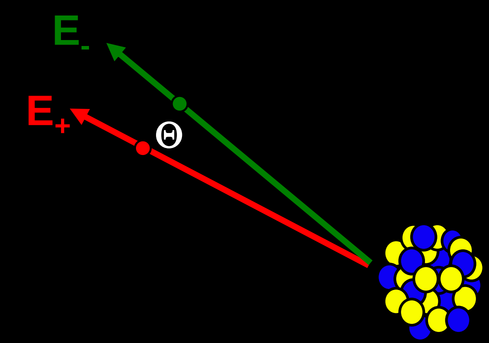

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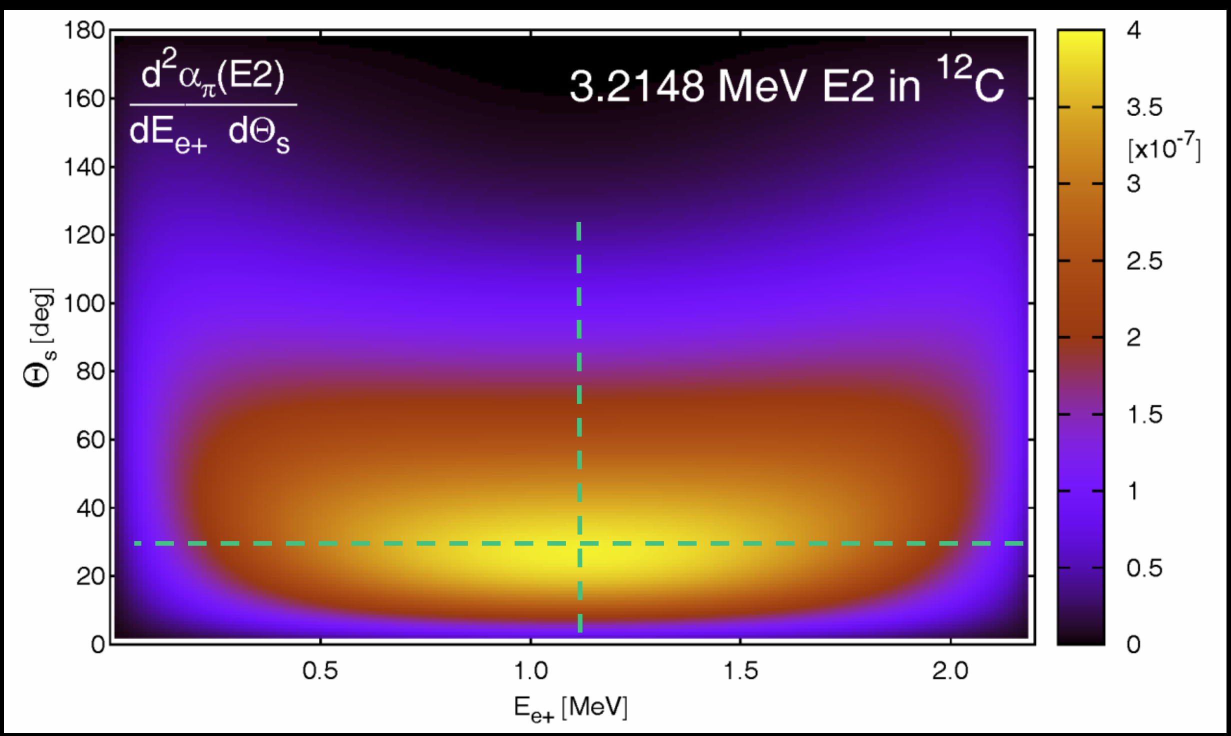


$\alpha_\pi(E2) = \Gamma_\pi(E2)/\Gamma_\gamma(E2)$

$E_+ \approx E_-$

$\theta_{sep} \approx 30°$

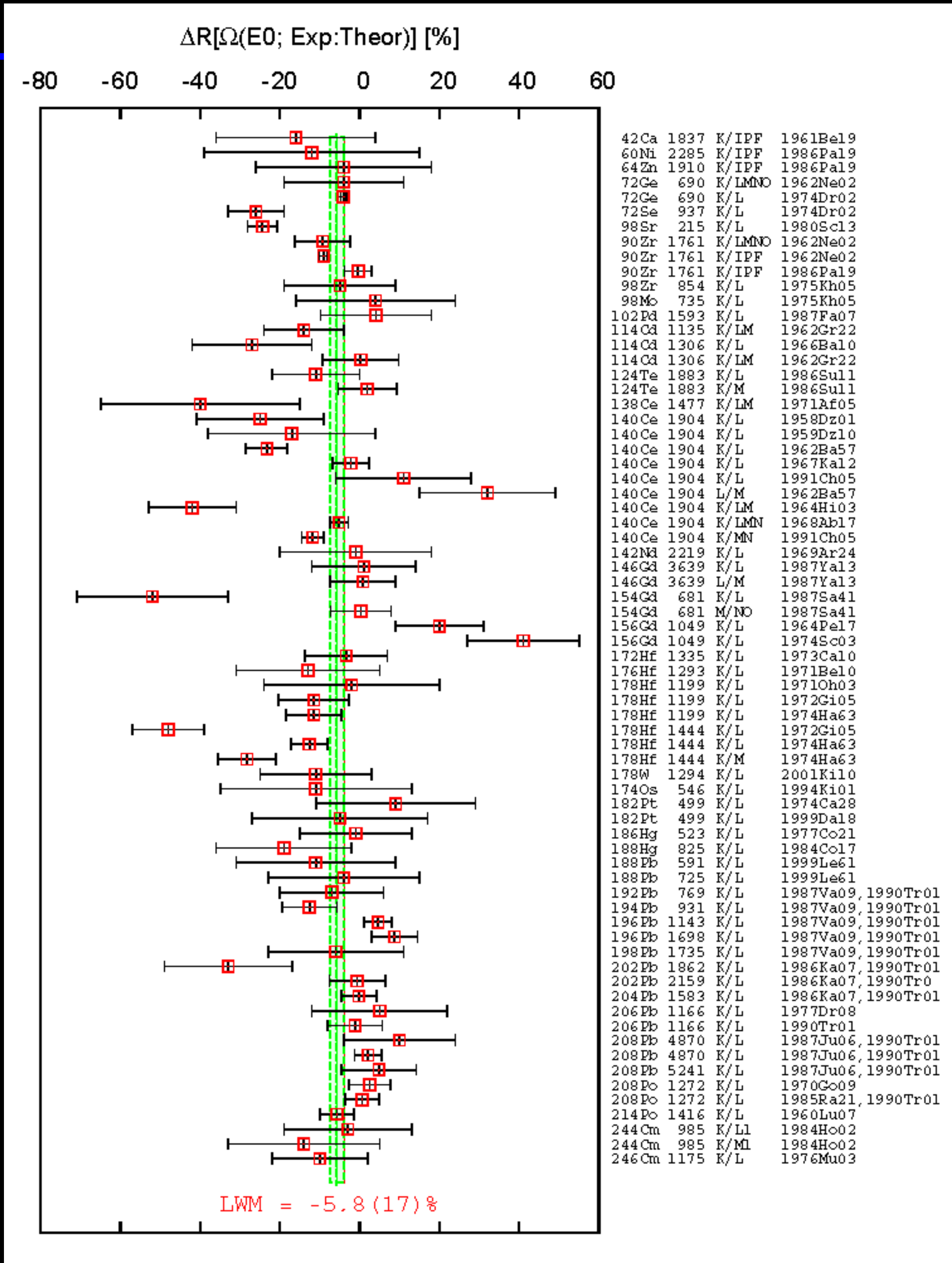
$W_\pi(E0) \sim \rho^2(E0) \times \Omega_\pi(E0)$

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

ICC

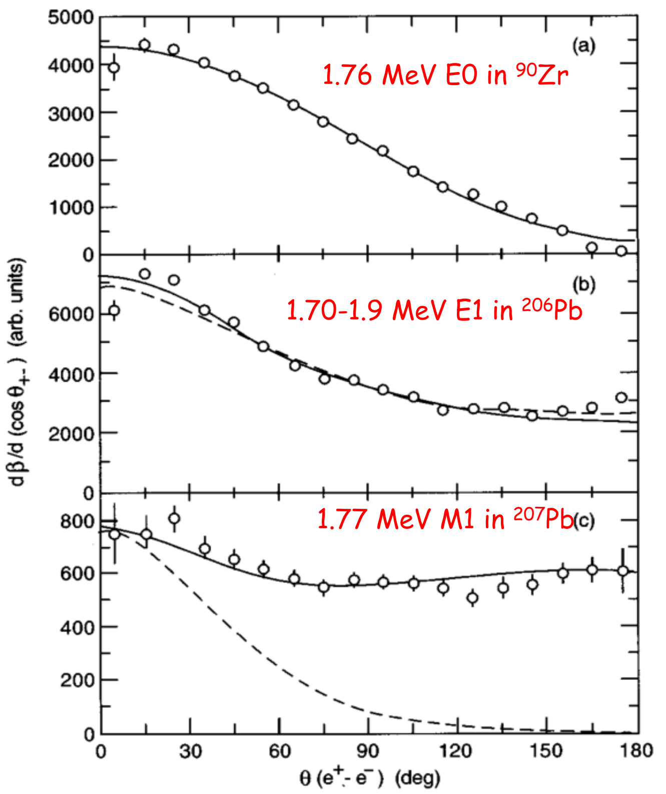
Ω(E0) experiment vs. theory

- Ω_π**(E0)** - not accessible from experiment
  W_π**(E0) ~** ρ^2**(E0) ×** Ω_π**(E0)**
- Ω_K**(E0) /** Ω_π**(E0)** is known for 5 cases only



