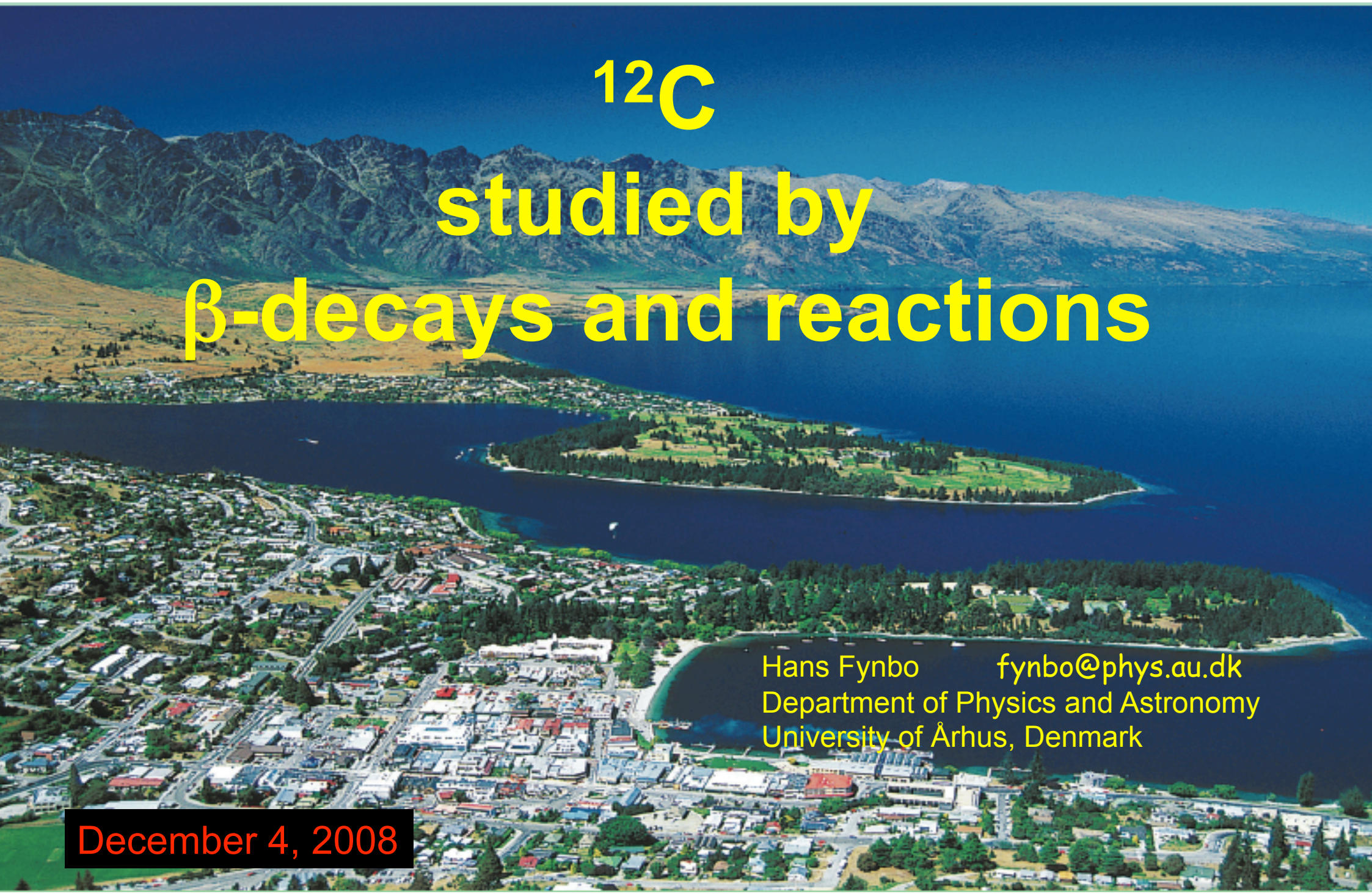

^{12}C studied by β-decays and reactions

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Department of Physics and Astronomy
University of Århus, Denmark

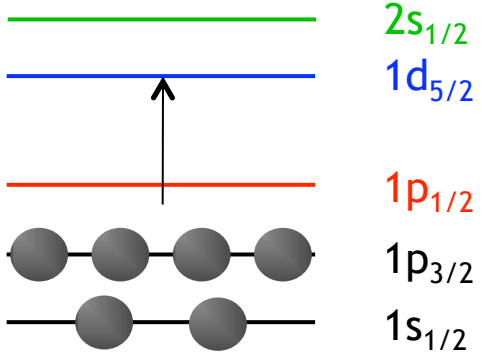
December 4, 2008

Low-energy level-structure in ^{12}C

experimentalists version…

-Single-nucleon excitations

to $1p_{1/2}$,$1d_{5/2}$ and $2s_{1/2}$:

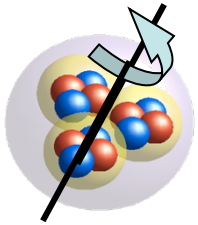


1^+, 2^+

1^-, 2^-, 3^-, 4^-

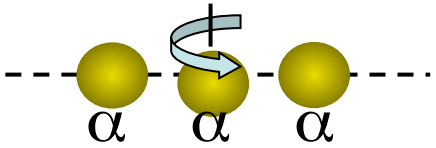
1^-, 2^-

- Collective motion



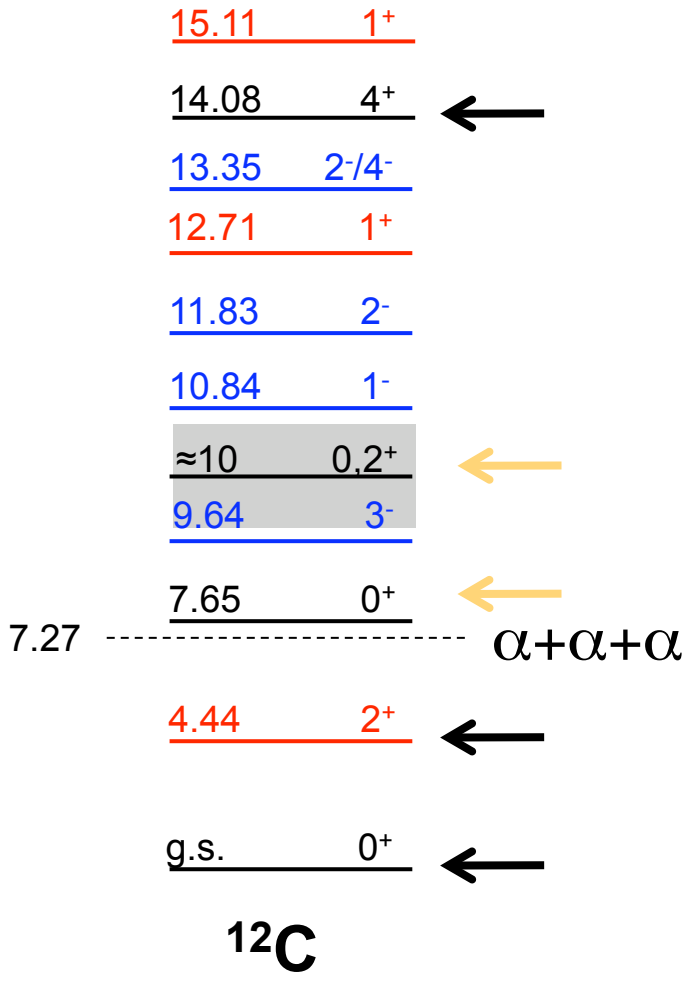
0^+, 2^+, 4^+, ...

Morinaga (1956) : chain

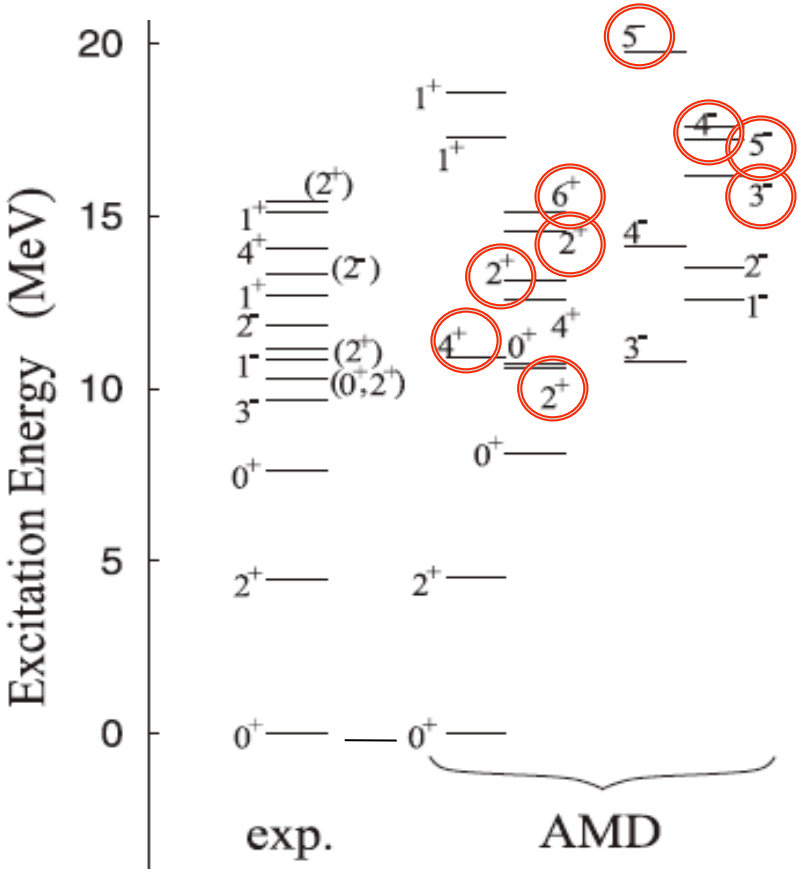


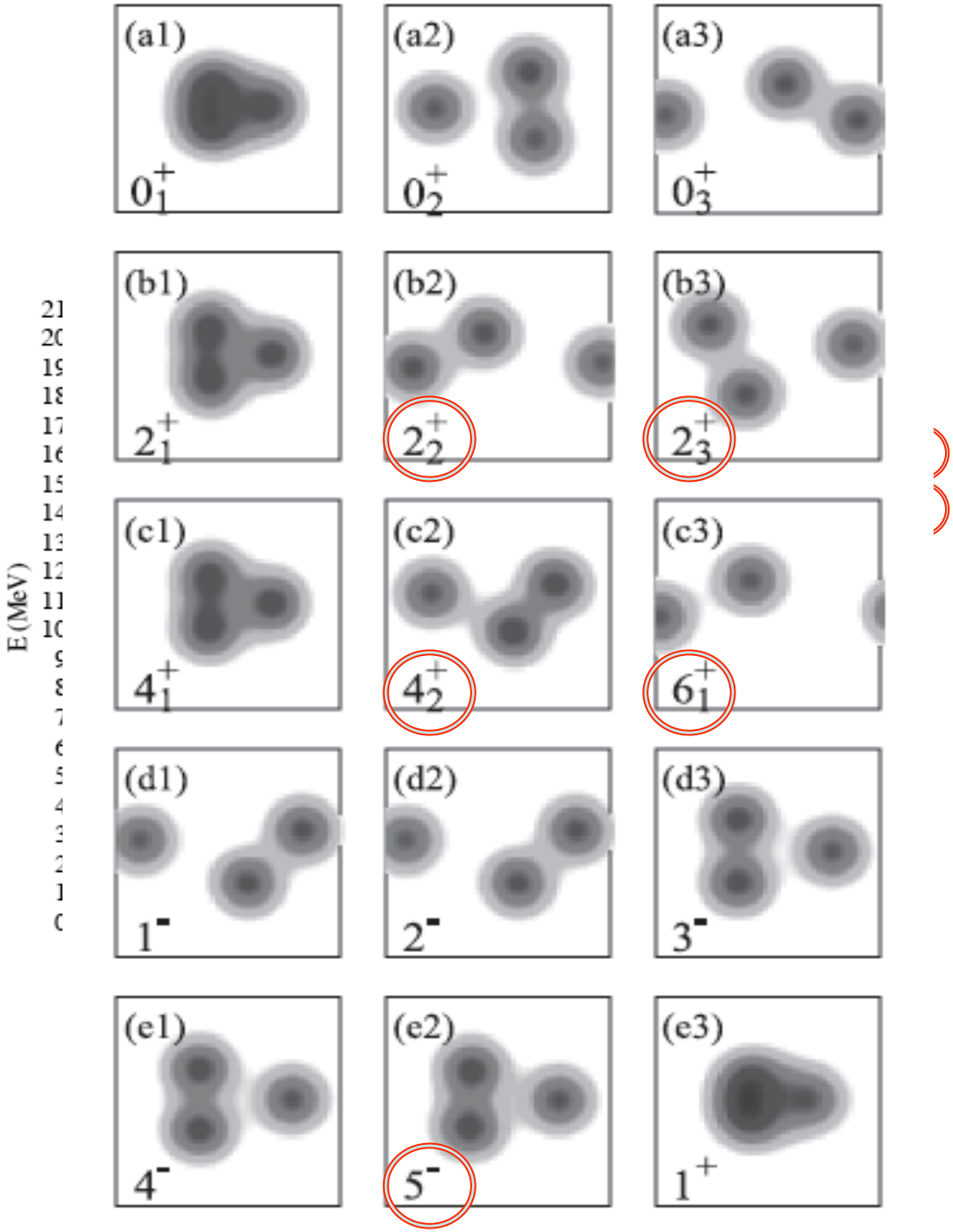
Uegaki *et al.* (1977) :
bose gas

Tohsaki *et al.* (2001) :
bose condensate gas ???



Antisymmetrised Molecular Dynamics





Kanada En'yo,
Prog. Theo. Phys. **117** (2007) 655.

Recent experiments

Not much help !

2^+ @ 11.5 MeV
$^{12}C(\alpha,\alpha')^{12}C^*$
Phys. Rev. C 68, 014305, 2003

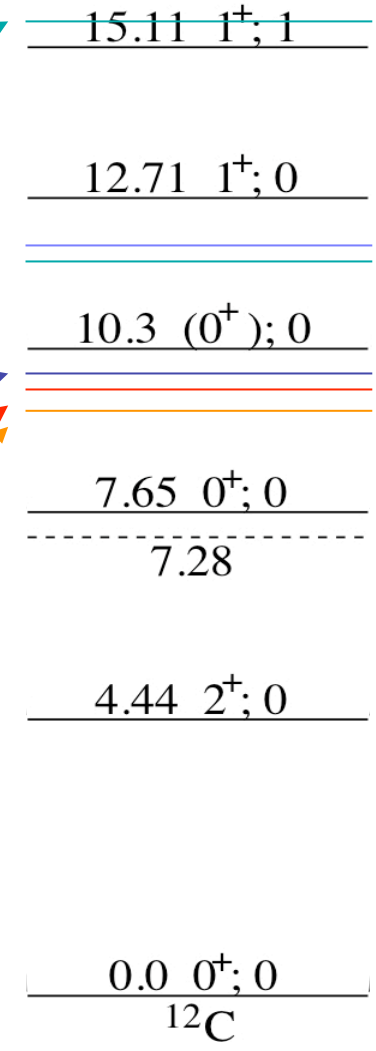
(2^+) @ 11.2 and 15.4 MeV
TUNL compilation
Nucl. Phys. A, 506, 1, 1990

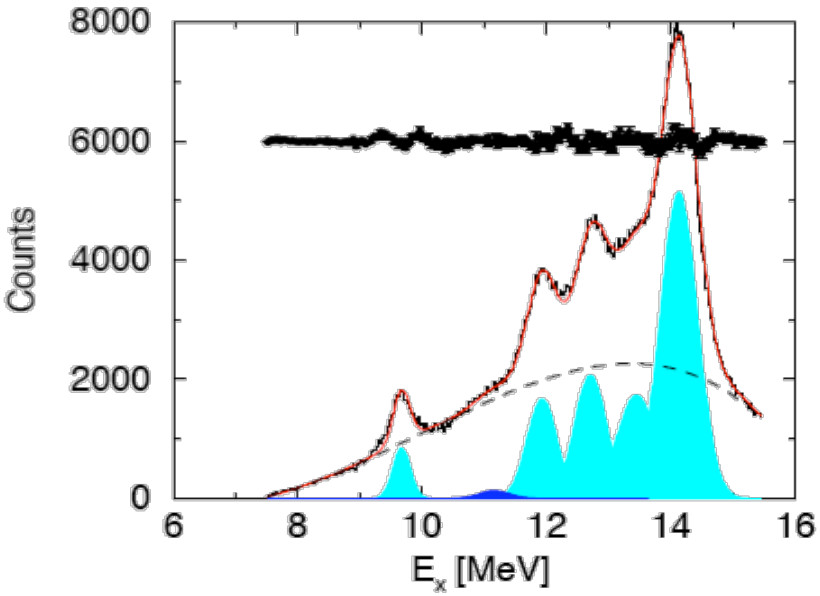
2^+ @ 11.16 MeV
$^{12}C(^{12}C,3\alpha)$
Phys. Rev. C 76, 034320, 2007. (also new 1^-, 3^-)

2^+ @ 9.9(3) MeV
$^{12}C(\alpha,\alpha')^{12}C^*$
Nucl. Phys. A, 738, 268, 2004

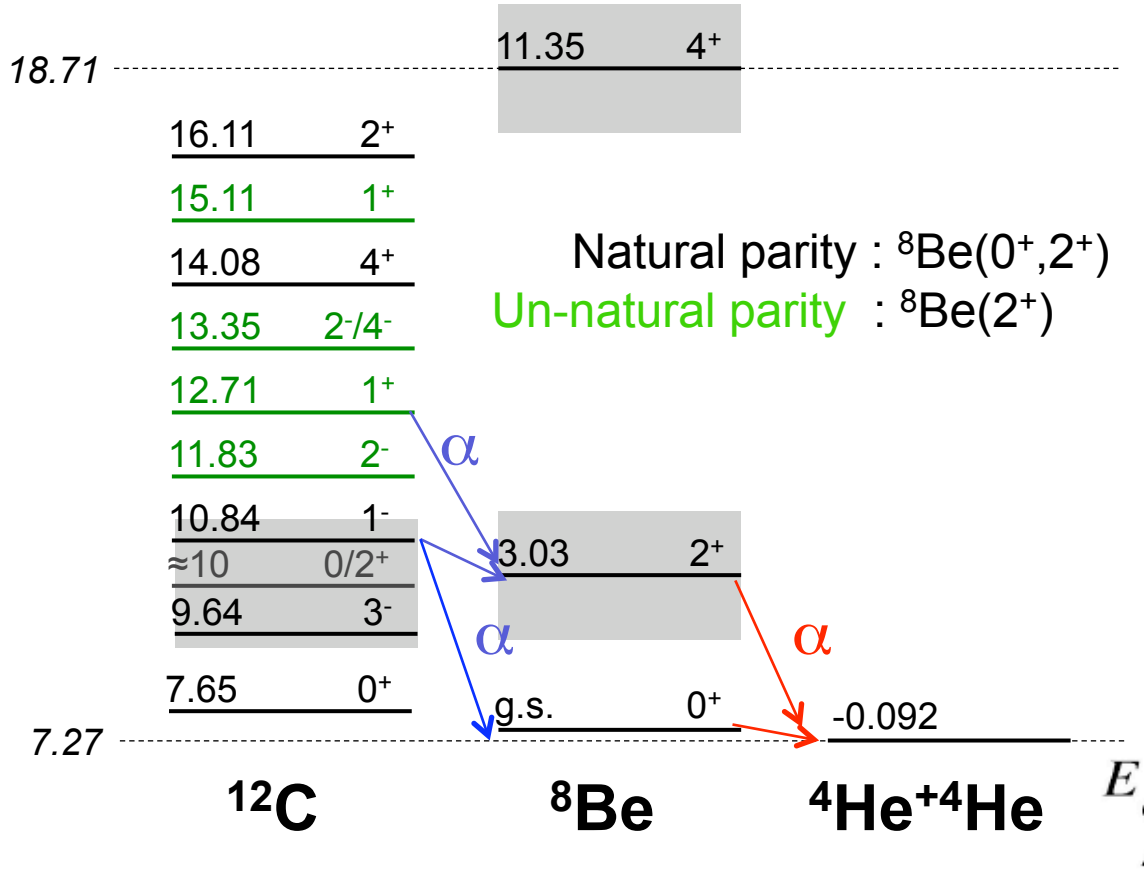
2^+ @ 9.7 MeV
$^{12}C(p,p')^{12}C^*$
M.Freer *private communication*