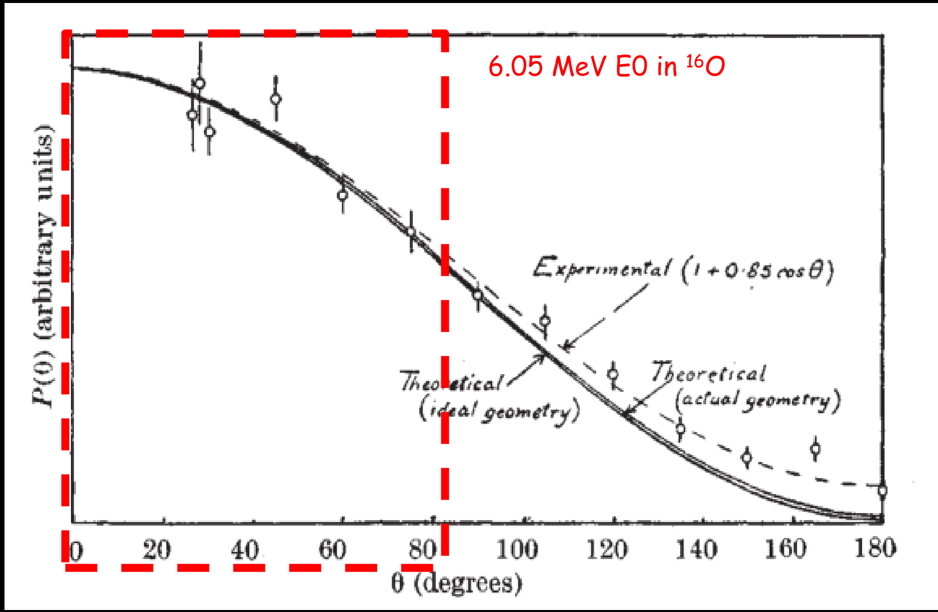
Ω(E0) experiment vs. theory

Angular correlation data for Ω_π**(E0)** is rare



A.H. Wuosmaa et al. (APEX ANL)
PRC **57** (1998) R2794

SOLID LINE: Ch. Hoffmann et al.
PRC 53 (1996) 2313
DASHED LINE: Born Approximation



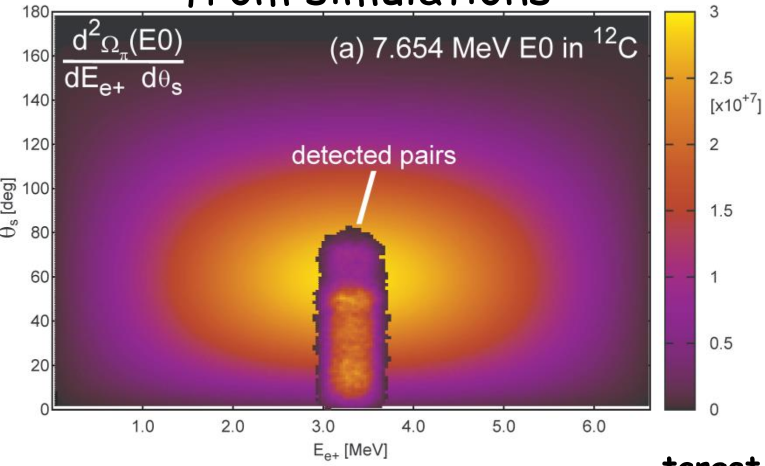
S. Devons and G.R. Lindsey
Nature (London) **164** (1949) 539

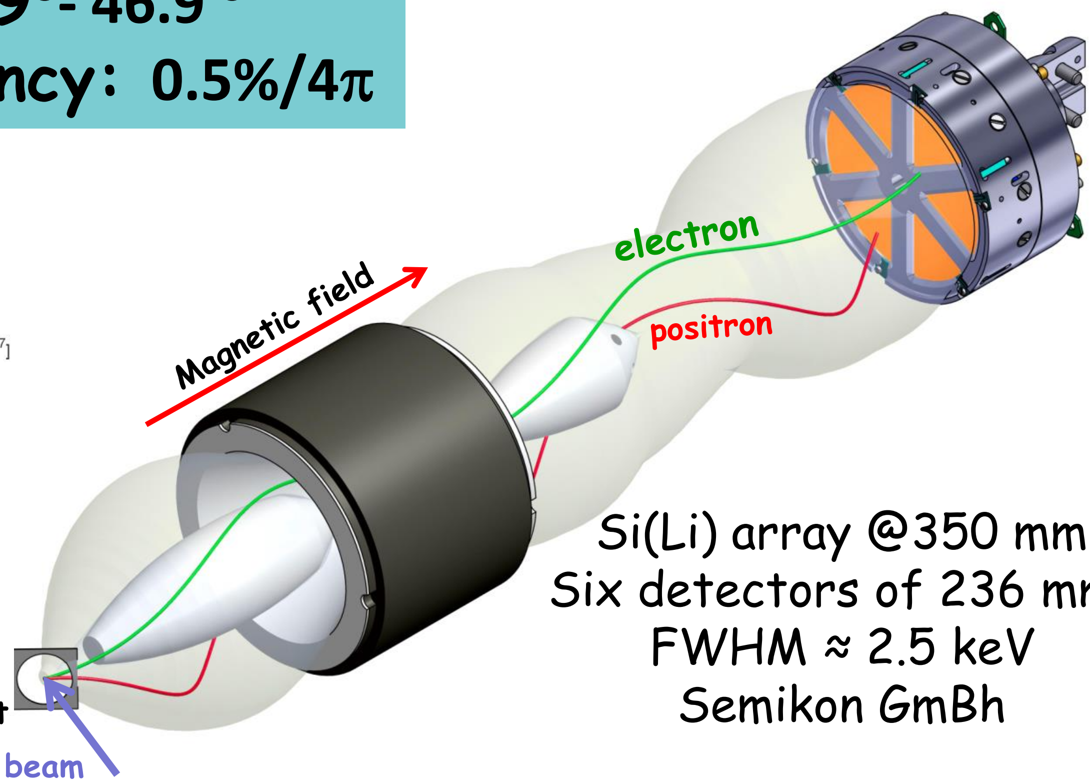
Born approximation for low Z and Θ_s<80° is sufficient

New pair spectrometer
Absorber system & detector

Acceptance angles: 15.9º- 46.9 º
Absolute singles efficiency: 0.5%/4π

Spectrometer response from simulations

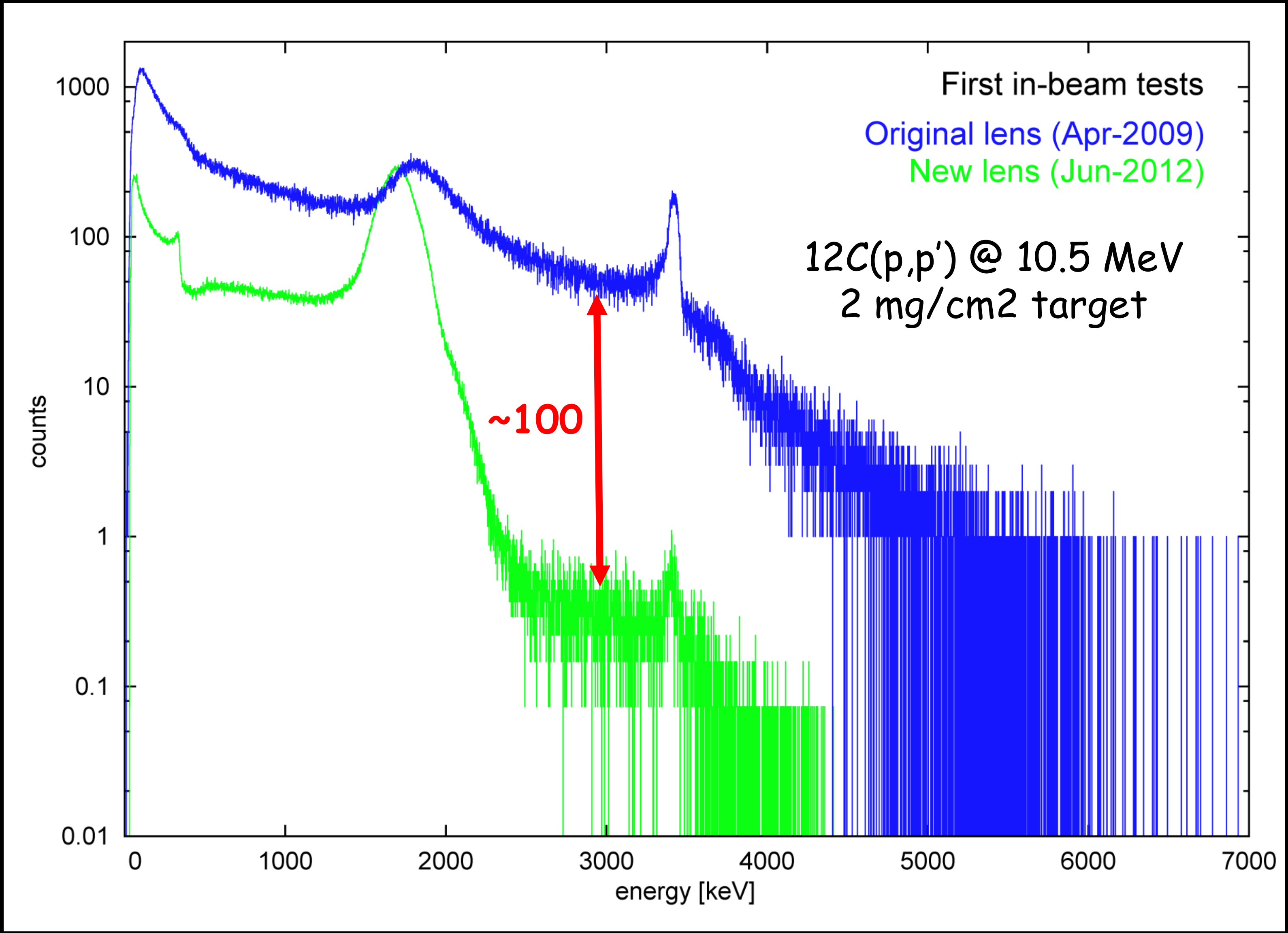




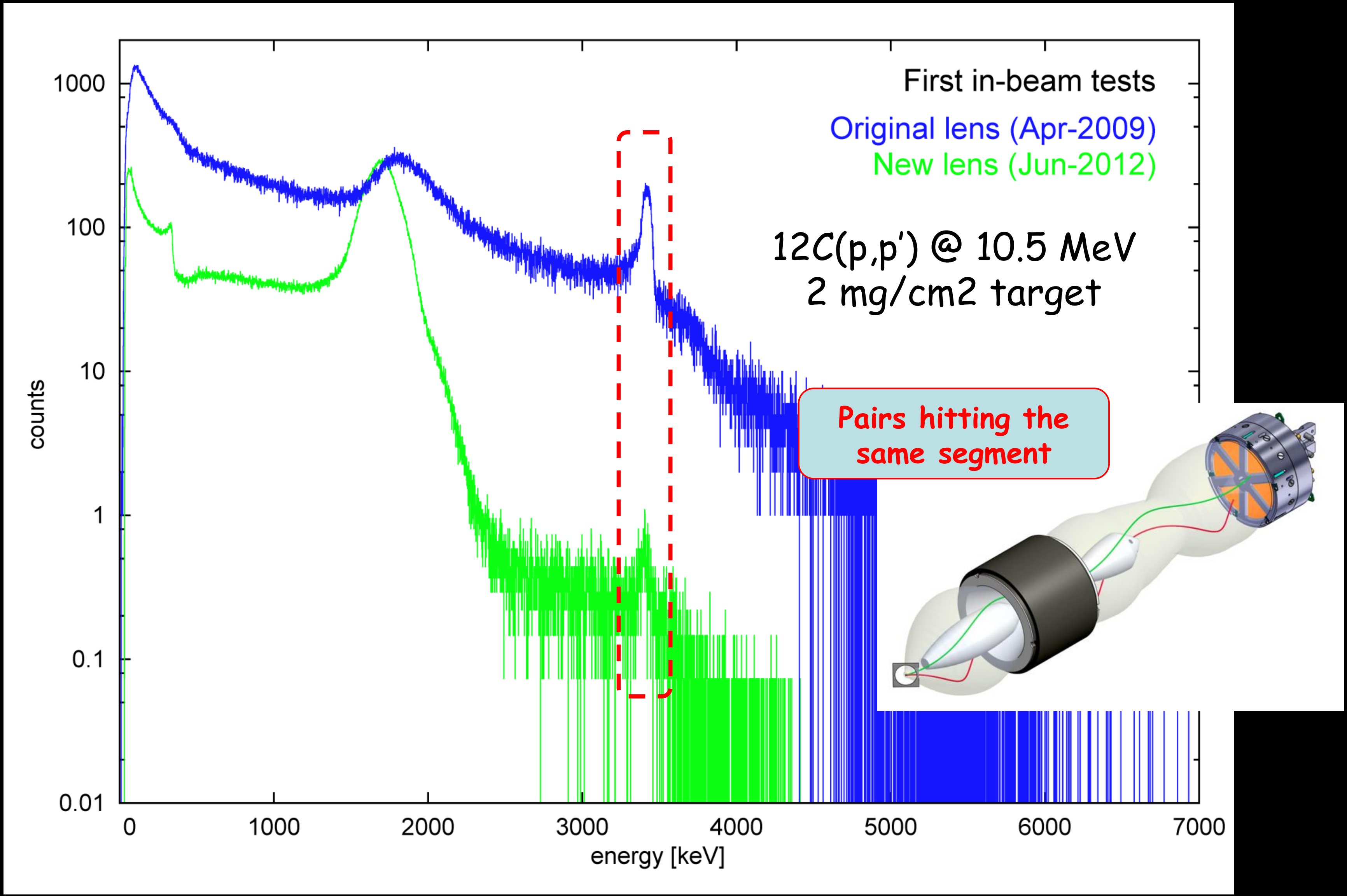
Si(Li) array @350 mm
Six detectors of 236 mm^2
FWHM ≈ 2.5 keV
Semikon GmbH

Absorbers made from HeavyMet
(density 18 gr/cm^3)
1 mm thick low Z skin (Torr Seal®)