2^+ @ 9.0 MeV
Included in the NACRE compilation
Nucl. Phys. A, 656,3,1999



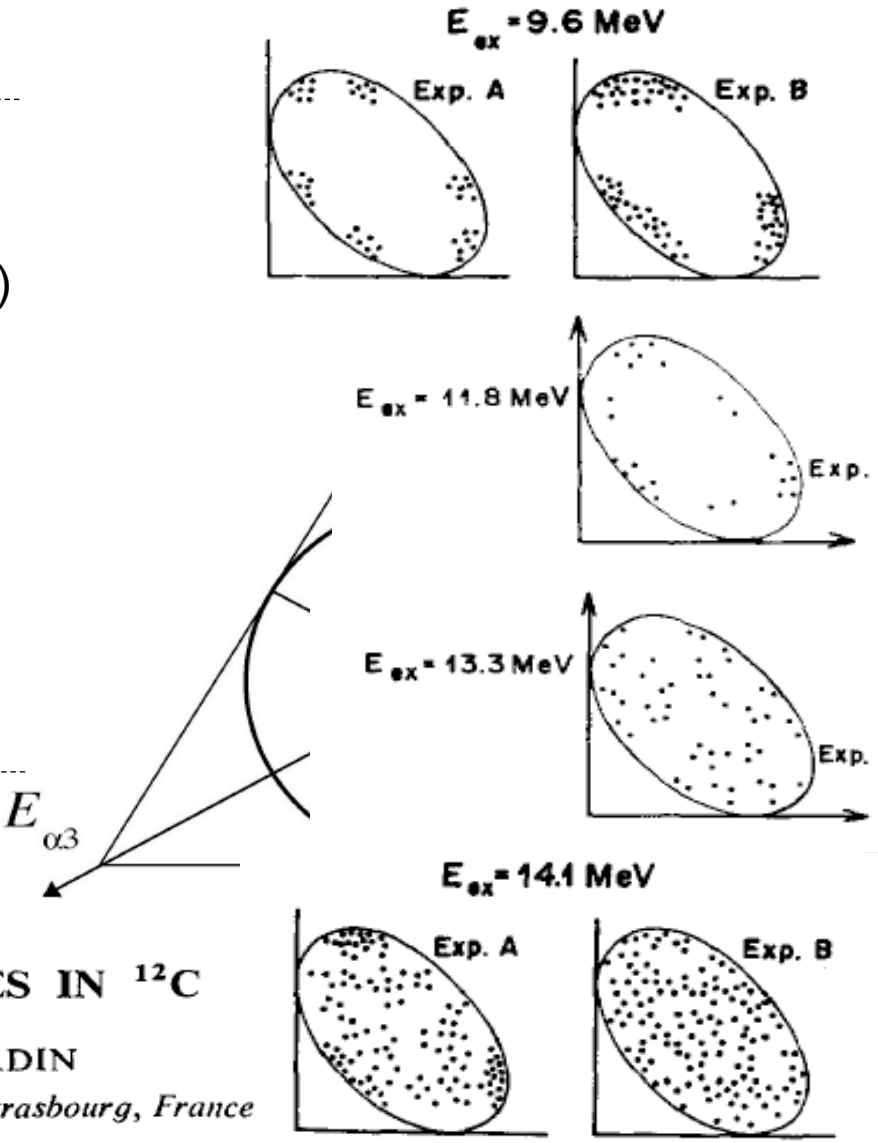


Dalitz distributions



Natural parity : $^8Be(0^+,2^+)$

Un-natural parity : $^8Be(2^+)$



SPIN-PARITY ASSIGNMENTS OF EXCITED STATES IN ^{12}C

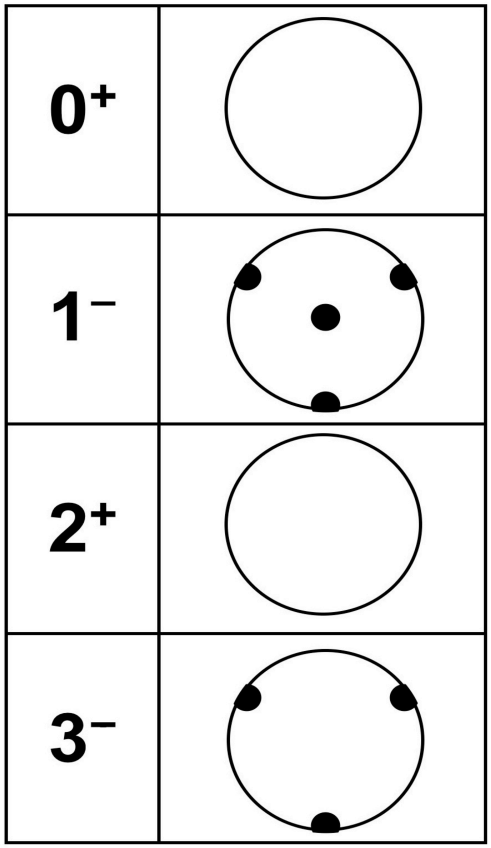
C. JACQUOT, Y. SAKAMOTO, M. JUNG and L. GIRARDIN

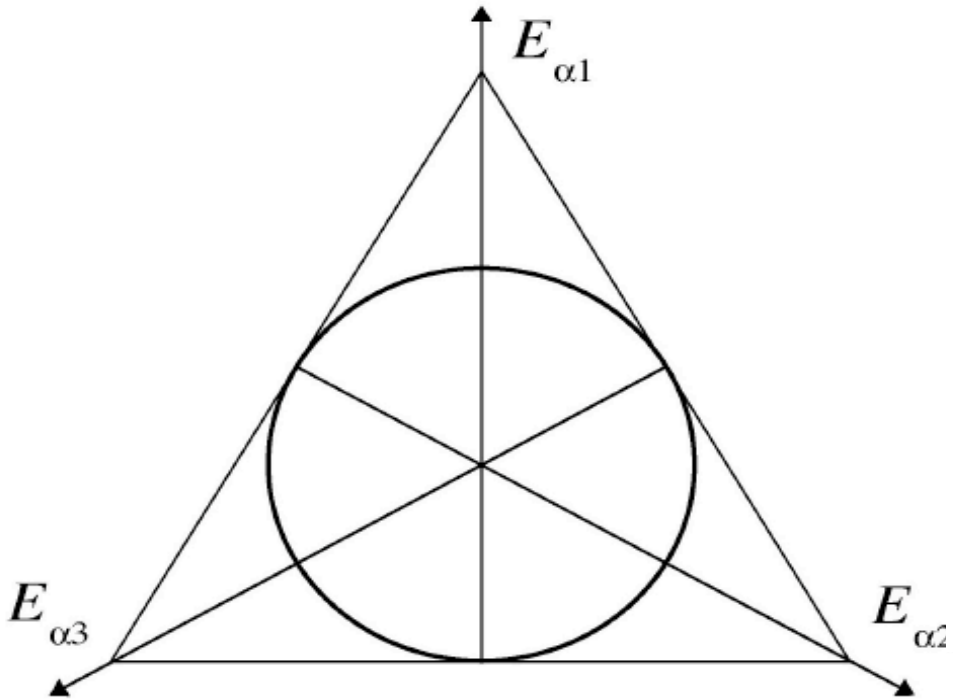
Laboratoire de Physique Corpusculaire, Centre de Recherches Nucléaires, Strasbourg, France

Nucl. Phys. **A201** (1973) 247.

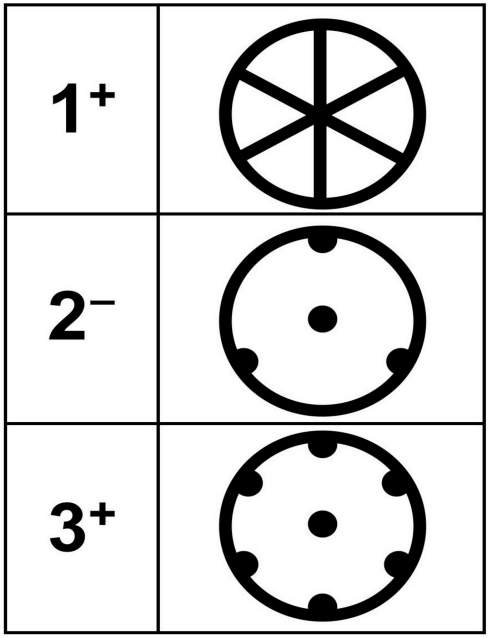
Symmetry constraints

Natural parity





Un-natural parity



C. Zemach, Phys Rev. **133** (1964) 1201 : Decay to 3π
Use results for I=3 case (isospin-symmetric)

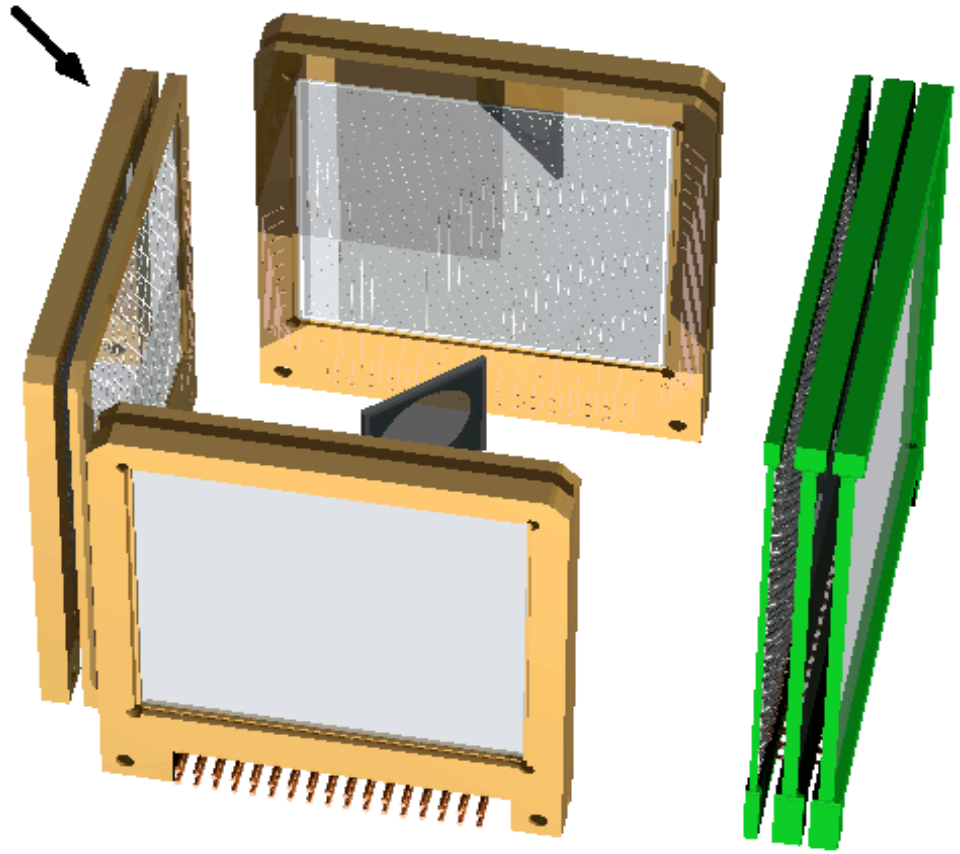
Two motivations:

- Missing states in the 8-14MeV region
  - Mainly 2^+, but also others
- Breakup spectra of known and unknown states
  - Interesting on their own, but also spectroscopic tool

Two experimental approaches :

- β-decay of ^{12}N and ^{12}B
  - Sensitive to 0^+ and 2^+ states
  - GT strength sensitive to cluster vs mean field structure
- ^{11}B(^{3}He,d)^{12}C* and ^{10}B(^{3}He,p)^{12}C* reactions
  - Access to all J^π
- Establish Dalitz distributions as spectroscopic tool

High Q-value reactions $^{11}B(^{3}He,d)^{12}C^{*}$ and $^{10}B(^{3}He,p)^{12}C^{*}$



4 telescopes: 1 x 32 strip DSSD

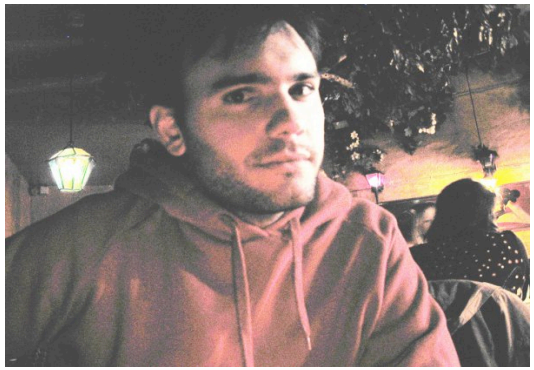
3 x 16 strip DSSD

3 days beam time

$^{3}He + ^{11}B$ @ 8.5 MeV $\rightarrow$ $d + ^{12}C^{*}$, $\alpha + ^{10}B^{*}$, $^{8}Be + ^{6}Li^{*}$

$^{3}He + ^{10}B$ @ 4.9 MeV $\rightarrow$ $p + ^{12}C^{*}$, $\alpha + ^{9}B^{*}$, $^{8}Be + ^{5}Li^{*}$

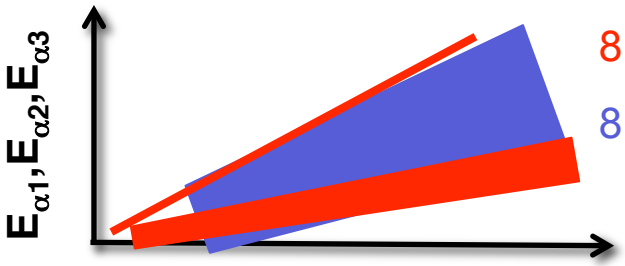
Oliver Kirsebom



Martin Alcorta

CMAM 2008

p/d+3α coincidences:

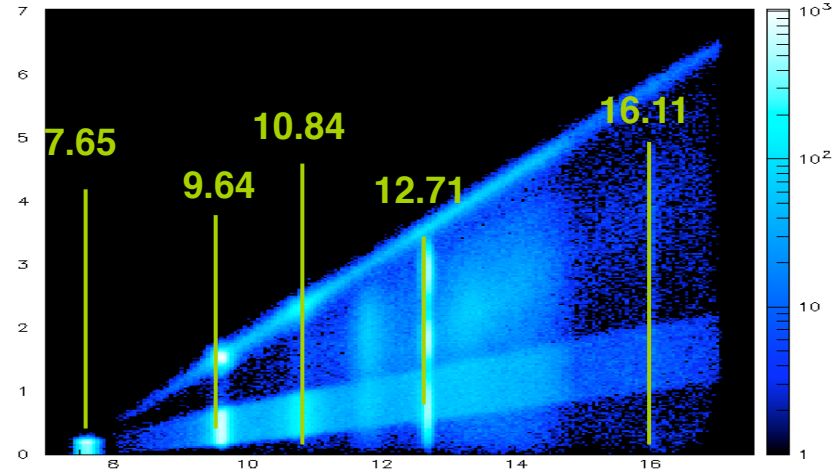


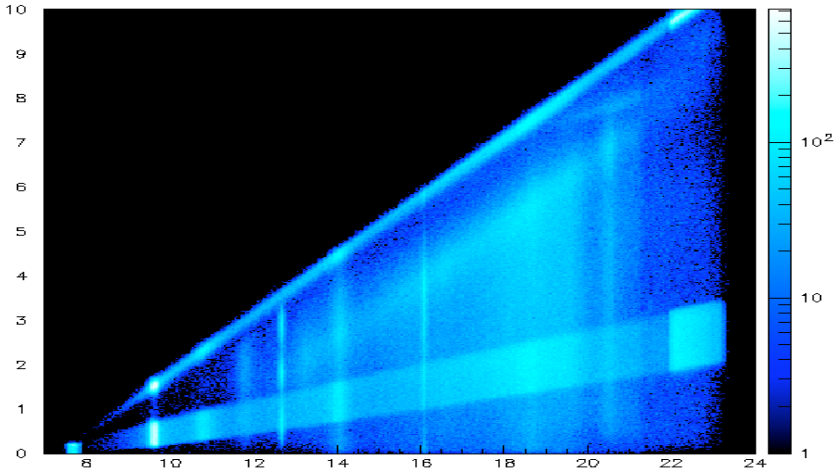
^{8}Be(0^{+})

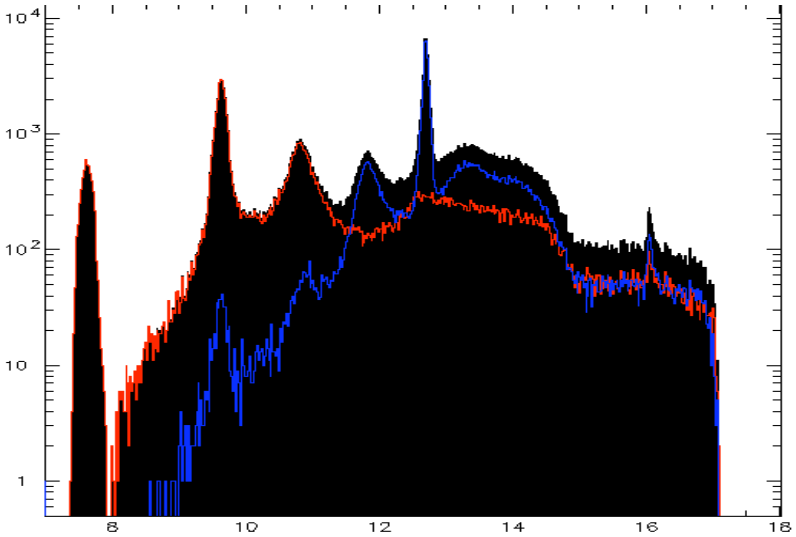
^{8}Be(2^{+}) or direct breakup

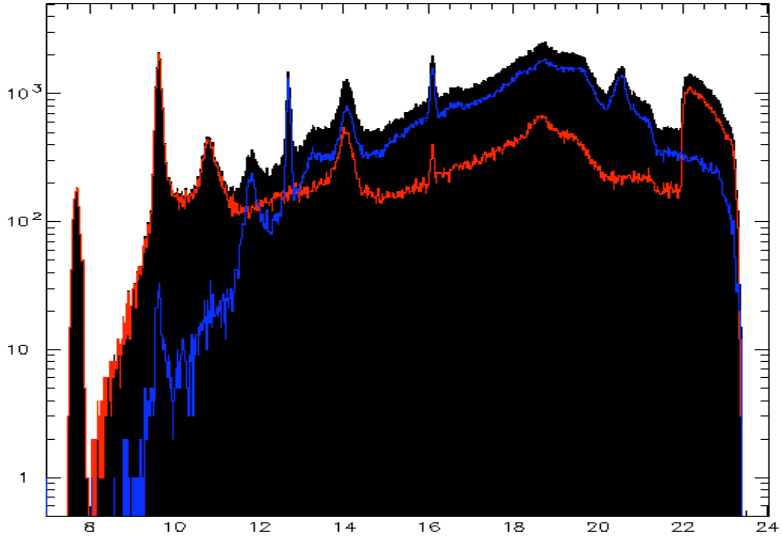
^{11}B

^{10}B





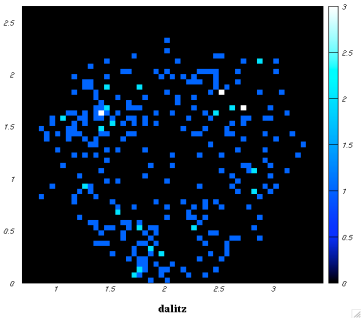




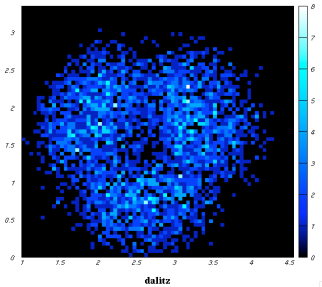
15.11	1^{+}
14.08	4^{+}
13.35	2^{-}/4^{-}
12.71	1^{+}
11.83	2^{-}
10.84	1^{-}
≈10	0,2^{+}
9.64	3^{-}
7.65	0^{+}
4.44	2^{+}
g.s.	0^{+}

^{12}C

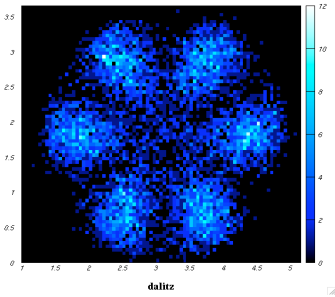
^{12}C Spectrum: Dalitz



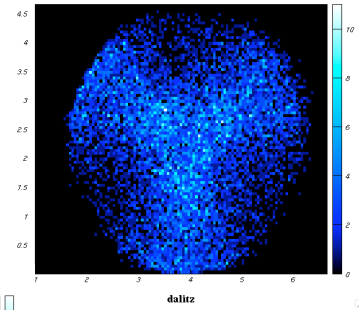
10.8 MeV 1^-



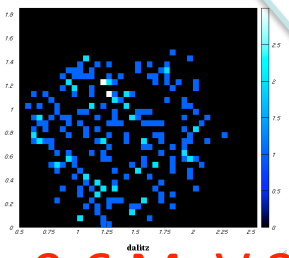
11.8 MeV 2^-



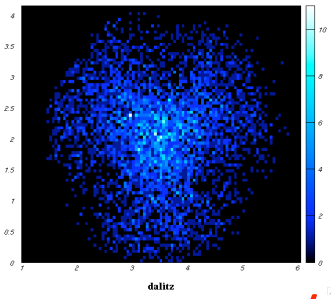
12.7 MeV 1^+



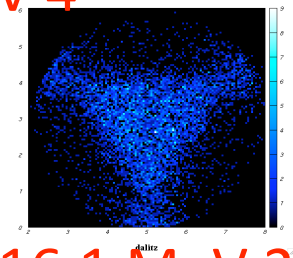
14.1 MeV 4^+



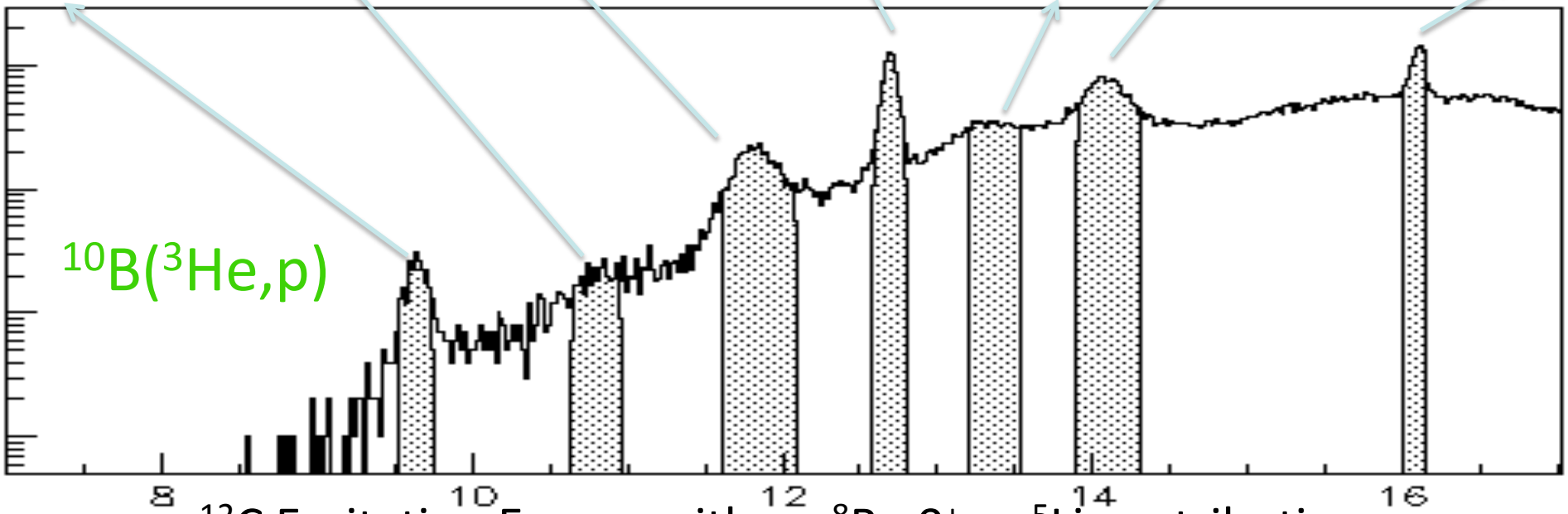
9.6 MeV 3^-



13.4 MeV $2^-/4^-$

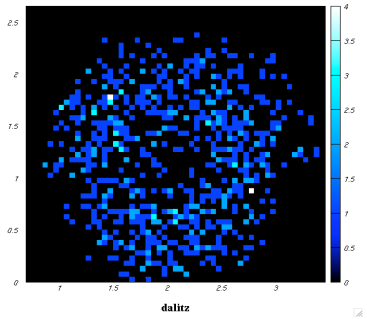


16.1 MeV 2^+

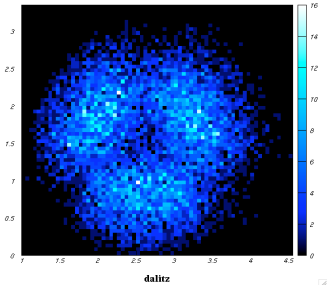


^{12}C Excitation Energy with no ^{8}Be 0^+ or ^{5}Li contribution

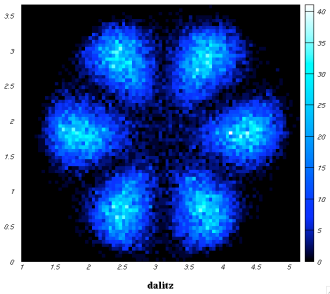
^{12}C Spectrum: Dalitz



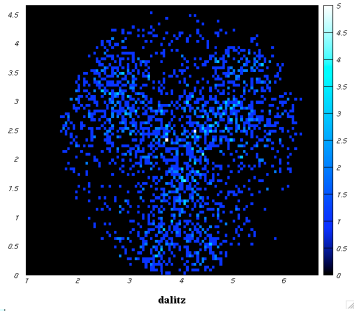
10.8 MeV 1^-



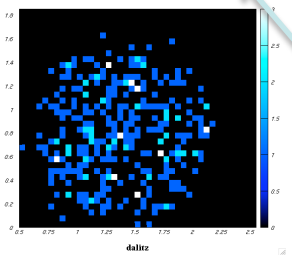
11.8 MeV 2^-



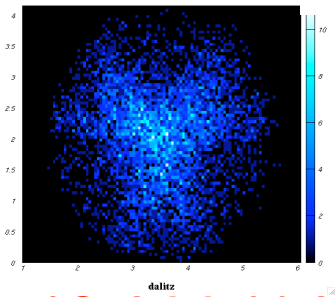
12.7 MeV 1^+



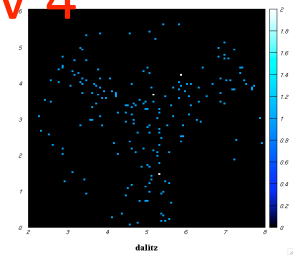
14.1 MeV 4^+



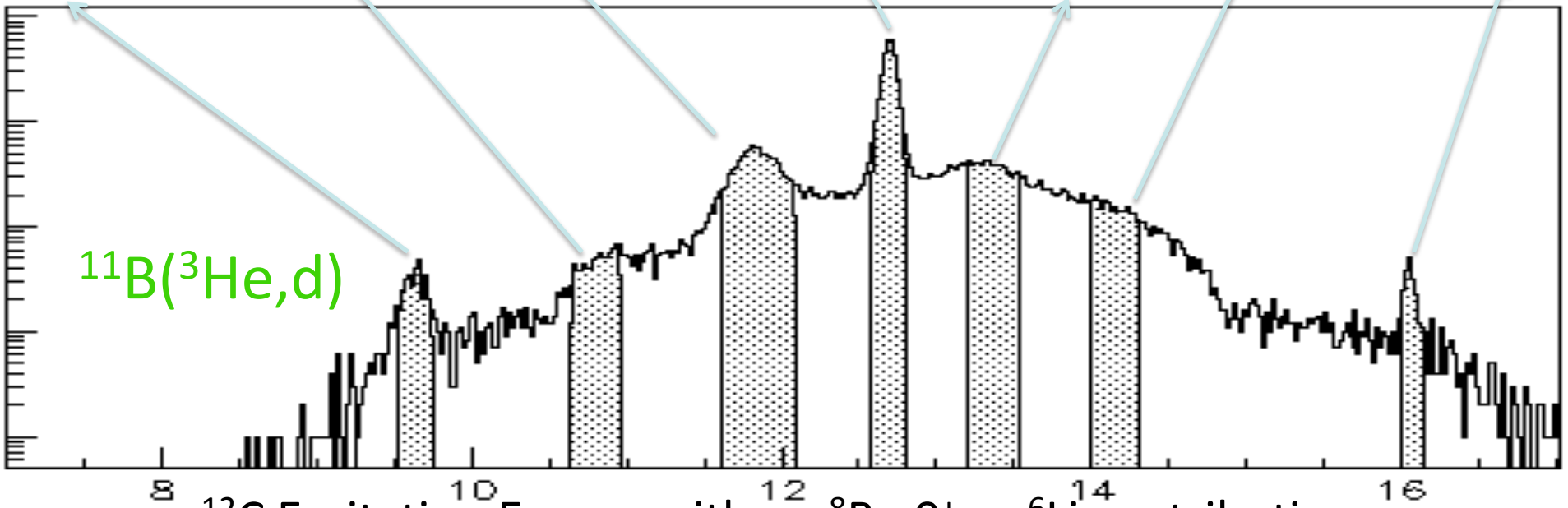
9.6 MeV 3^-



13.4 MeV 4^-



16.1 MeV 2^+

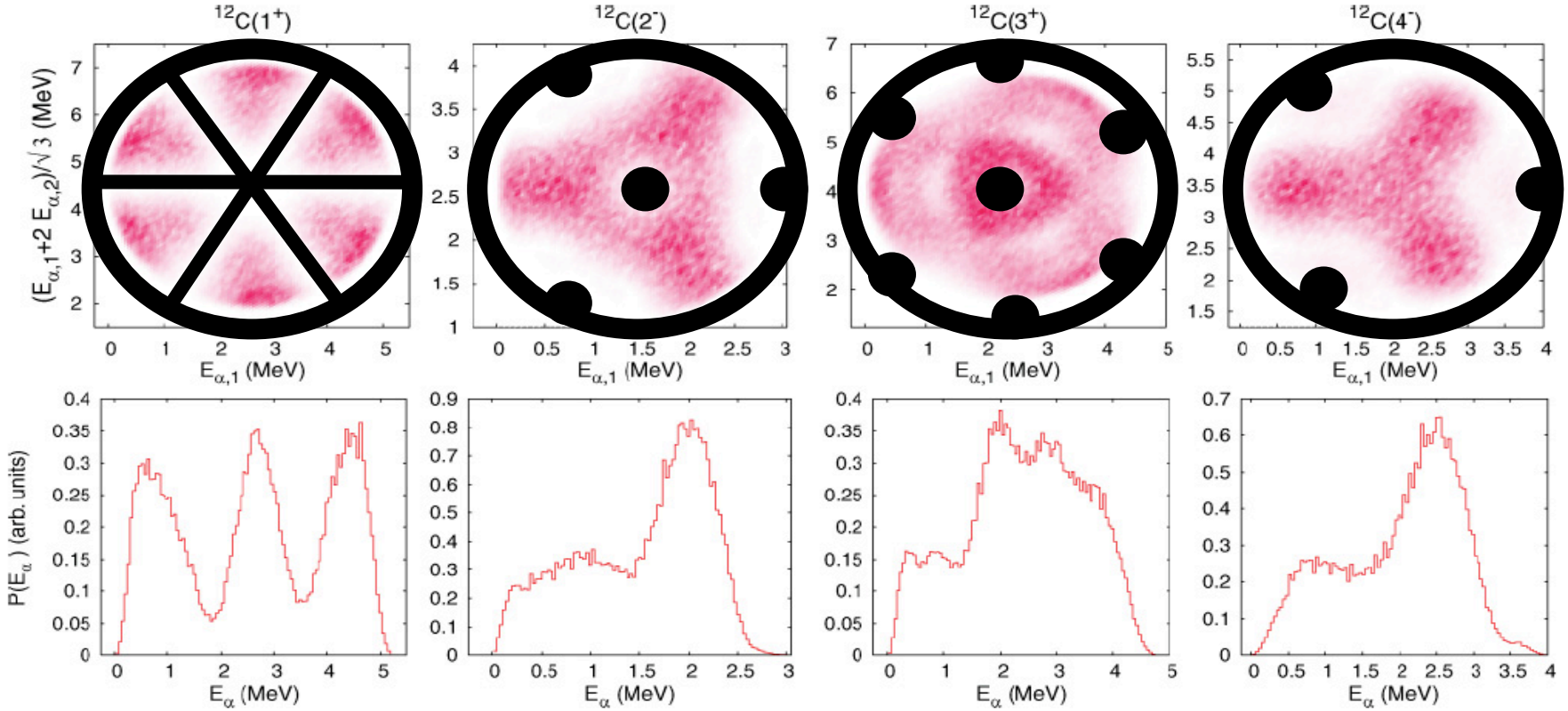


^{12}C Excitation Energy with no ^{8}Be 0^+ or ^{6}Li contribution

PHYSICAL REVIEW C 77, 064305 (2008)

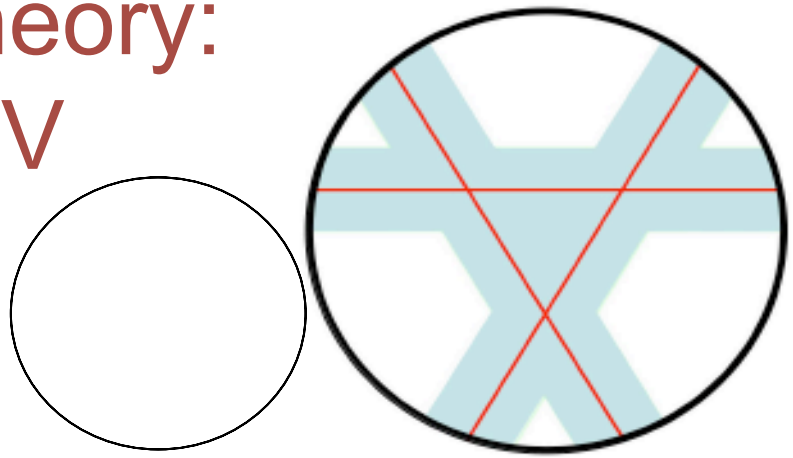
Momentum distributions of α particles from decaying low-lying ^{12}C resonances

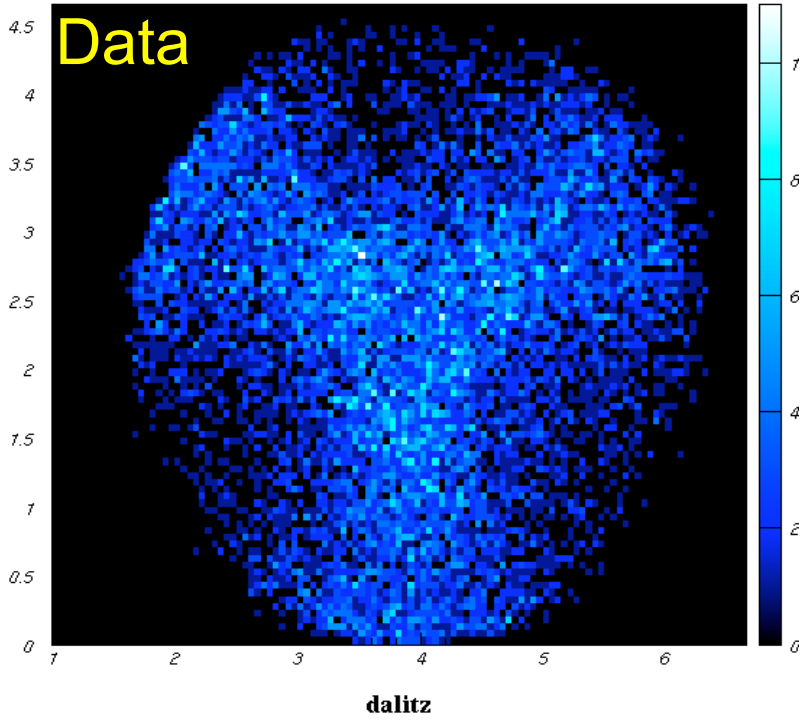
R. Álvarez-Rodríguez,[1] A. S. Jensen,[1] E. Garrido,[2] D. V. Fedorov,[1] and H. O. U. Fynbo[1]
[1]*Department of Physics and Astronomy, University of Aarhus, DK-8000 Aarhus C, Denmark*
[2]*Instituto de Estructura de la Materia, Consejo Superior de Investigaciones Científicas, Serrano 123, E-28006 Madrid, Spain*
(Received 15 February 2008; revised manuscript received 4 April 2008; published 4 June 2008)

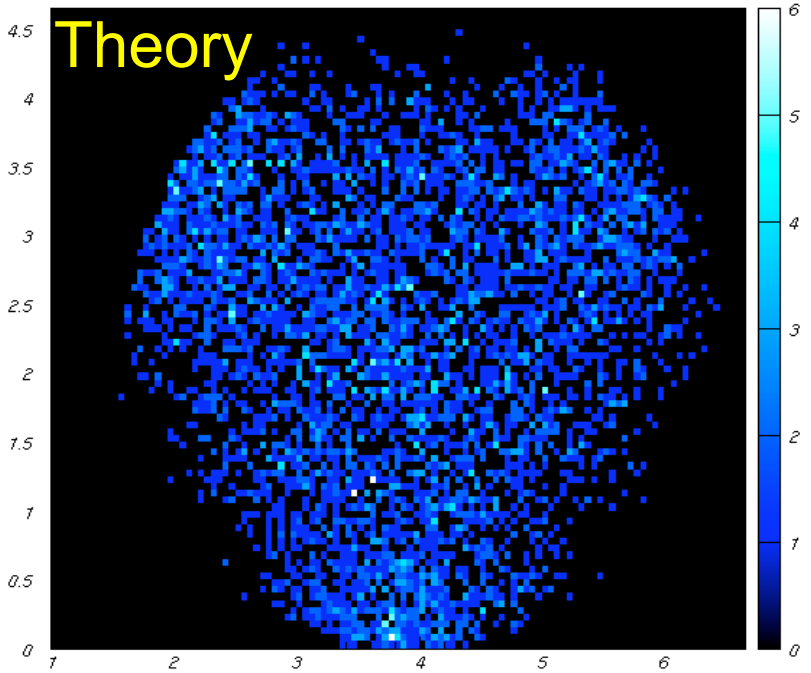


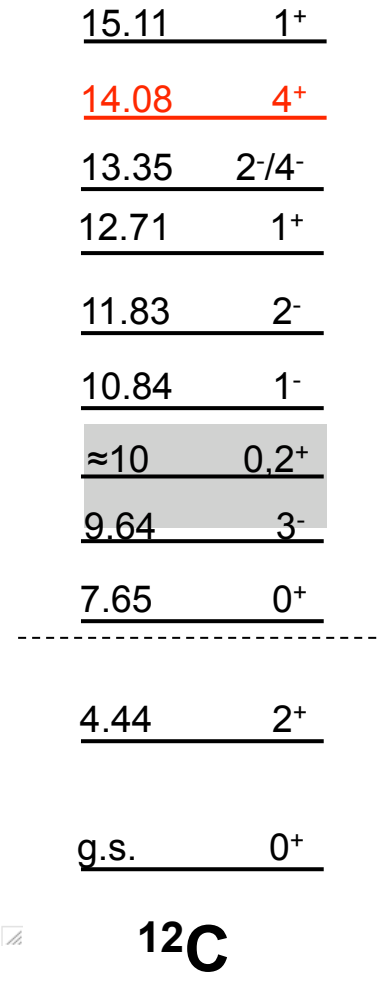
Faddeev equations in coordinate space.
Adiabatic expansion. Complex rotation.