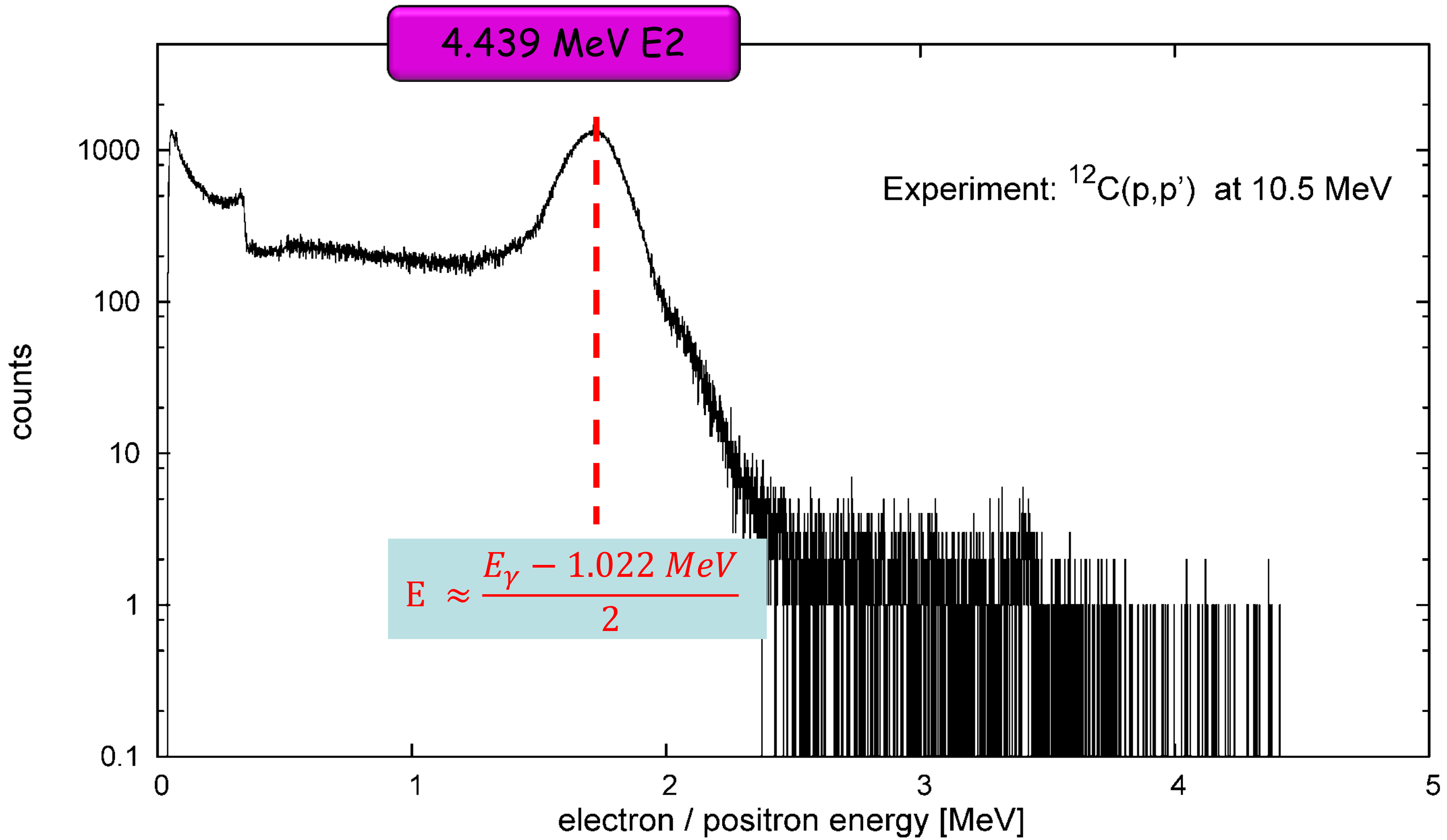
Old/New Absorber system
Singles data



Old/New Absorber system
Singles data



New Absorber system
Electrons & Positrons in coincidence



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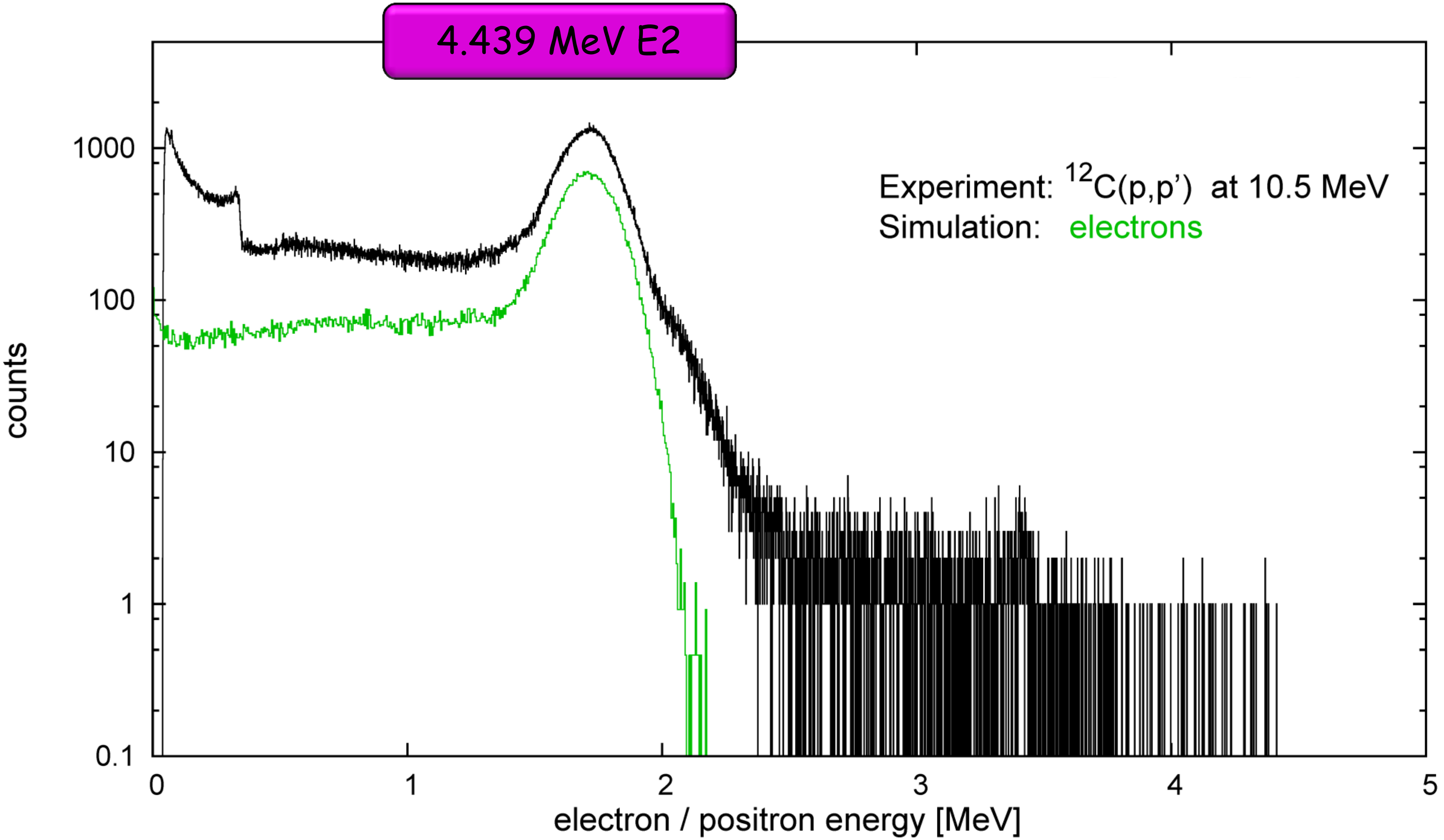

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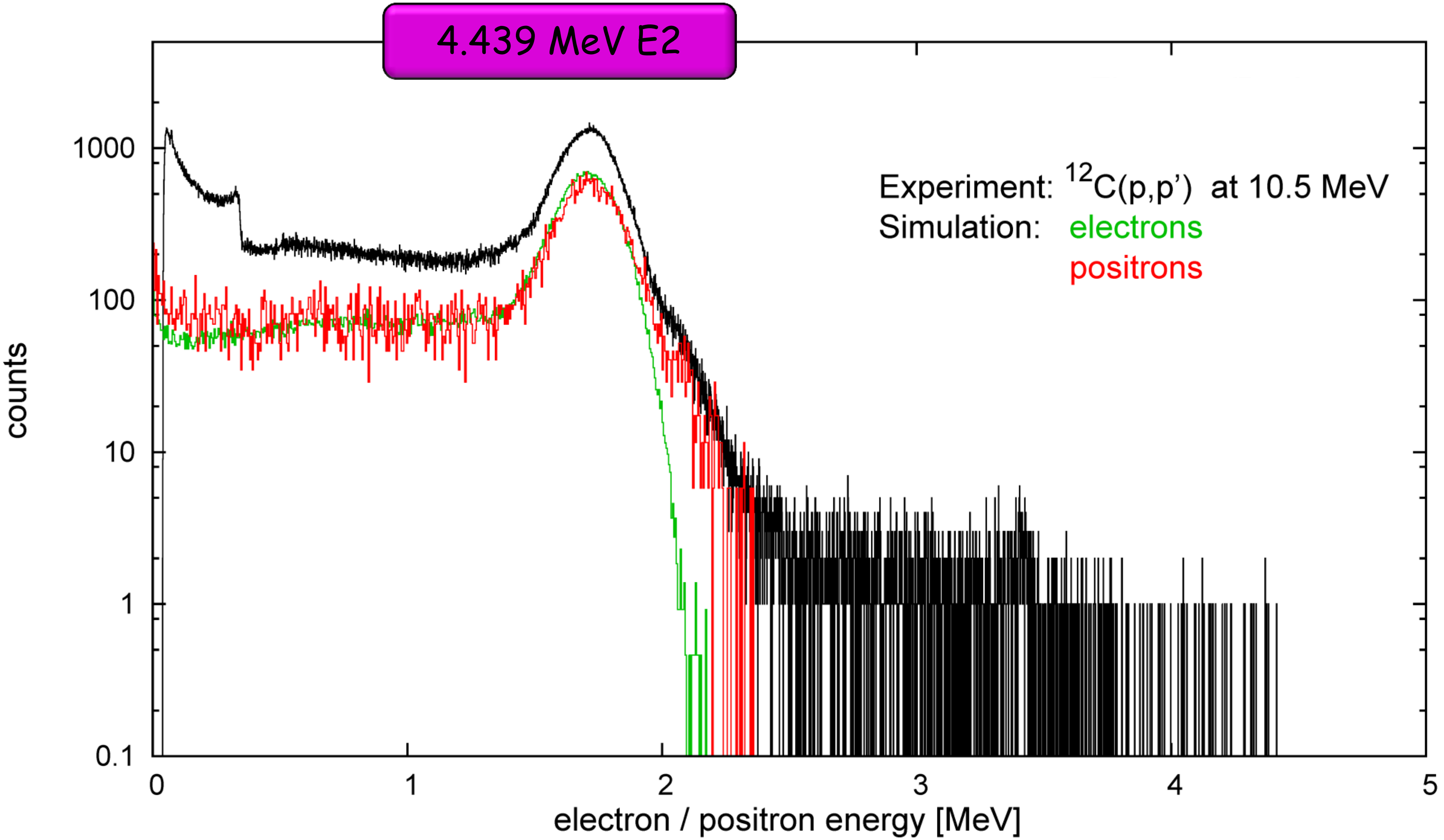

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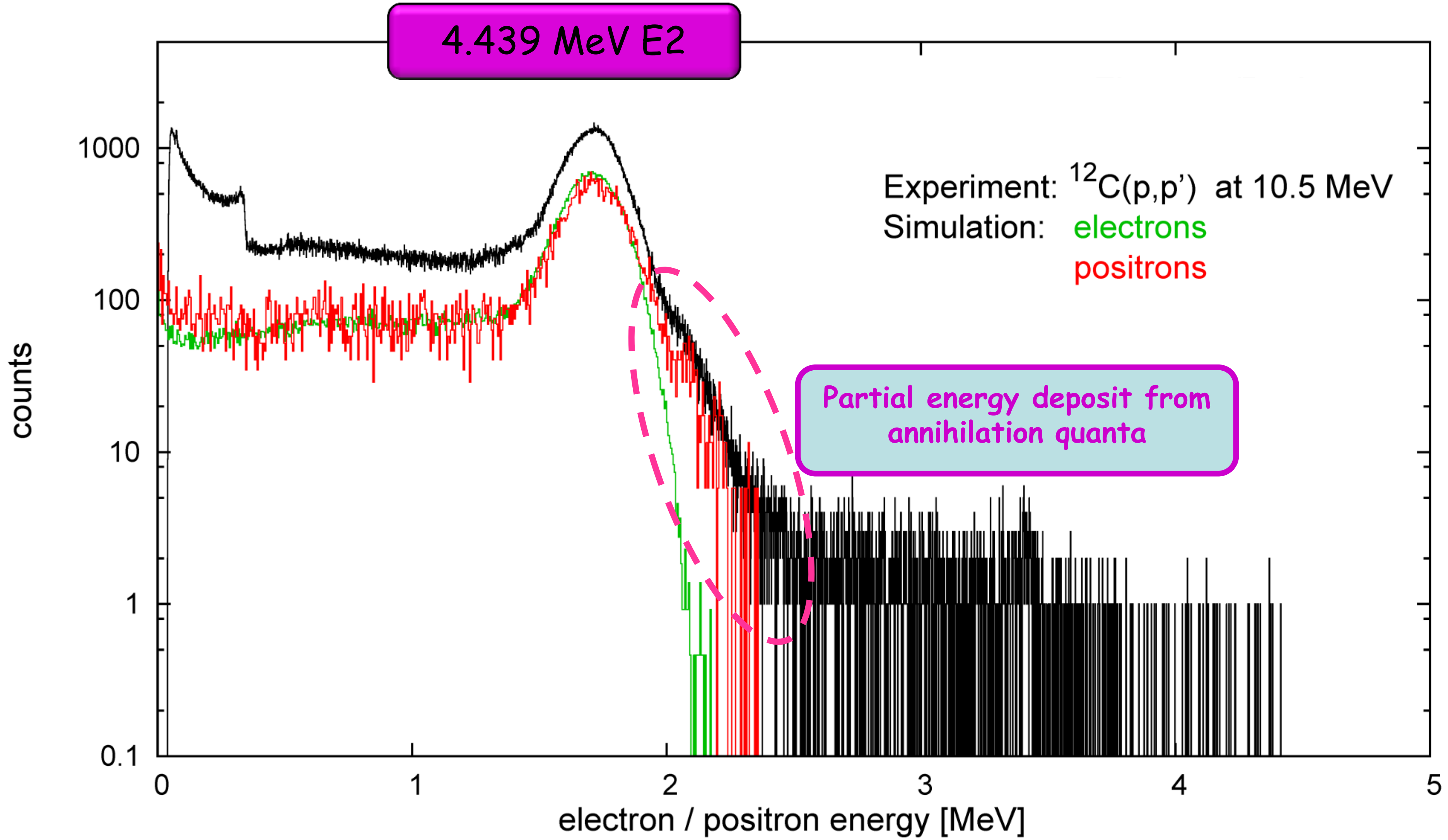