Comparison to Theory: 4^+ at 14.1 MeV

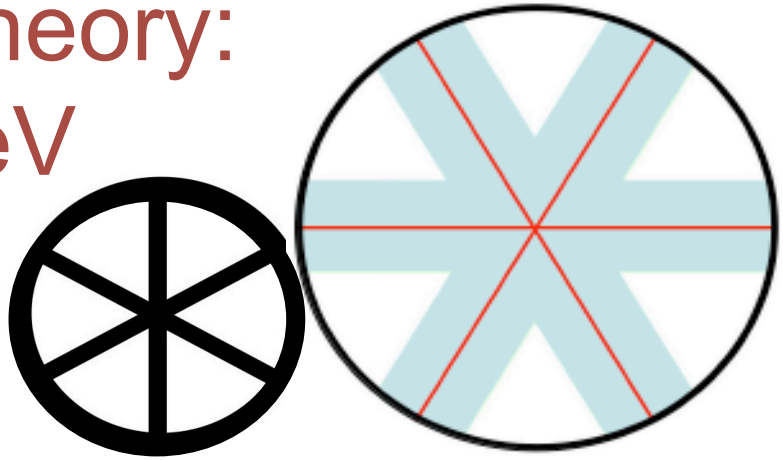


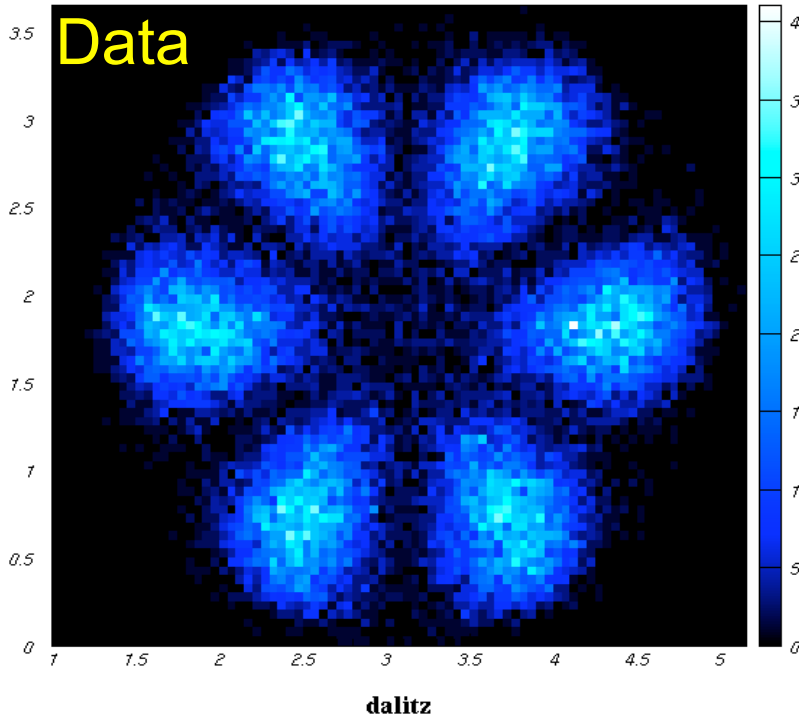


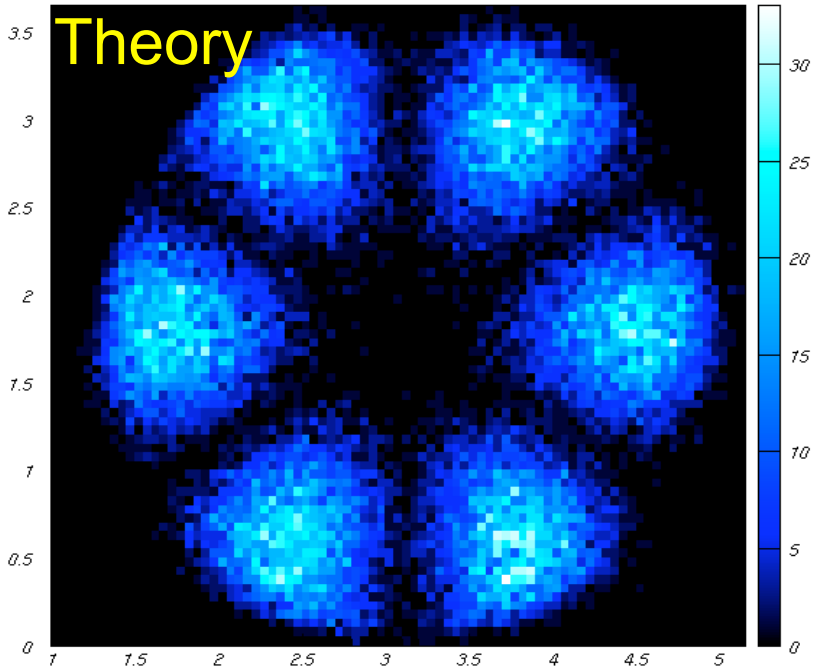




Comparison to Theory: 1^+ at 12.7 MeV



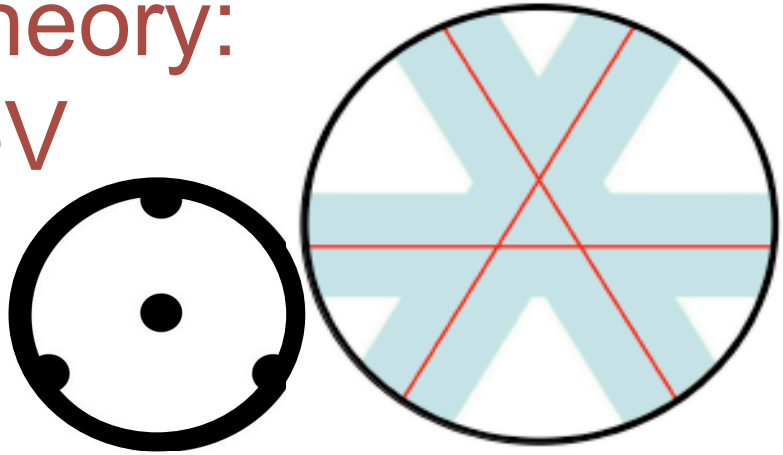


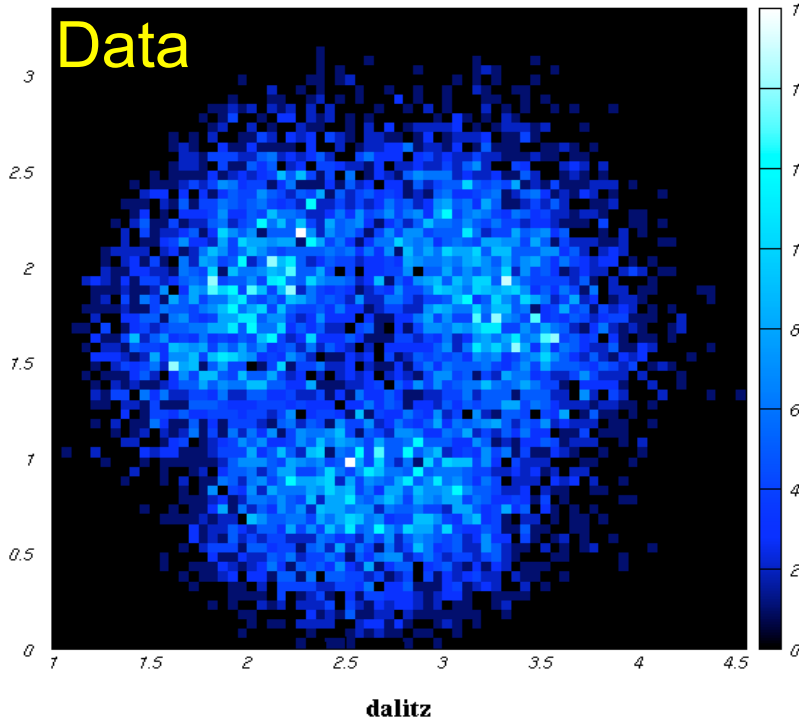


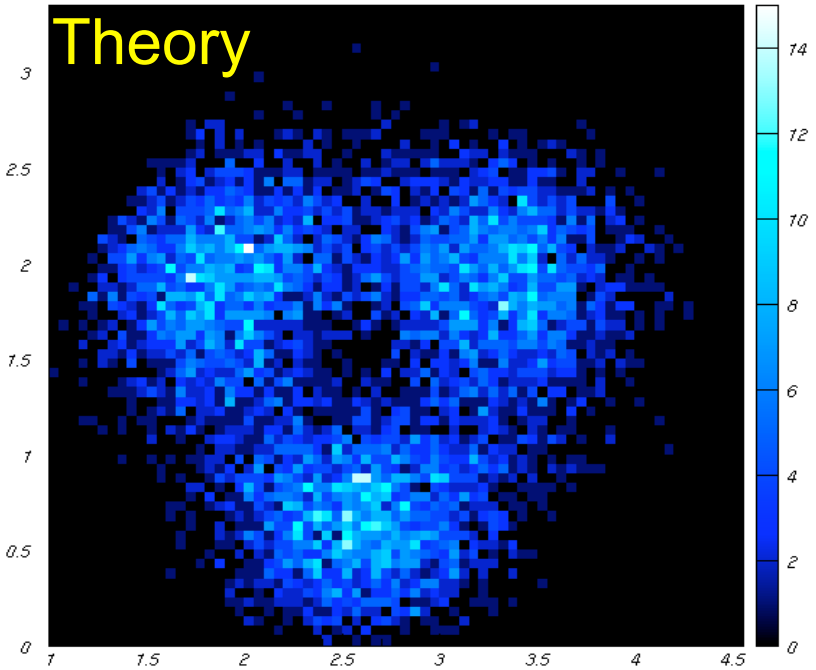
15.11	1^+
14.08	4^+
13.35	$2^-/4^-$
12.71	1^+
11.83	2^-
10.84	1^-
≈10	$0,2^+$
9.64	3^-
7.65	0^+
4.44	2^+
g.s.	0^+

^{12}C

Comparison to Theory: 2^- at 11.8 MeV



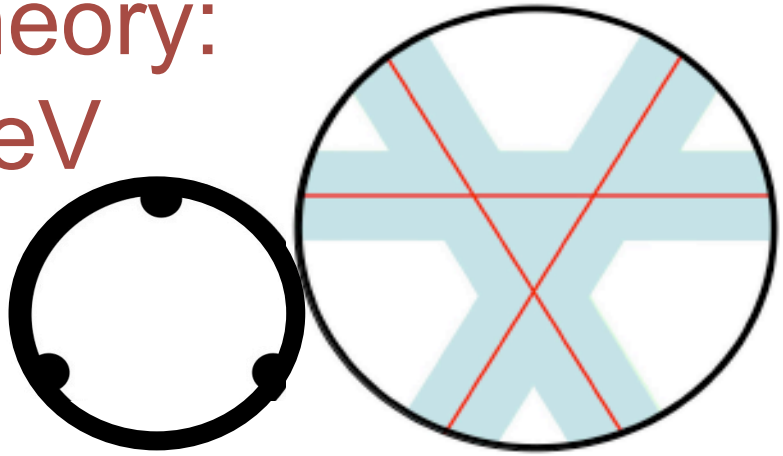


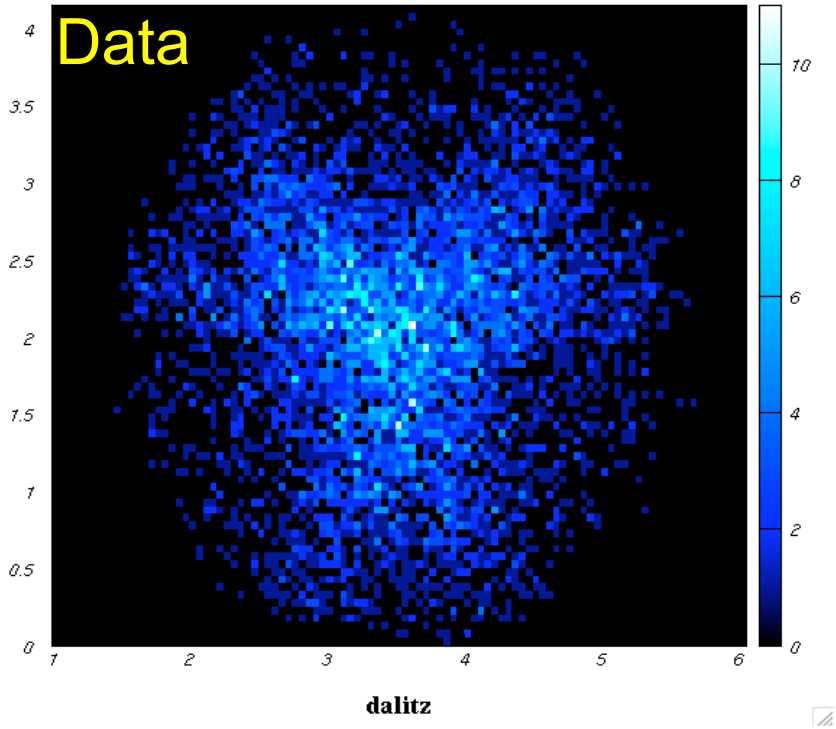


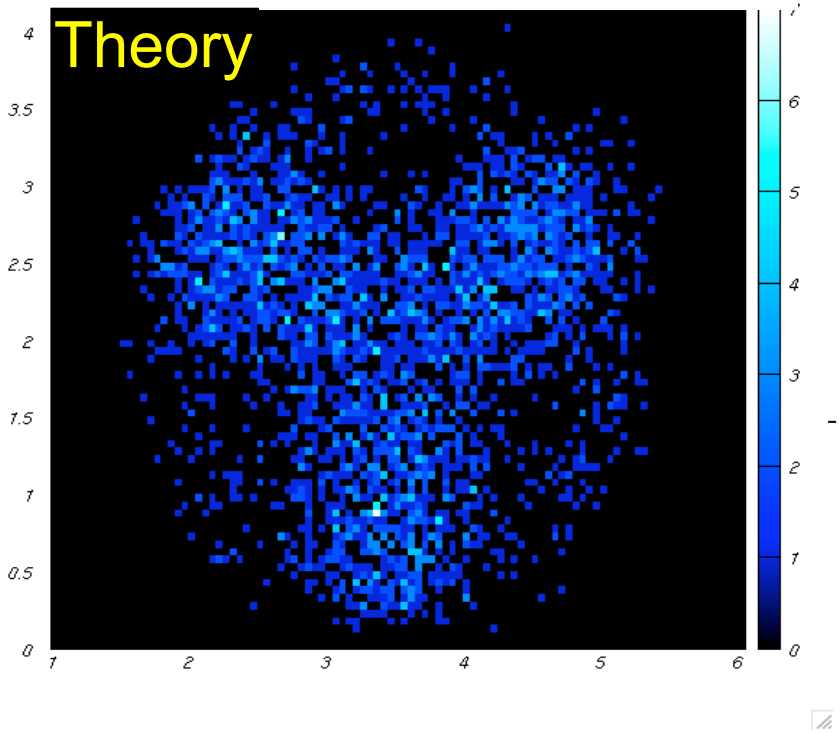
15.11	1^+
14.08	4^+
13.35	$2^-/4^-$
12.71	1^+
11.83	2^-
10.84	1^-
≈10	$0,2^+$
9.64	3^-
7.65	0^+
4.44	2^+
g.s.	0^+

^{12}C

Comparison to Theory: $2^-/4^-$ at 13.4 MeV



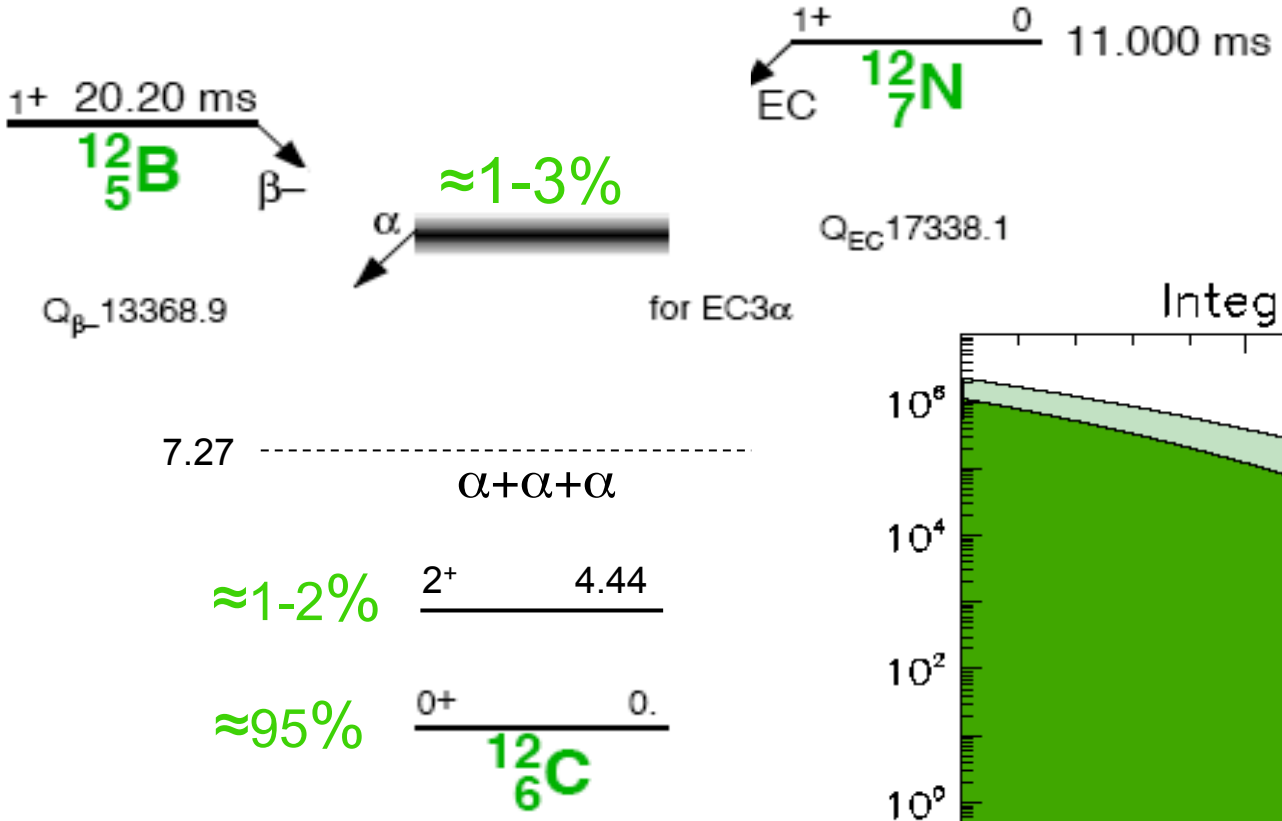


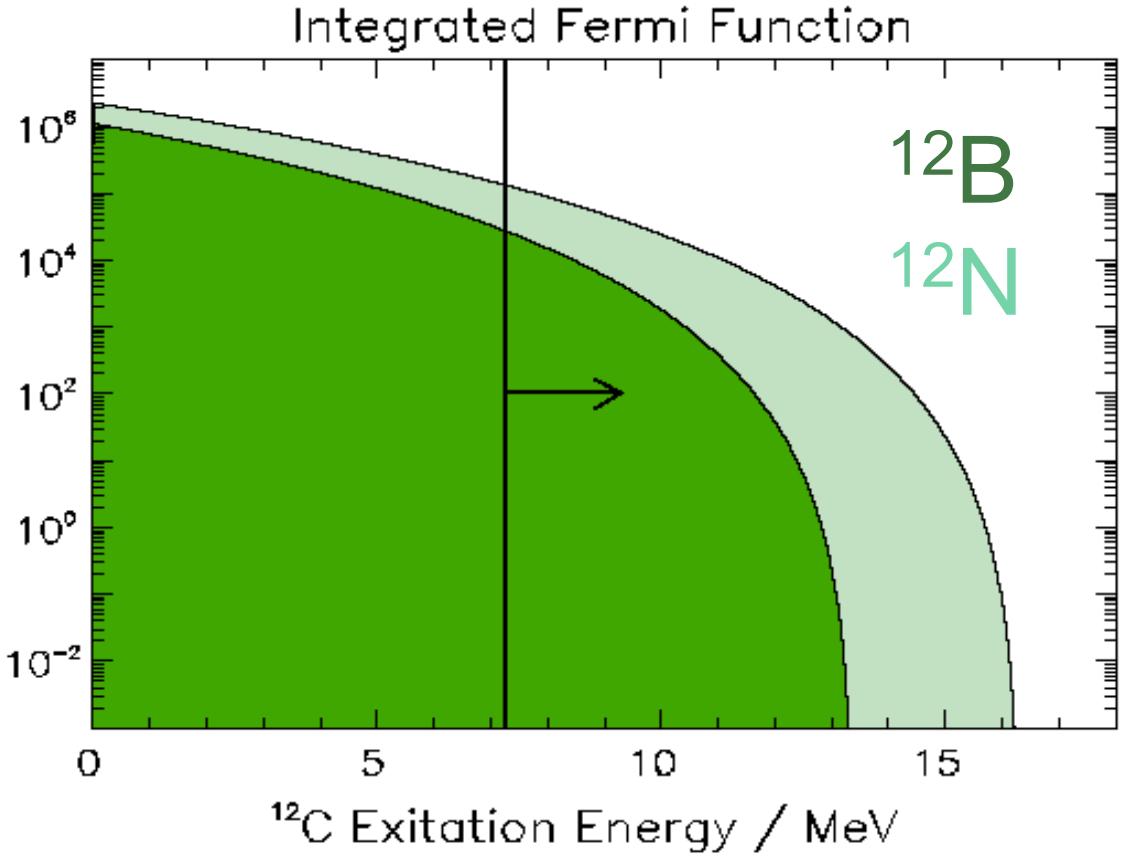


15.11	1^+
14.08	4^+
13.35	$2^-/4^-$
12.71	1^+
11.83	2^-
10.84	1^-
≈10	$0,2^+$
9.64	3^-
7.65	0^+
4.44	2^+
g.s.	0^+

^{12}C

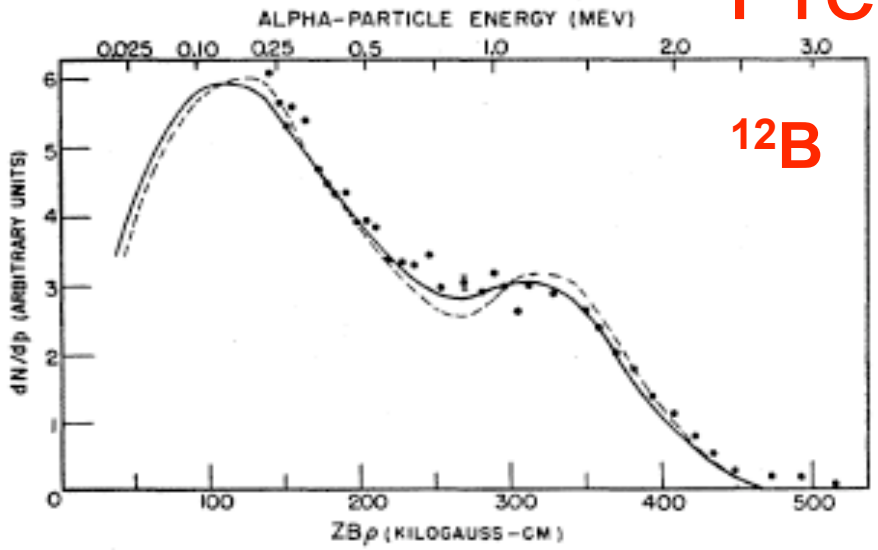
Two β-decays leading to ^{12}C



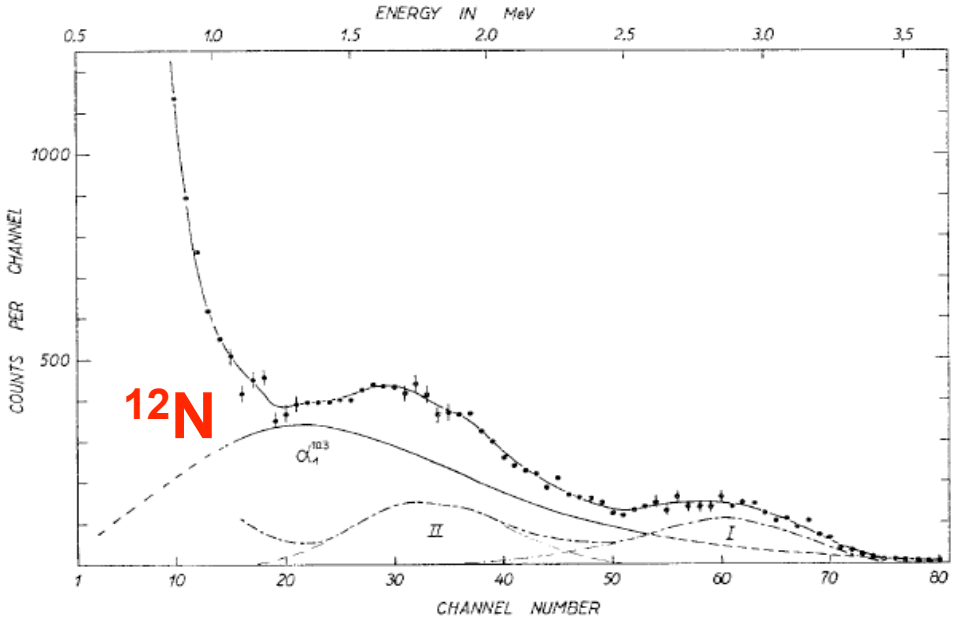


$$ft^{-1} = \frac{B.R.}{fT_{1/2}} \propto \left|M_{if}\right|^2$$

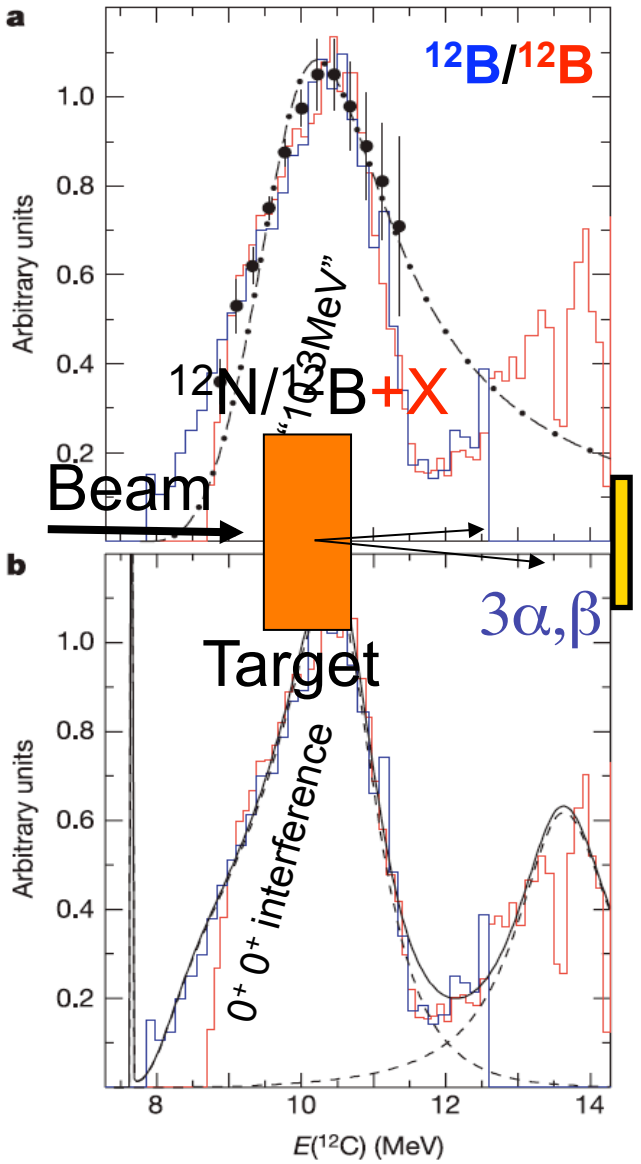
Previous work



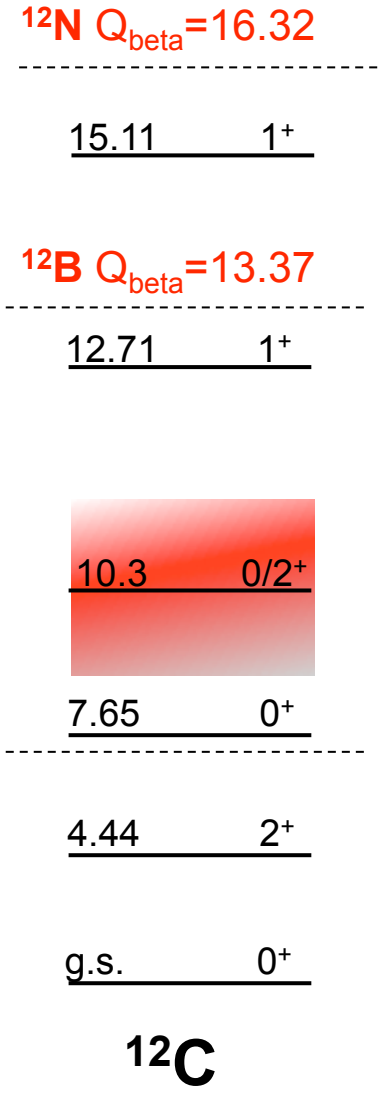
Phys. Rev. **111** (1958) 567 (Fowler)



Nucl. Phys. **A89** (1966) 401 (Schwalm)
Phys. Rev. **130** (1963) 1953. (Wilkinson+Alburger)

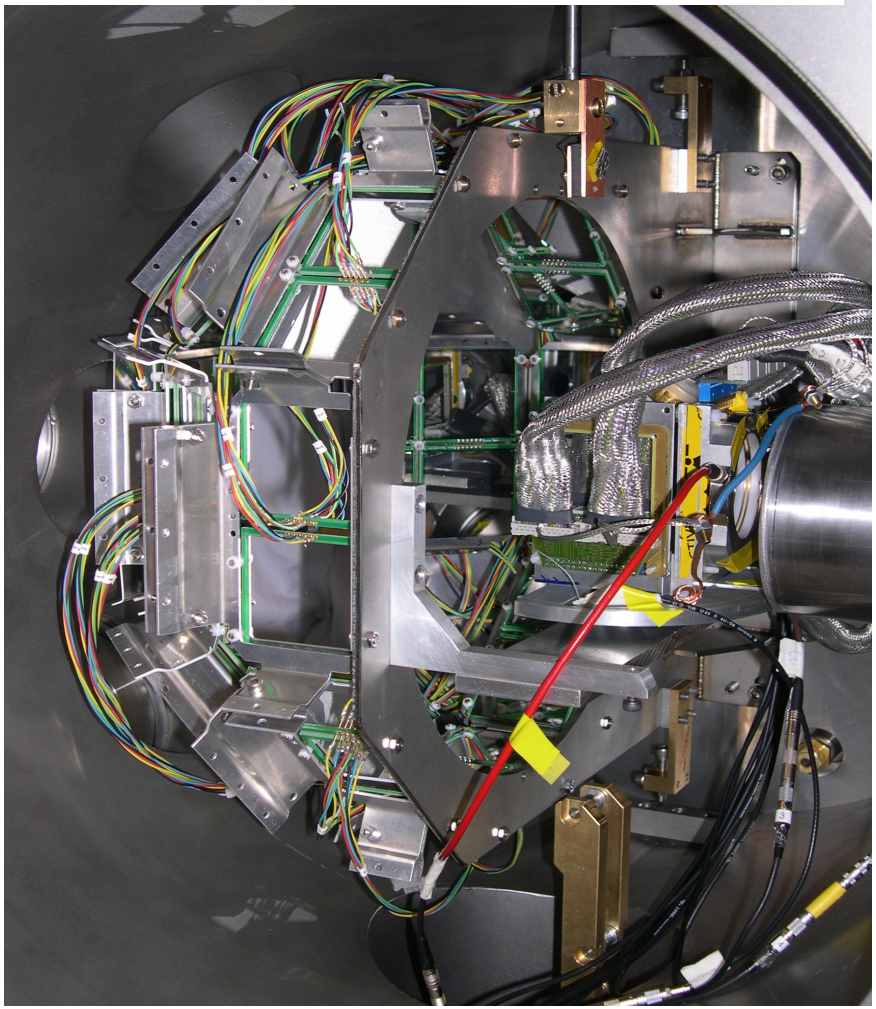


Nature **433** (2005) 136.

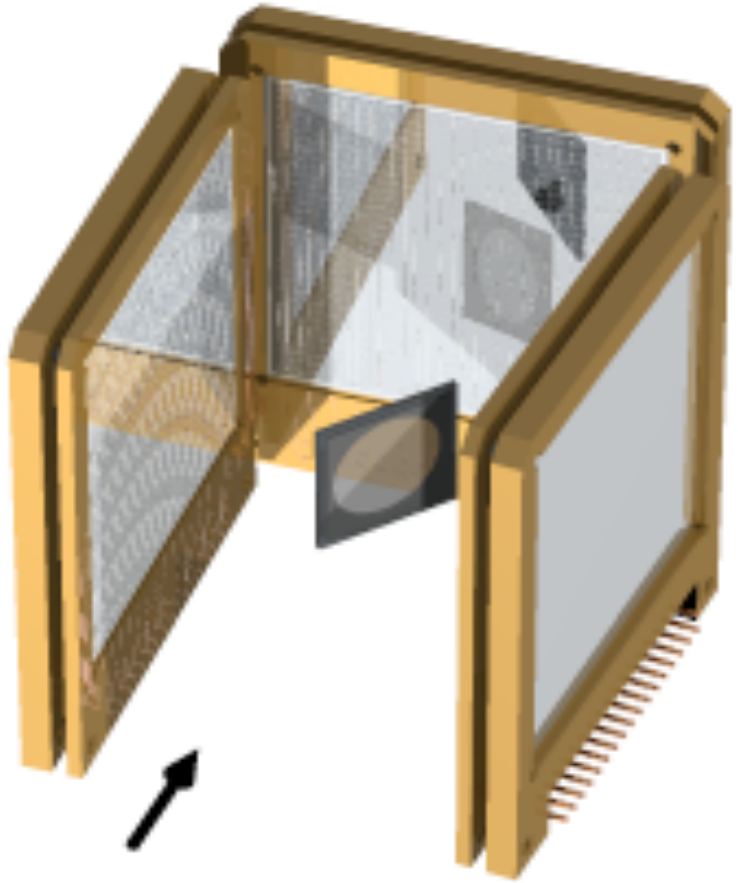


ISOL Experi

L.M. Fraile & J.Äystö, NIM**A**513 (2003) 287.