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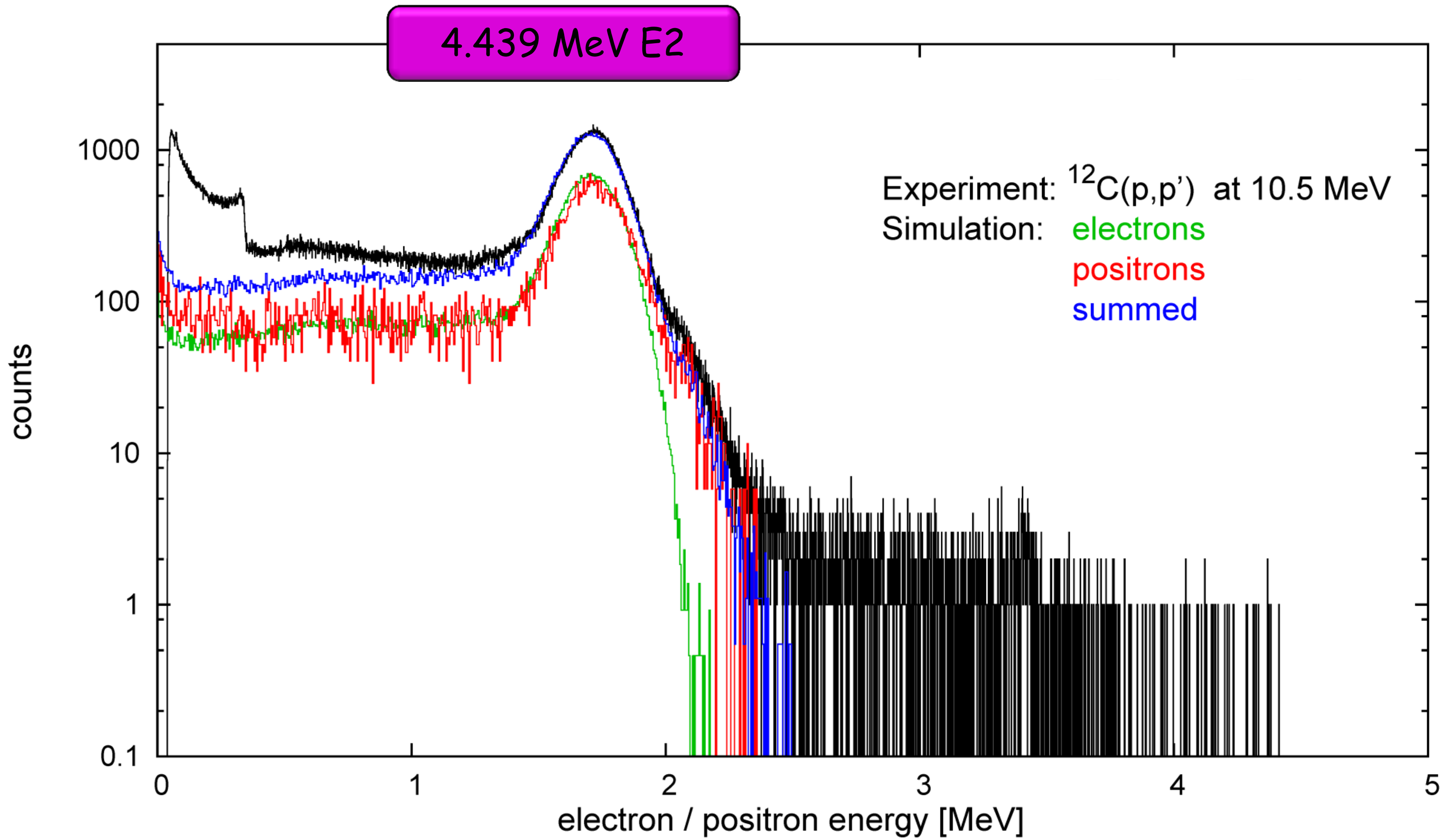