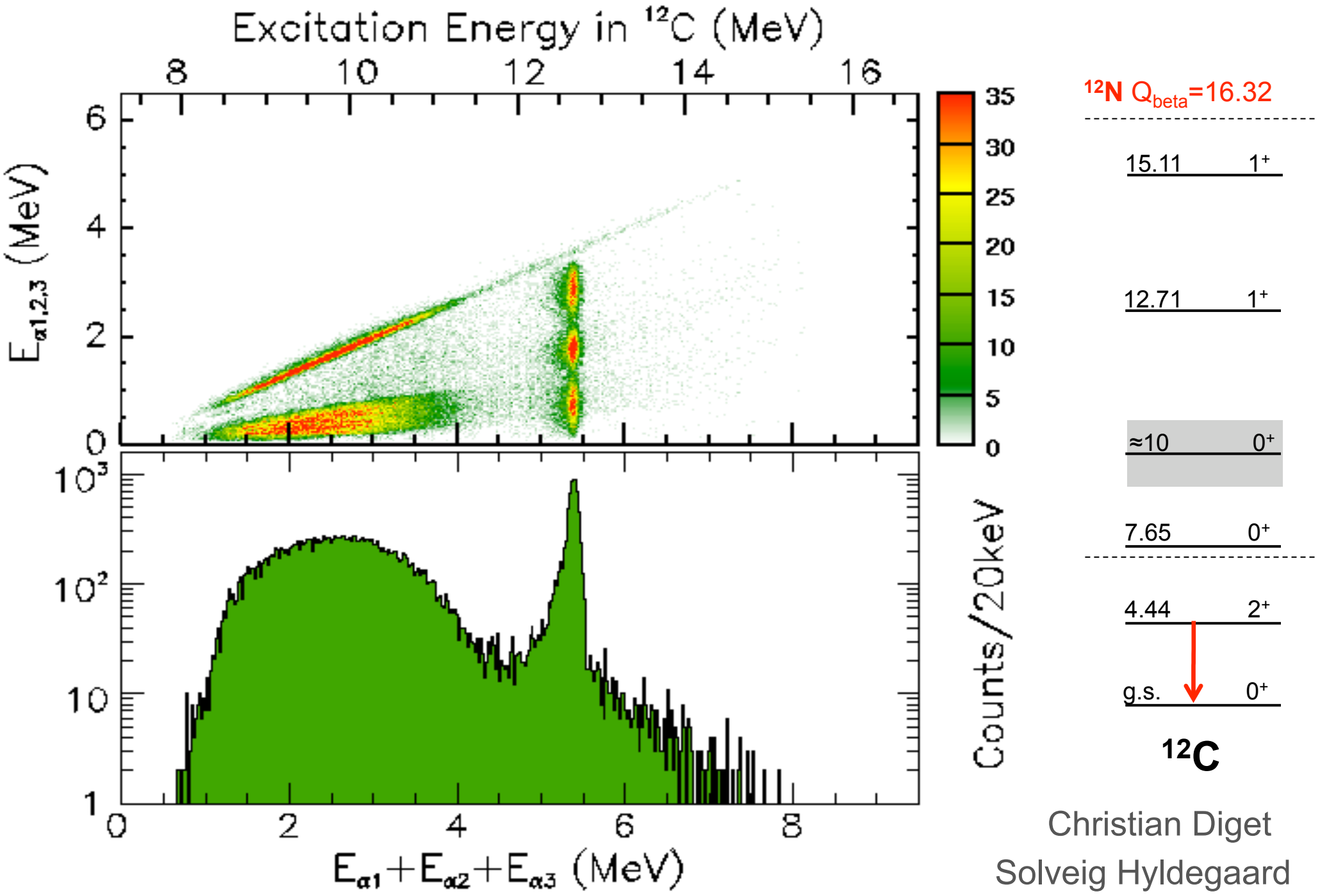
14 days beam time



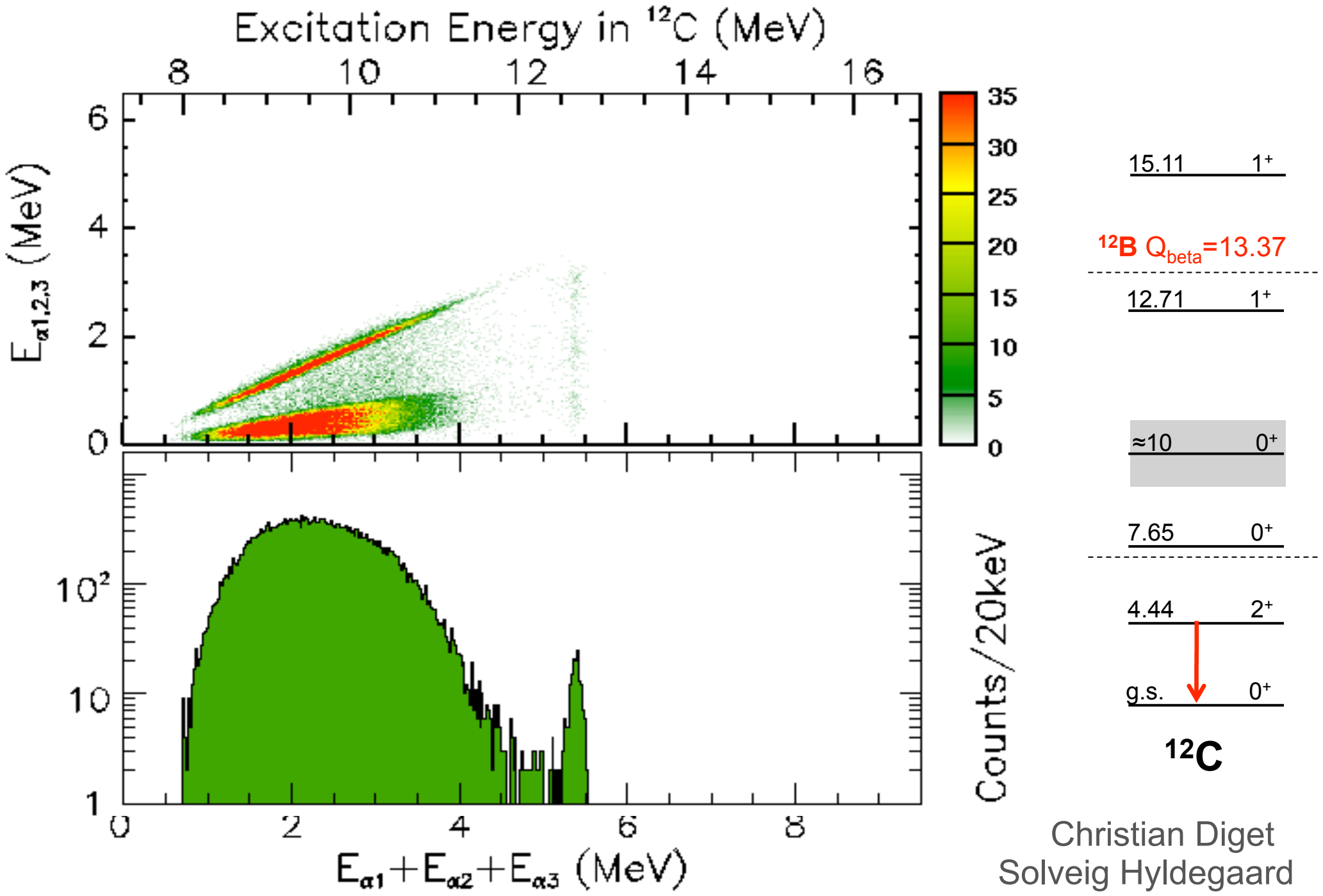
$^{12}N/^{12}B$

C. Diget

Solveig Hyldegaard



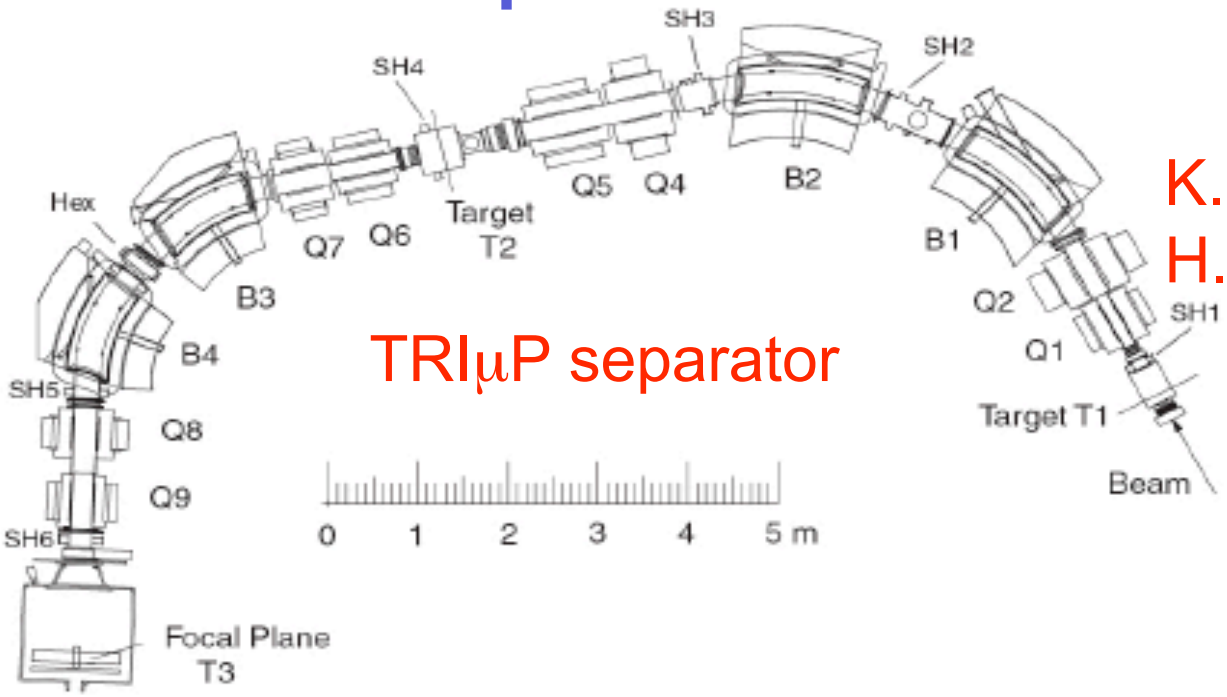
Christian Diget
Solveig Hyldegaard



Christian Diget
Solveig Hyldegaard

KVI Experiment

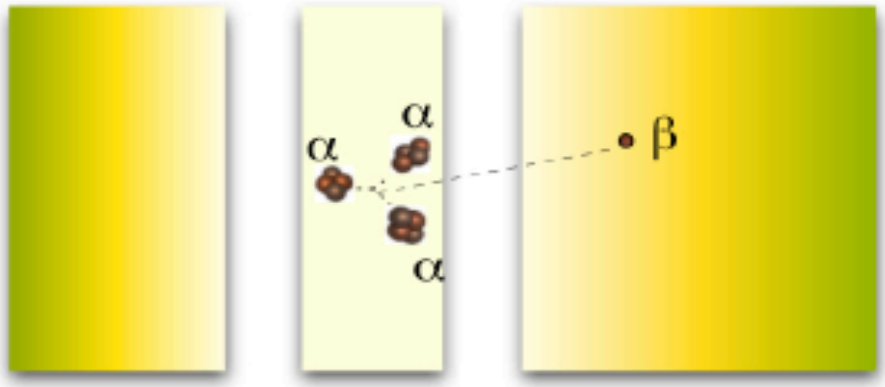
Solveig Hyldegaard

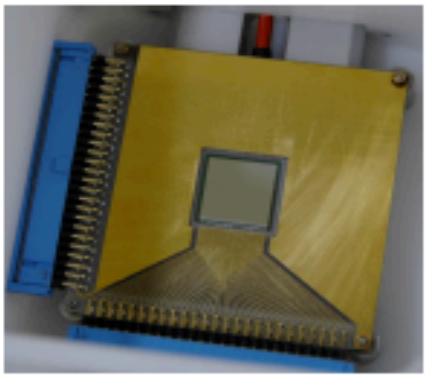


TRIμP separator

K. Jungmann
H. Wilschut

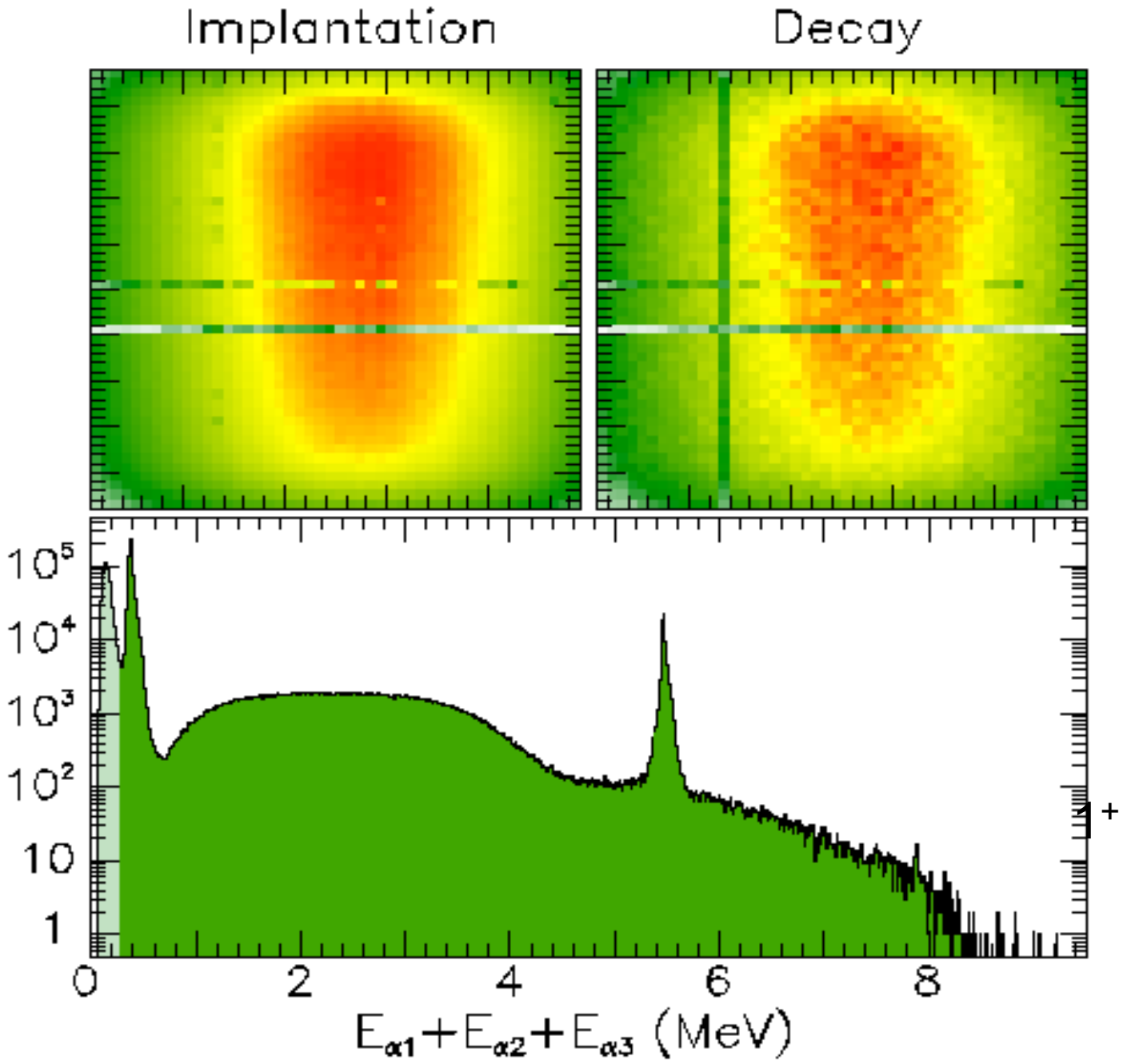
$^{12}N/^{12}B$ ⟹





5 days beam time

R.Raabe



^{12}N Q_{beta}=16.32

15.11 1$^+$

12.71 1$^+$

≈10 0$^+$

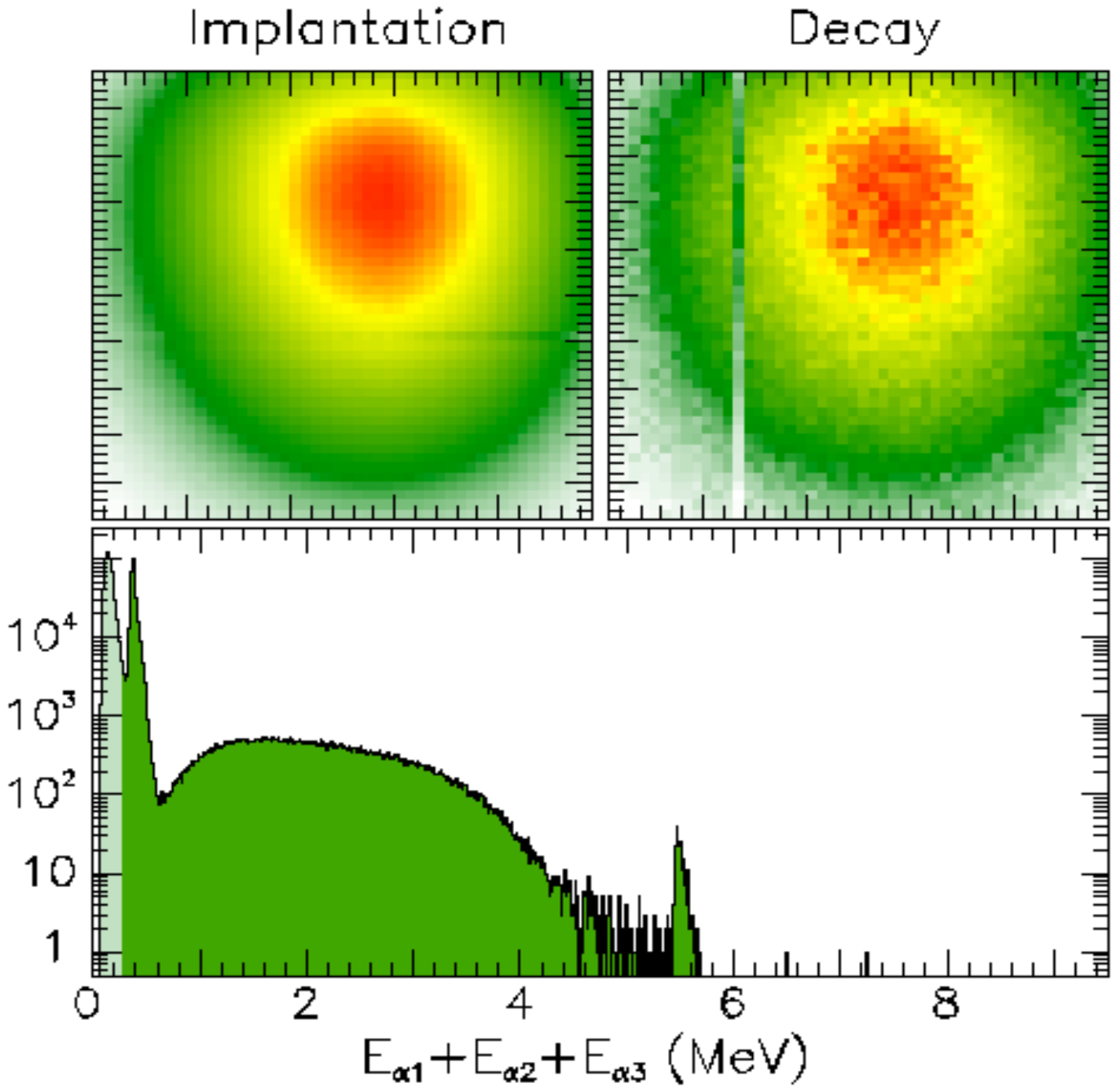
7.65 0$^+$

4.44 2$^+$

g.s. 0$^+$

^{12}C

Solveig Hyldegaard



15.11 1^+

^{12}B Q_{beta}=13.37

12.71 1^+

≈10 0^+

7.65 0^+

4.44 2^+

g.s. 0^+

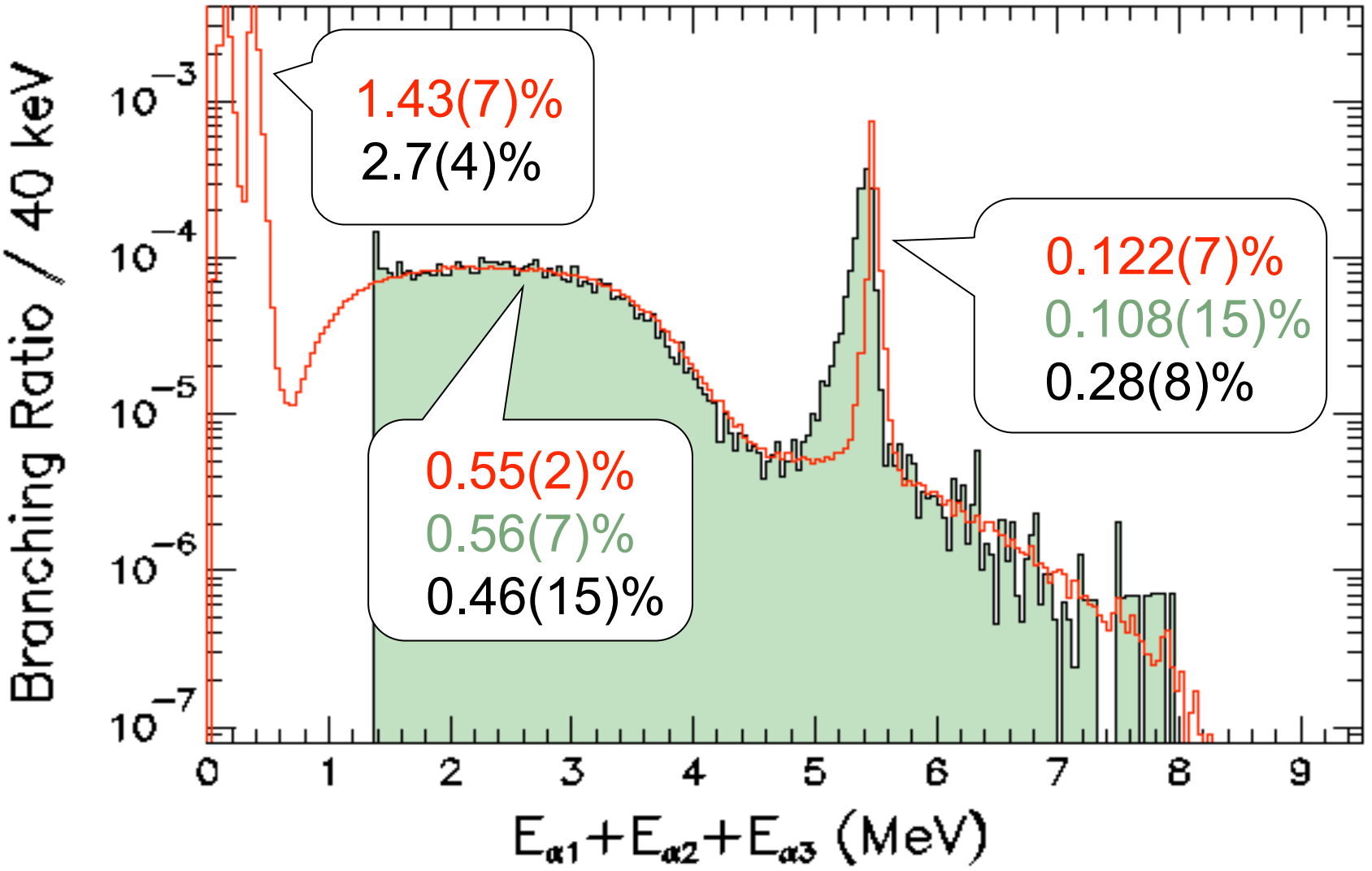
^{12}C

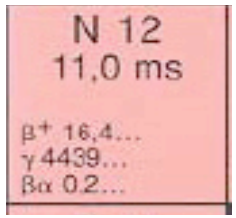
Solveig Hyldegaard

Comparing the two experiments

KVI
#^{12}N =
8.8×10^{7}

JYFL
#^{12}N =
1.2×10^{8}

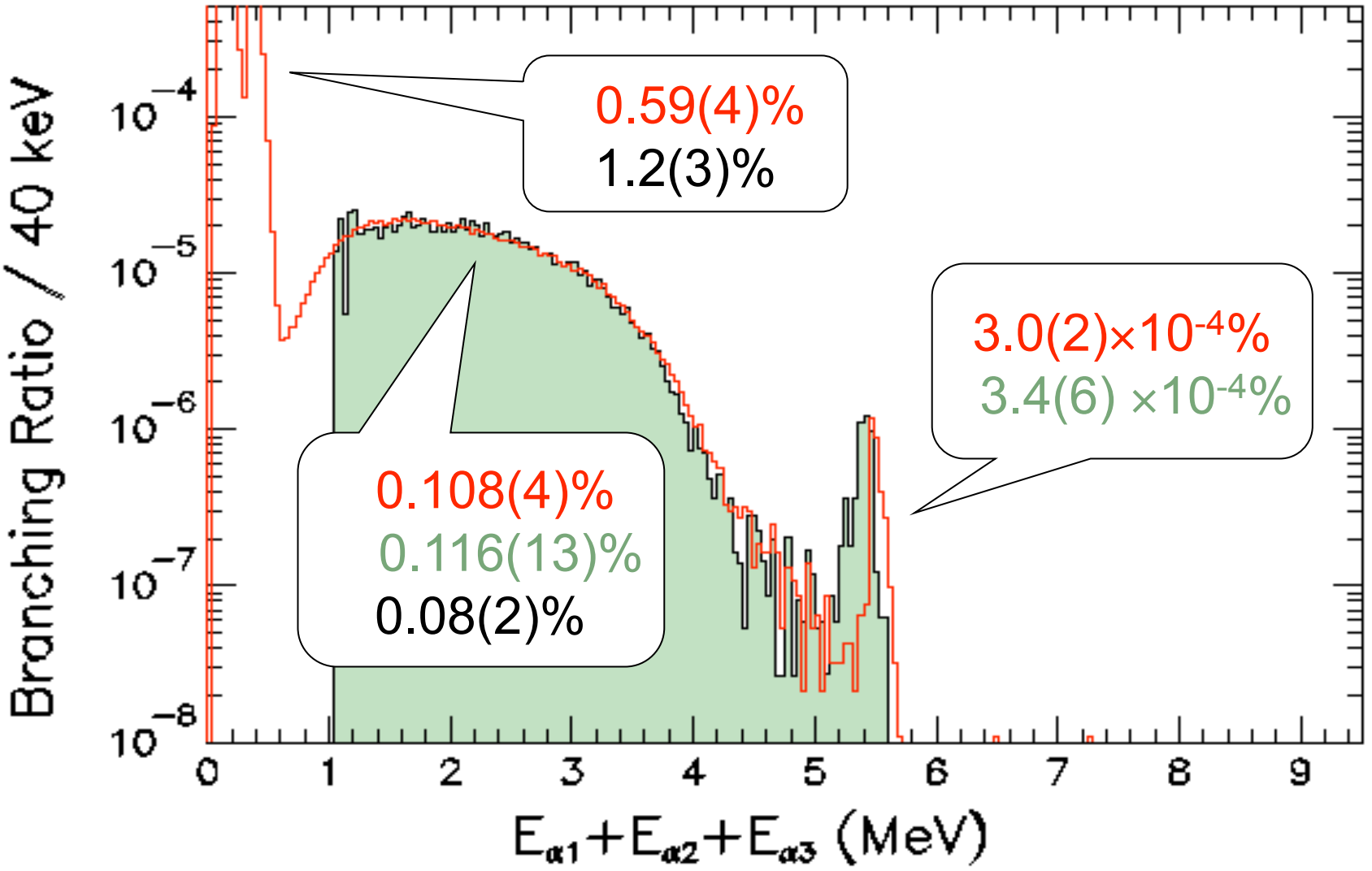


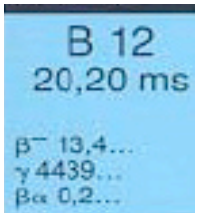


Comparing the two experiments

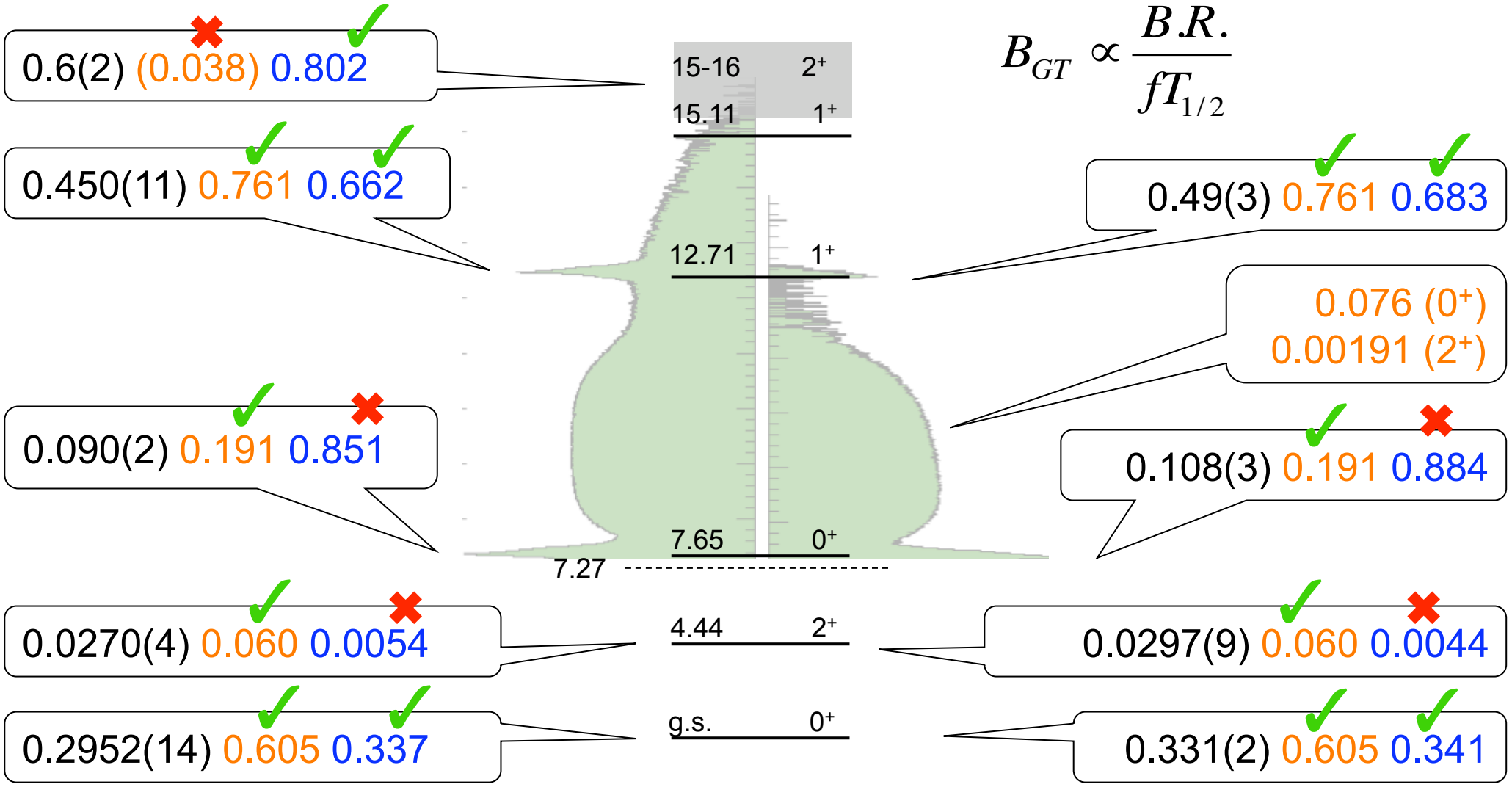
KVI
#^{12}B =
9.3×10^{7}

JYFL
#^{12}B =
9.7×10^{8}





Comparing DATA to AMD & no-core SM

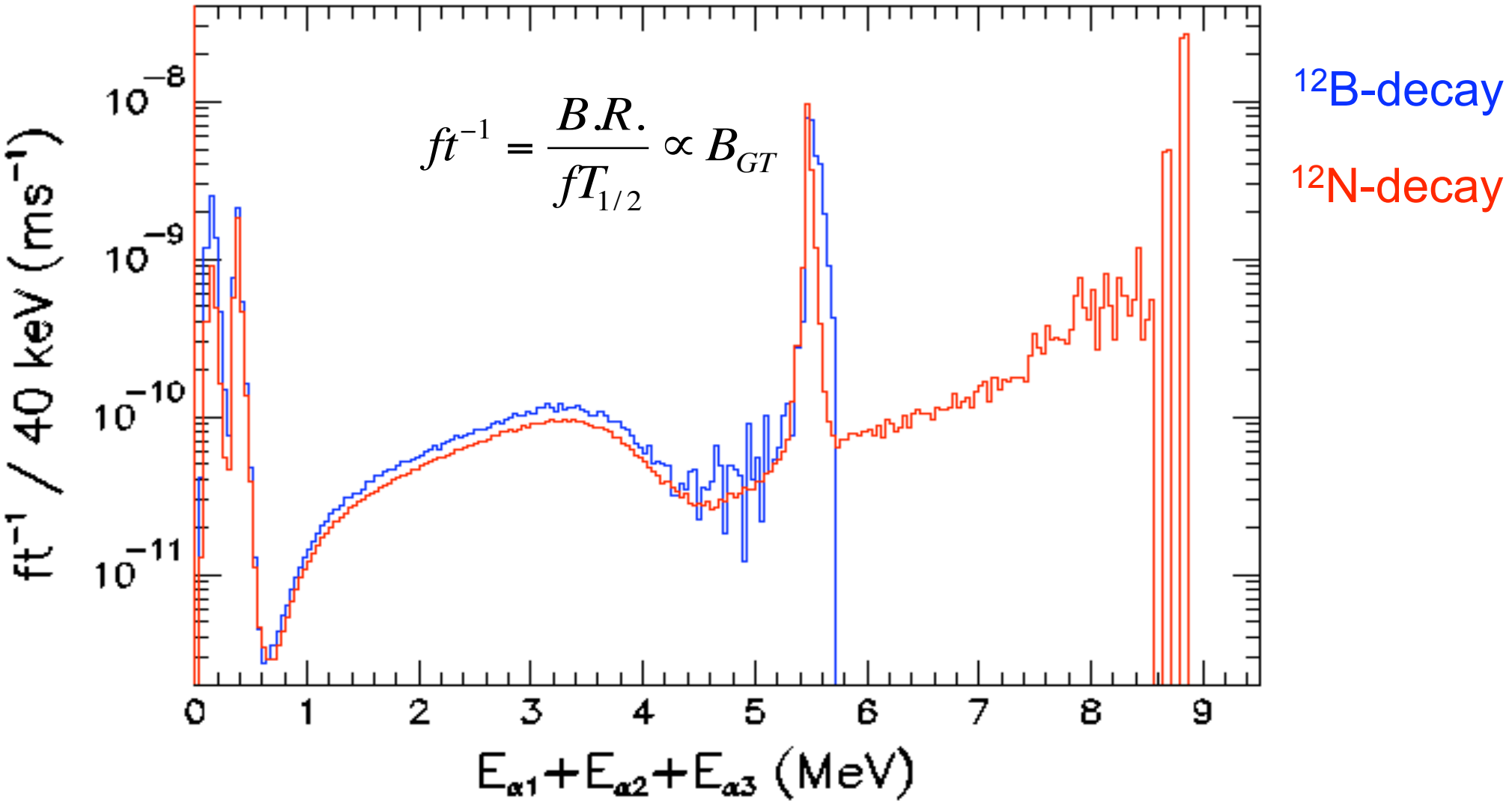


$$B_{GT} \propto \frac{B.R.}{fT_{1/2}}$$

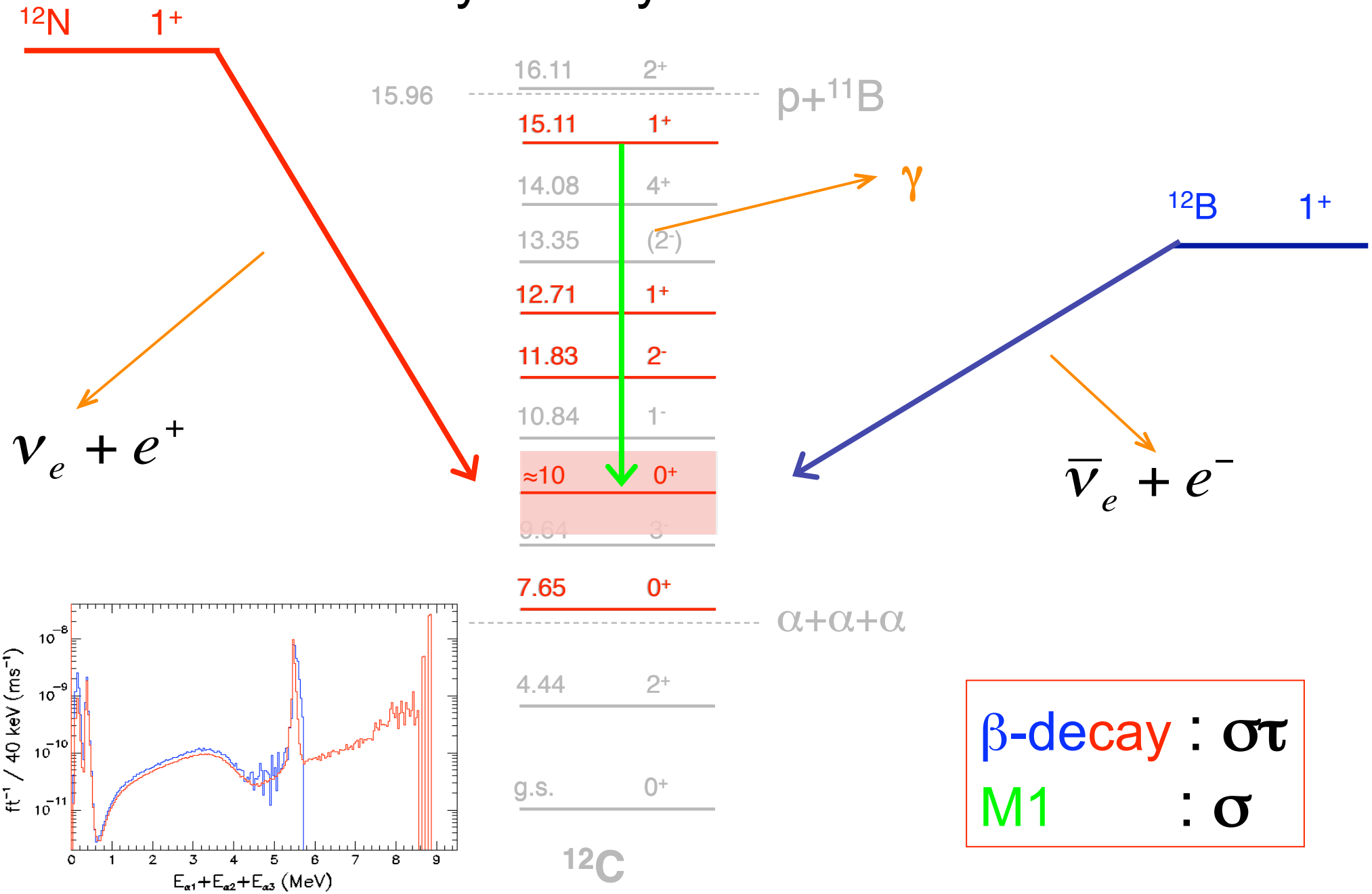
AMD : Kanada En'yo, Prog. Theo. Phys. **117** (2007) 655.

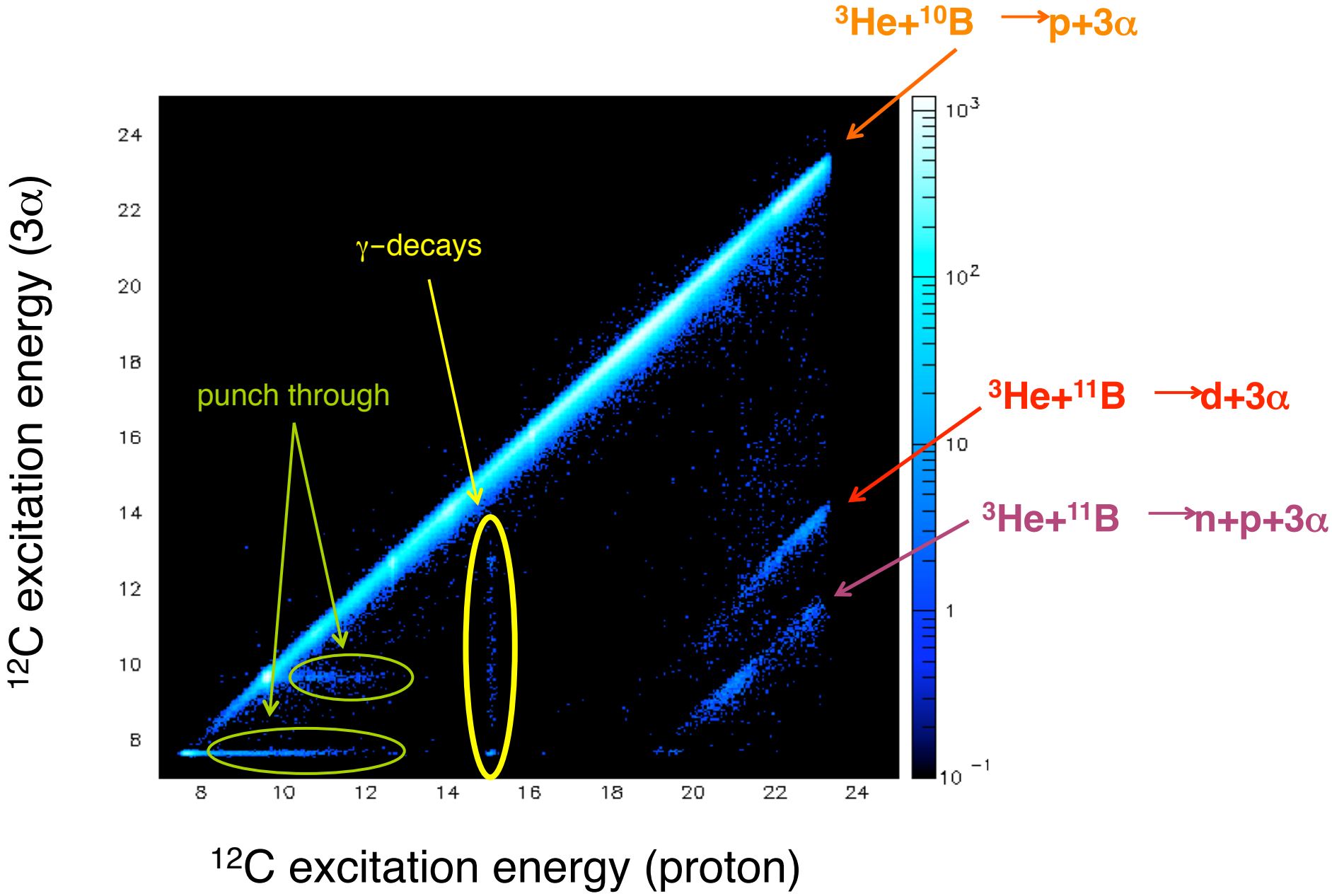
No-core SM : C. Forssén *et al*. private communication

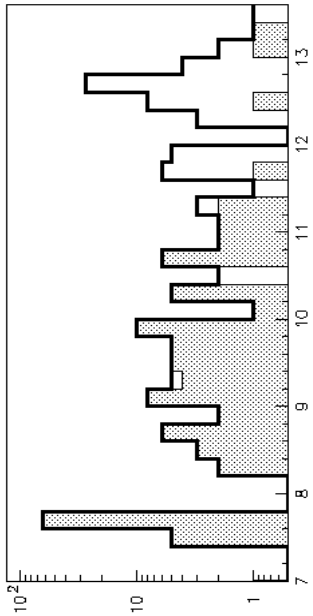
Mirror symmetry for unbound states

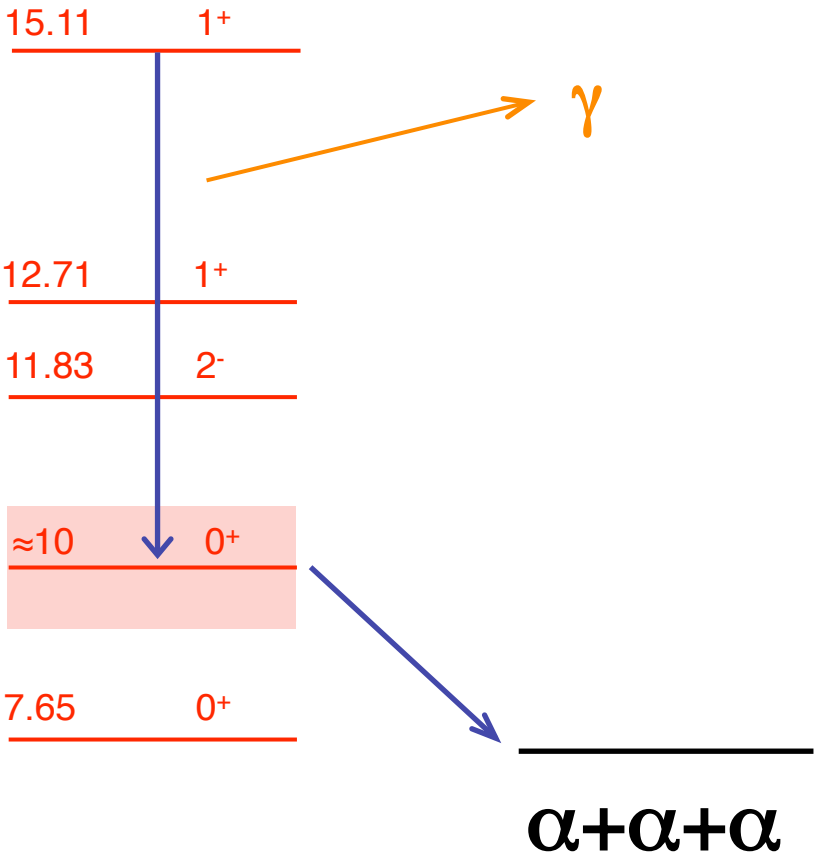


Mirror symmetry for unbound states



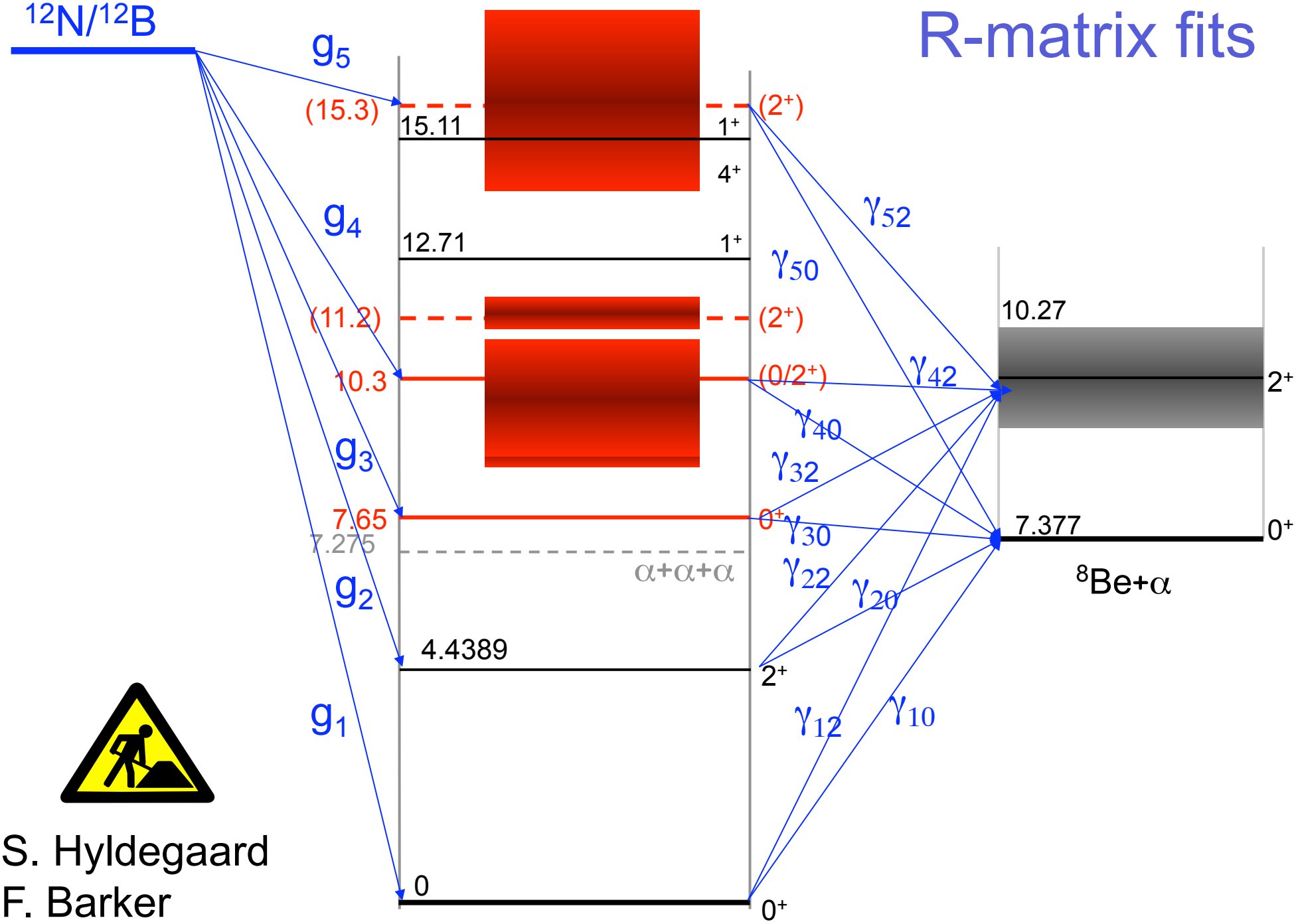

$^{3}He+^{10}B \rightarrow p+3\alpha$
$^{3}He+^{11}B \rightarrow d+3\alpha$
$^{3}He+^{11}B \rightarrow n+p+3\alpha$
γ−decays
punch through
^{12}C excitation energy (3α)
^{12}C excitation energy (proton)
24
22
20
18
16
14
12
10
8
8
10
12
14
16
18
20
22
24
10^{3}
10^{2}
10
1
10^{-1}





Alburger & Wilkinson, Phys. Rev. **C5** (1972) 384.