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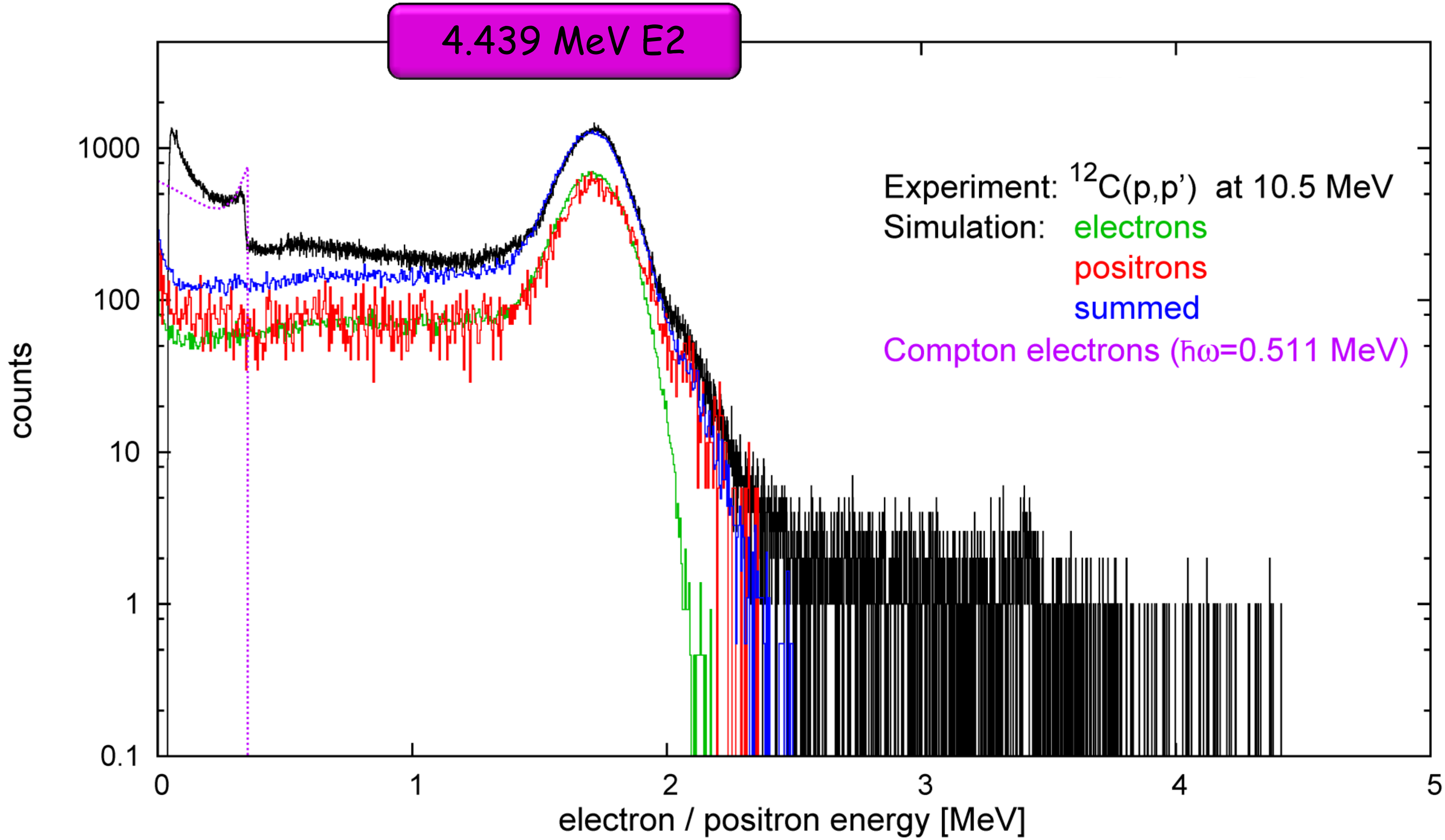
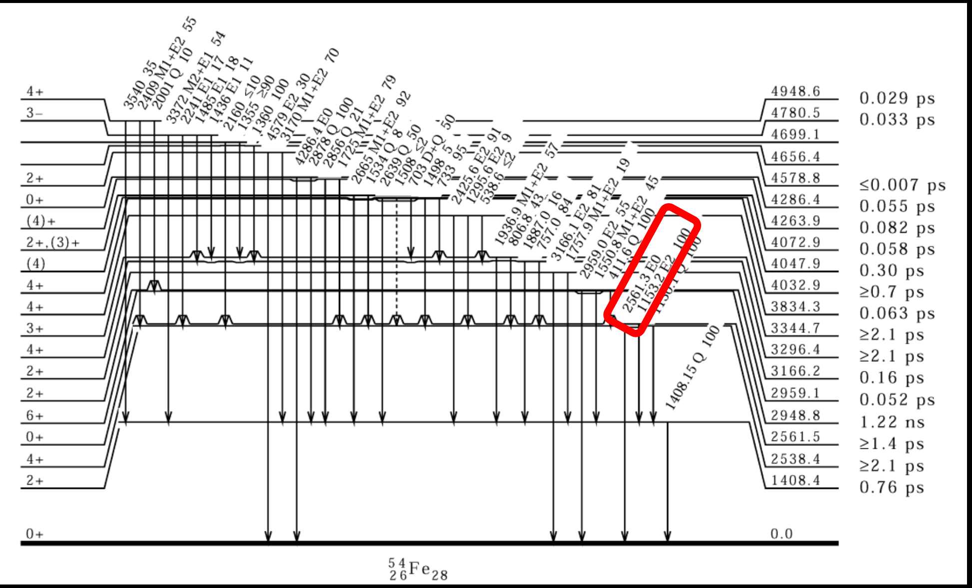
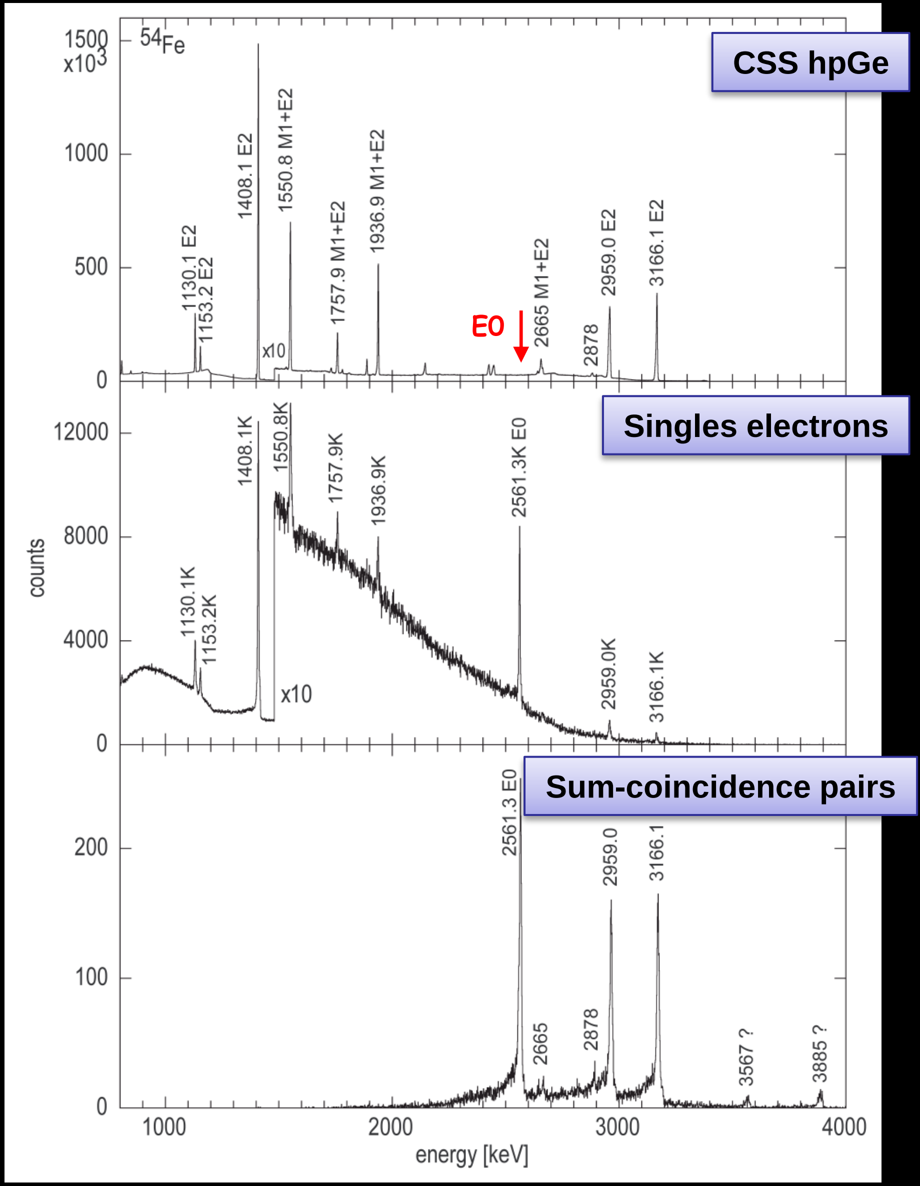


^{54}Fe(p,p'g) @ 6.9 MeV





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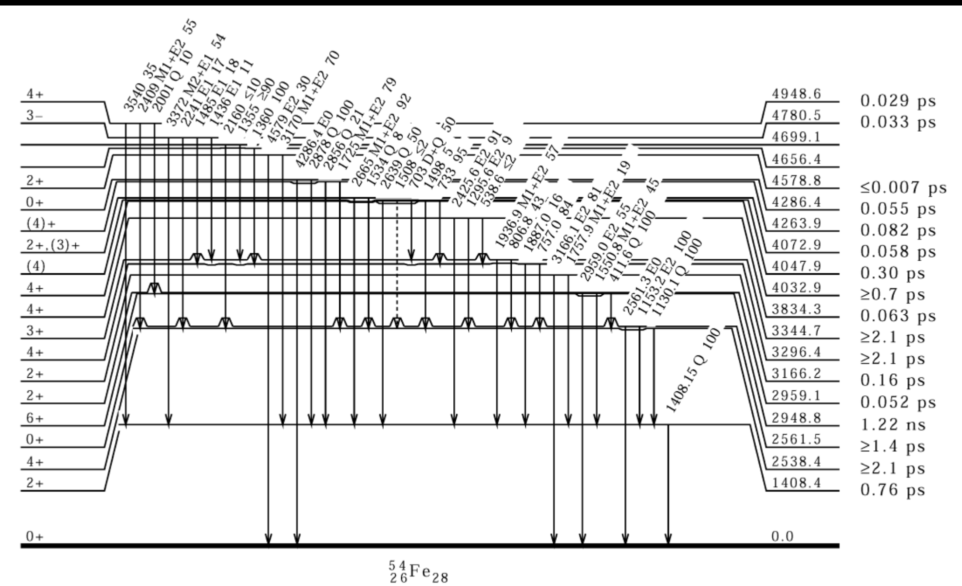
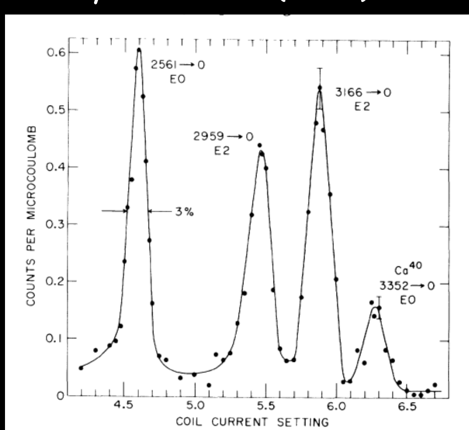
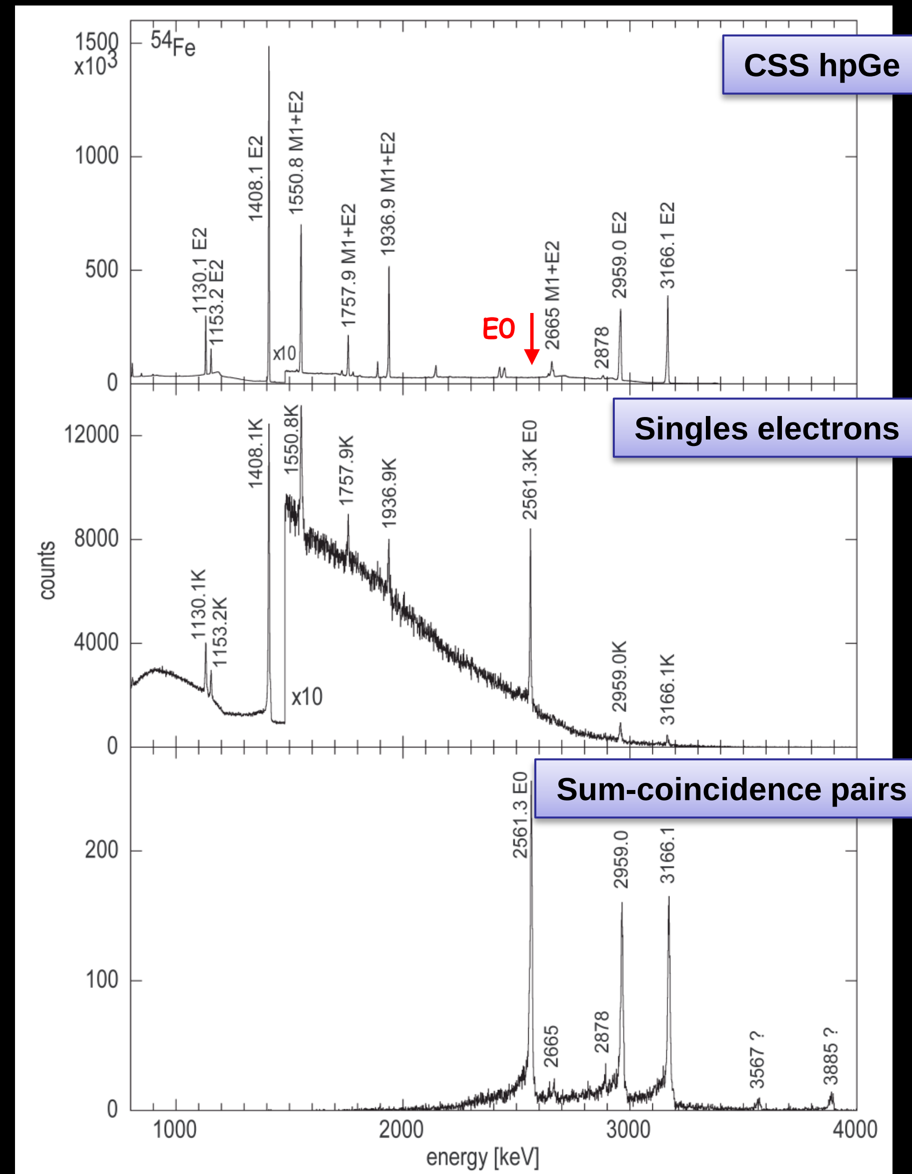


E.K. Warburton and D.E. Alburger, Phys. Rev. **C 6** (1972) 1224





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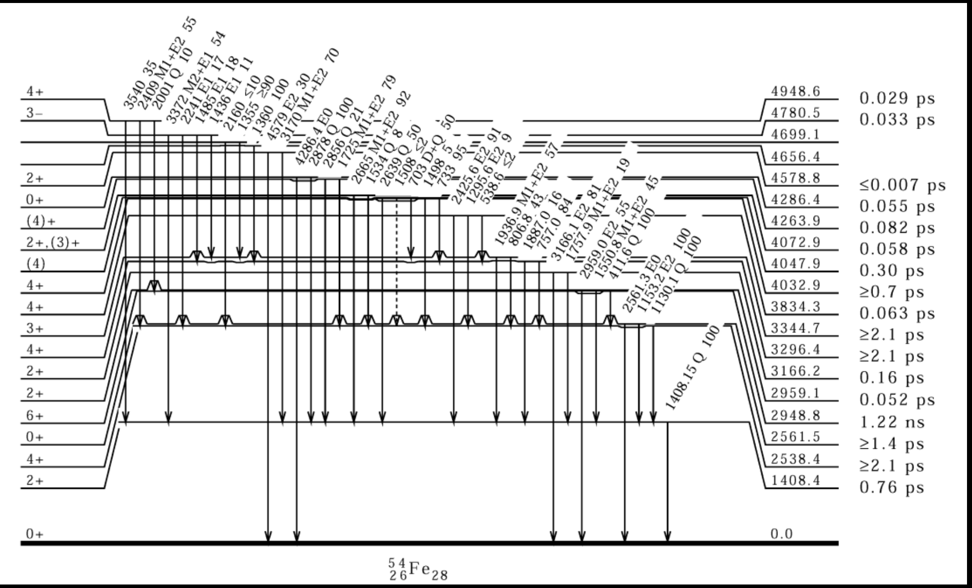
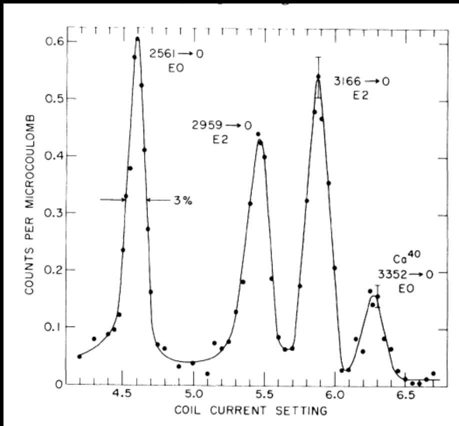
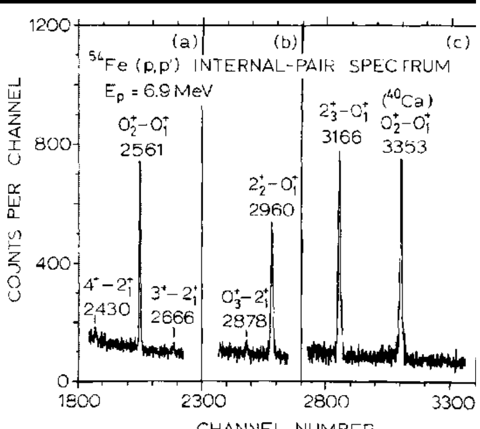
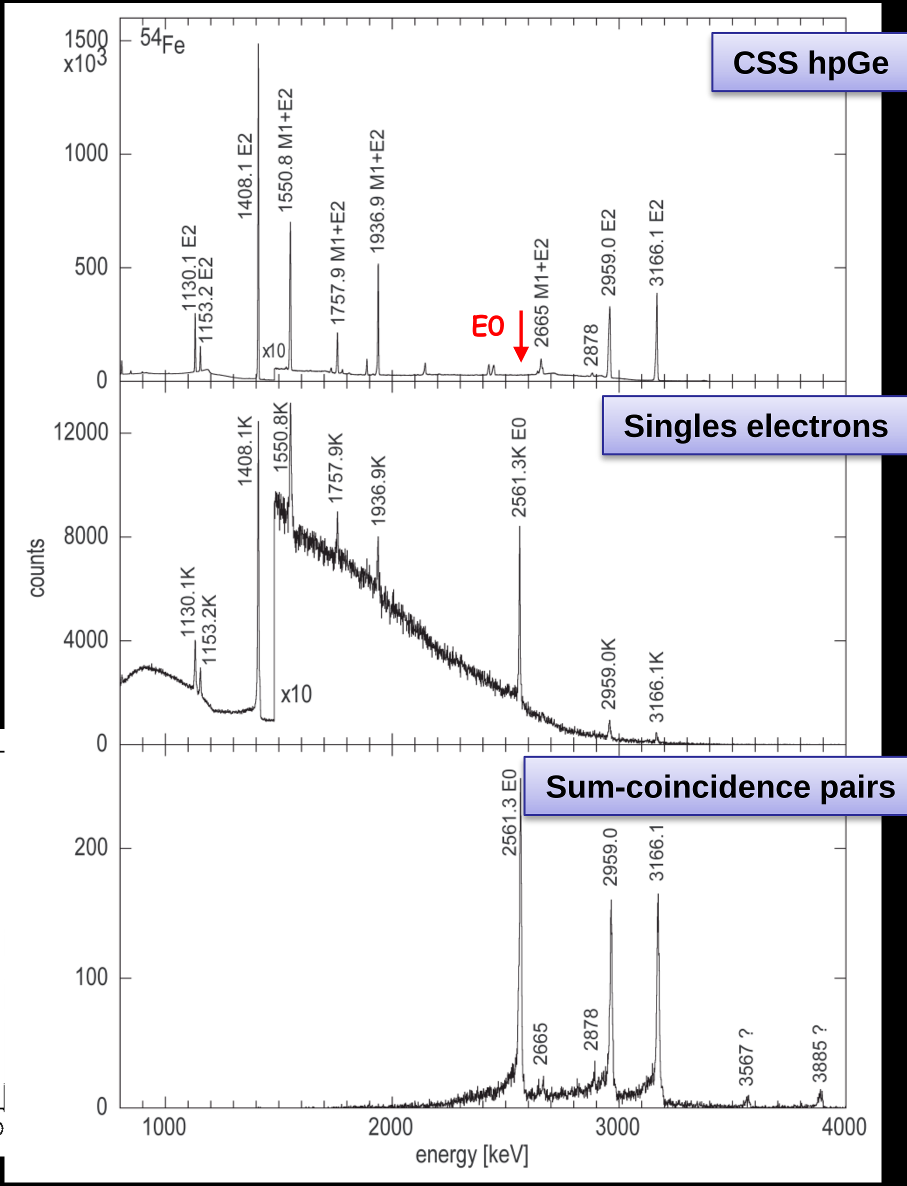


E.K. Warburton and D.E. Alburger, Phys. Rev. **C 6** (1972) 1224

A. Passoja, Z.Phys. **A325** (1981) 299



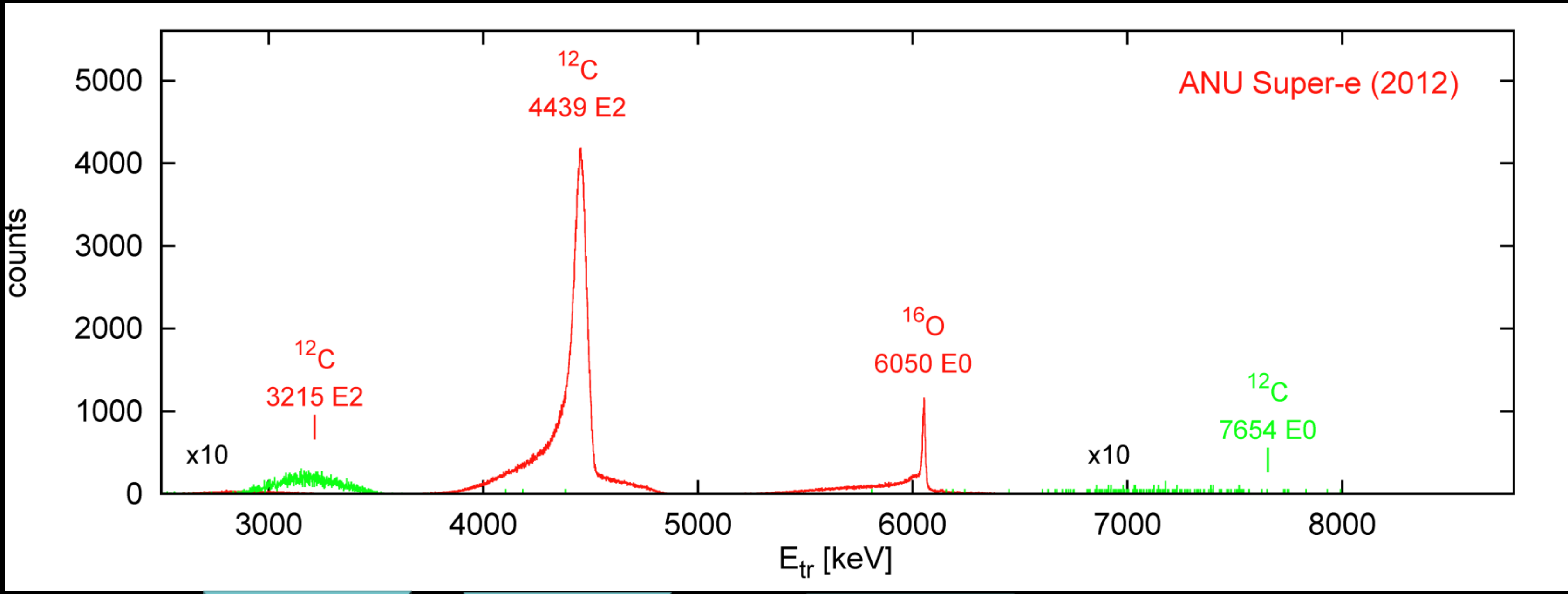




$^{12}C(p,p`)^{12}C^*$ pair measurements

(Jun-2012)

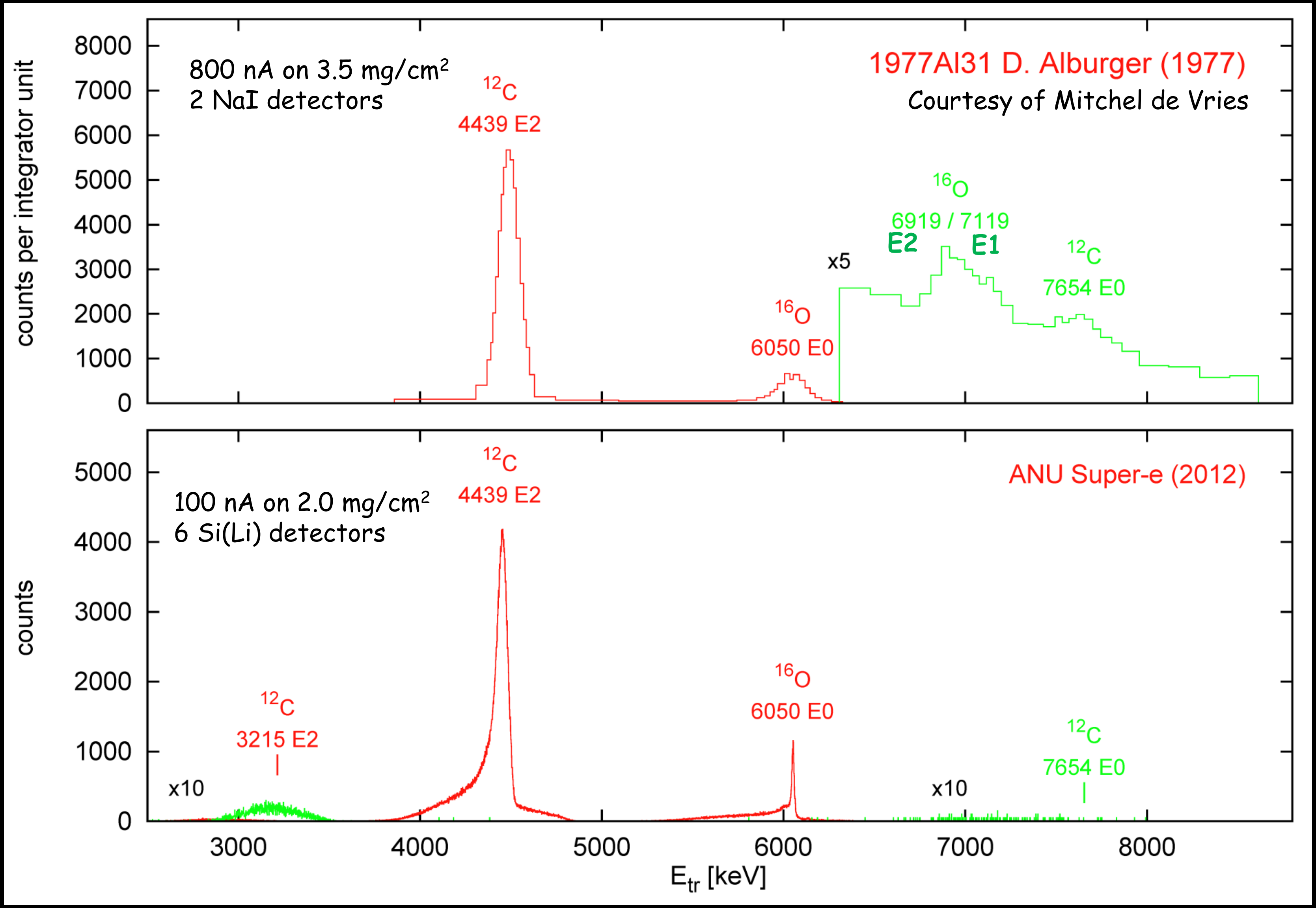
- 55 h beam time with 100 nA on a 2 mg/cm^2 target
- "old" Honey detector (1997), 4.2 mm thick, reduced efficiency, continuous gain shifts
- TDC gate of +/- 6 ns wide!



4.803 A | 6.807 A | 9.396 A | 12.450 A

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

(Jun-2012)



Conclusion and outlook

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- New pair spectrometer based on six Si(Li) detectors combined with a magnetic lens transporter
- High energy photon background drastically reduced
- High coincidence efficiency, optimized for E0 and E2: 1:1 vs. 500:1 (Alburger 1977)
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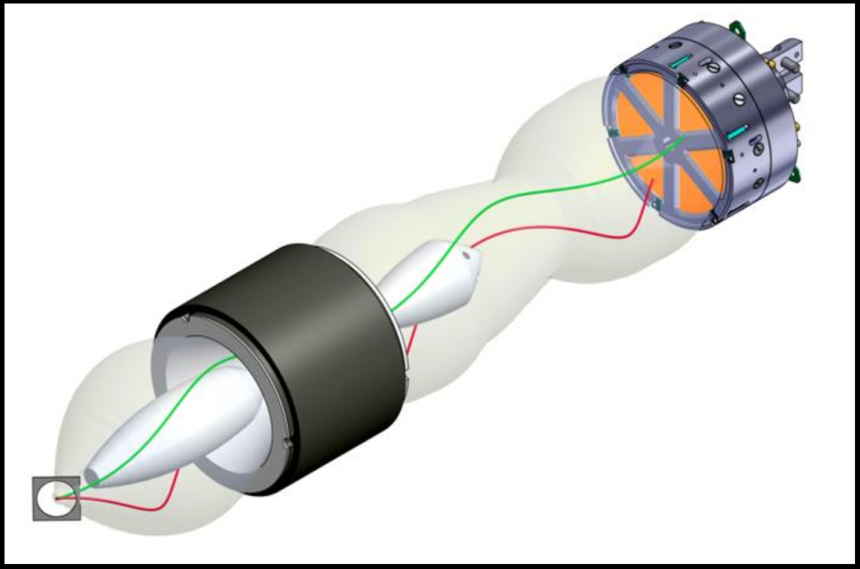

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Improvements

- 9 mm thick Si(Li) array: factor 2 higher efficiency for 7.7 MeV pairs
- 500 nA proton beam intensity: factor 5 higher yield

Challenges

- Evaluation of pair conversion efficiency accurately for up to 8 MeV transition energy

  MC simulations, radiactive source (^{207}Bi, Fermi-Kurie plot, known E0 transitions (E_γ > 4 MeV; ^{10}Be : 6.179 MeV; ^{14}C: 6.588 MeV; ^{16}O : 6.049 MeV; ^{20}Ne : 6.725 MeV, 7.191 MeV; ^{24}Mg: 6.433 MeV; ^{28}Si: 4.979 MeV; ^{48}Ca: 4.284 MeV; ^{54}Fe: 4.291 MeV)

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