R-matrix fits



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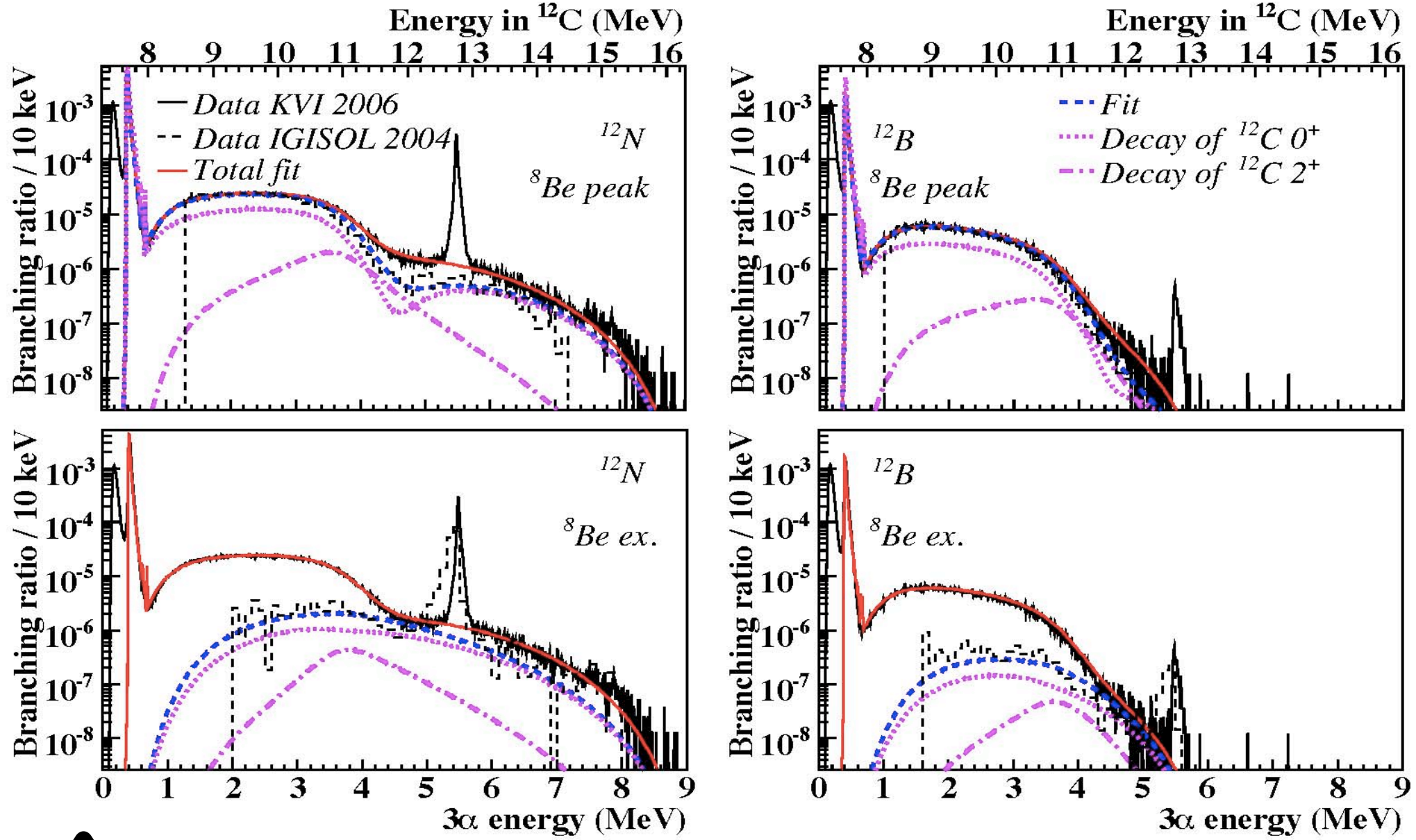
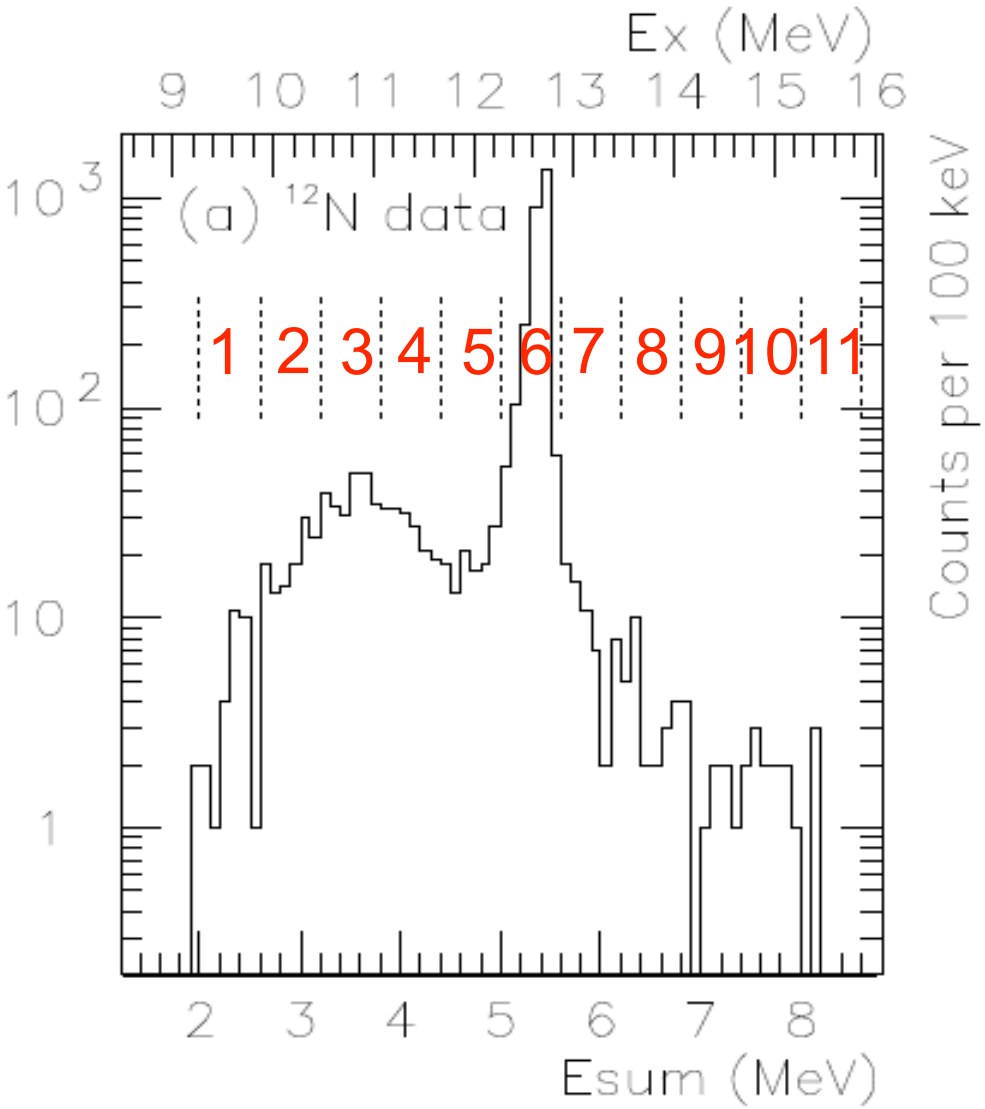
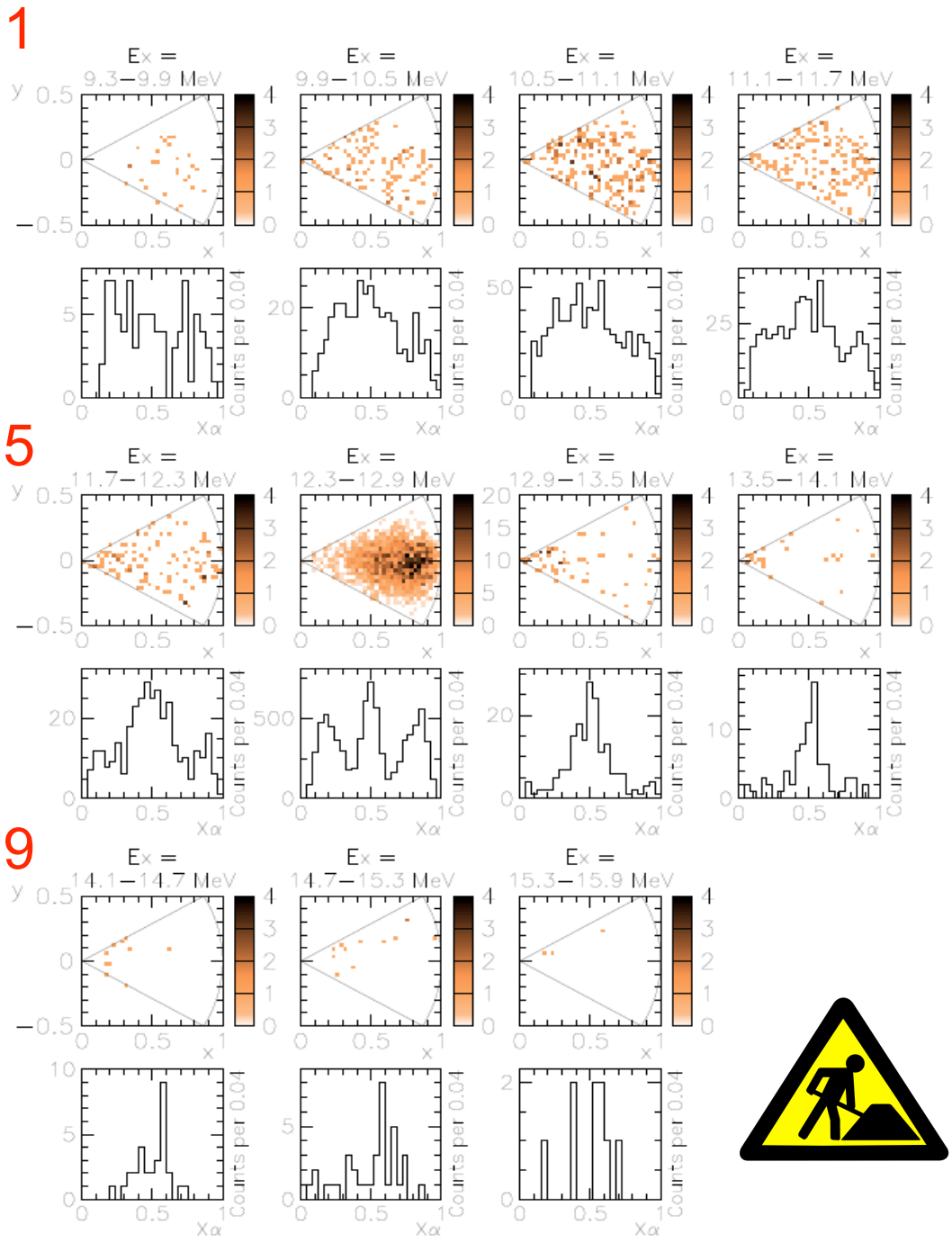
F. Barker


Energy in ^{12}C (MeV)
8 9 10 11 12 13 14 15 16
Branching ratio / 10 keV
10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8}
Data KVI 2006
Data IGISOL 2004
Total fit
^{12}N
^{8}Be peak
^{12}N
^{8}Be ex.
0 1 2 3 4 5 6 7 8 9
3α energy (MeV)
Energy in ^{12}C (MeV)
8 9 10 11 12 13 14 15 16
Branching ratio / 10 keV
10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8}
Fit
Decay of ^{12}C 0^{+}
Decay of ^{12}C 2^{+}
^{12}B
^{8}Be peak
^{12}B
^{8}Be ex.
0 1 2 3 4 5 6 7 8 9
3α energy (MeV)

Dalitz distributions as Spectroscopic tool





Summary

- β-decay now well measured with two methods
  - 10-20 times more precise branching ratios.
  - R-matrix fits in progress.
  - There is a 0^+_3 state around 11MeV (Seen in both decay and scattering).
  - One or more 2^+ states at 11-16MeV.
  - If a lower 2^+ state exists it is weakly populated in decay.
- Dalitz distributions now well measured
  - Spectroscopic tool for J^π determination (symmetry).
  - Population of 10MeV region in 15.11MeV γ−decay.
  - Need consistent understanding of decay and reaction data.
  - Search for “new” states.
- Need better theory to interpret results !

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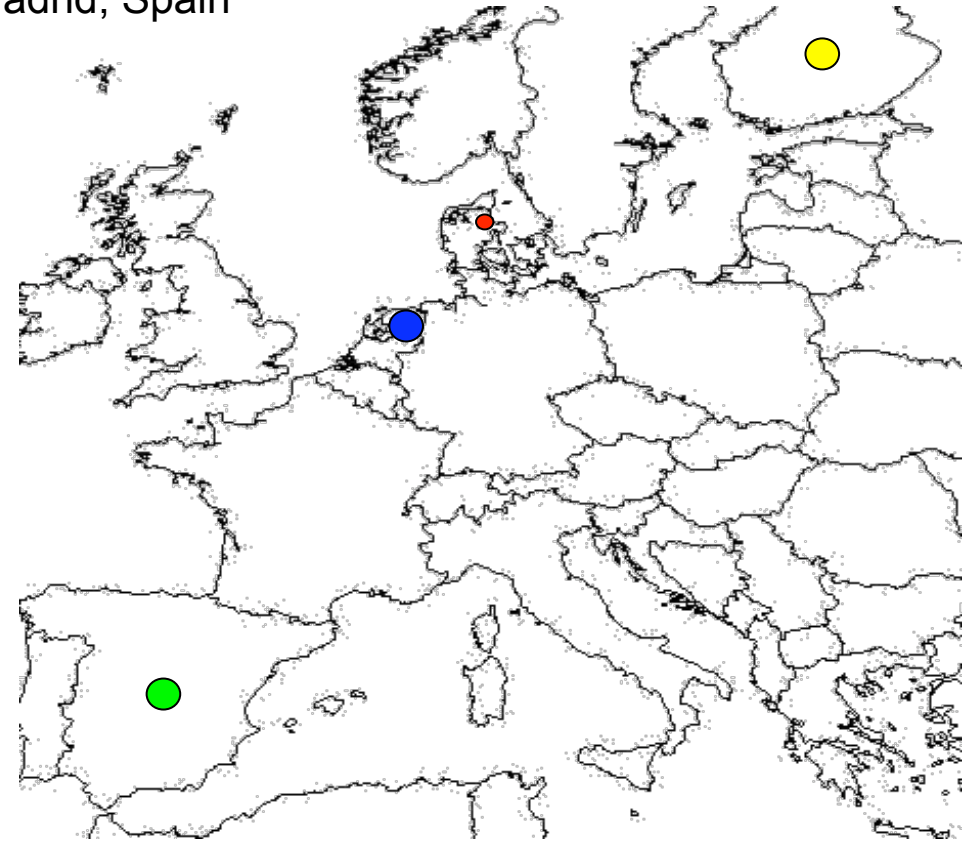
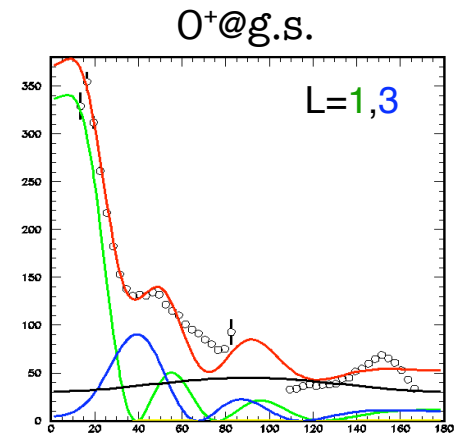
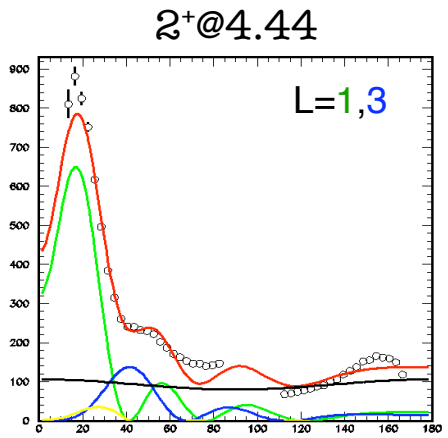
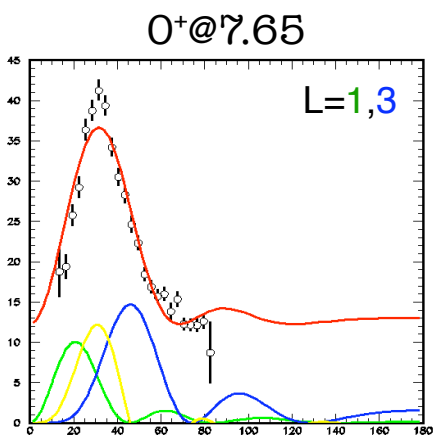
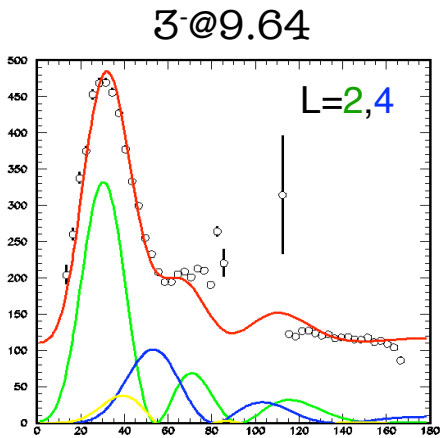


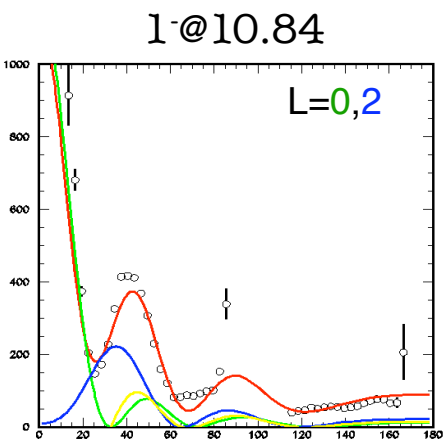
• K. Jungmann, S. Brandenburg, H. Wilschut, P. Dendooven, A. Rogachevskiy,
G. Onderwater, E. Traykov, M. Sohani, KVI, Groningen, The Netherlands

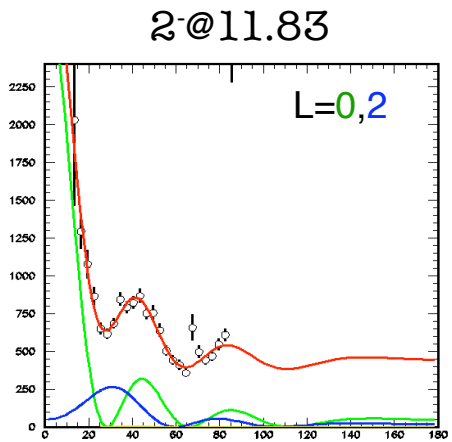


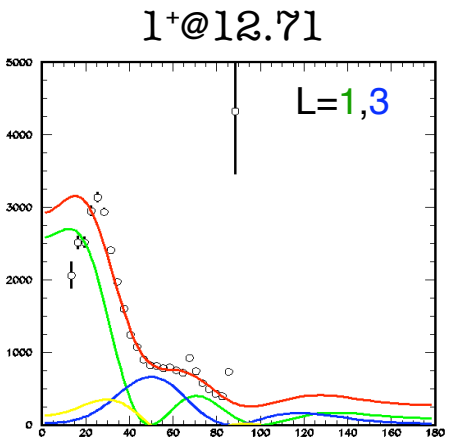


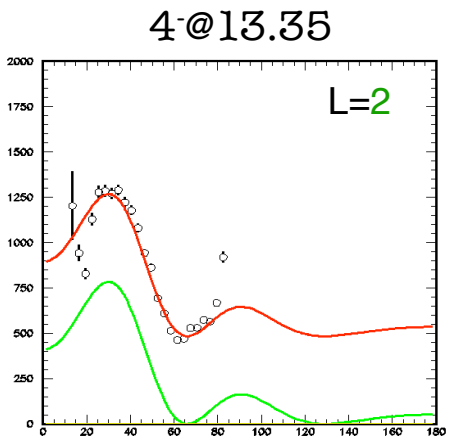


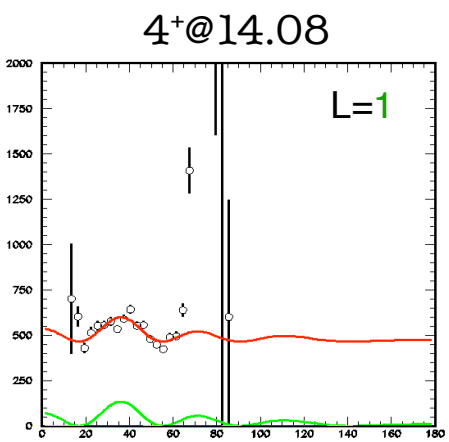










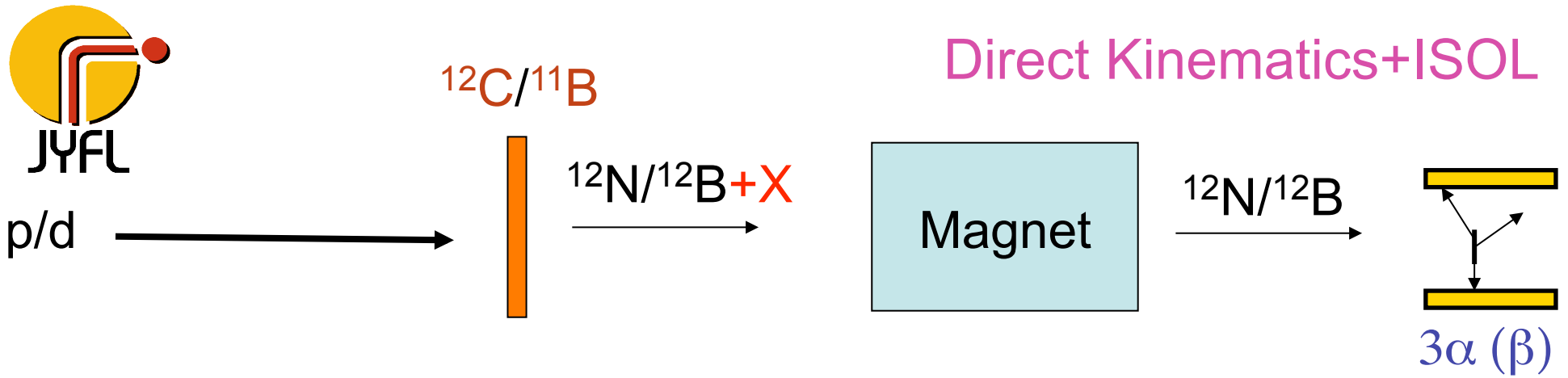


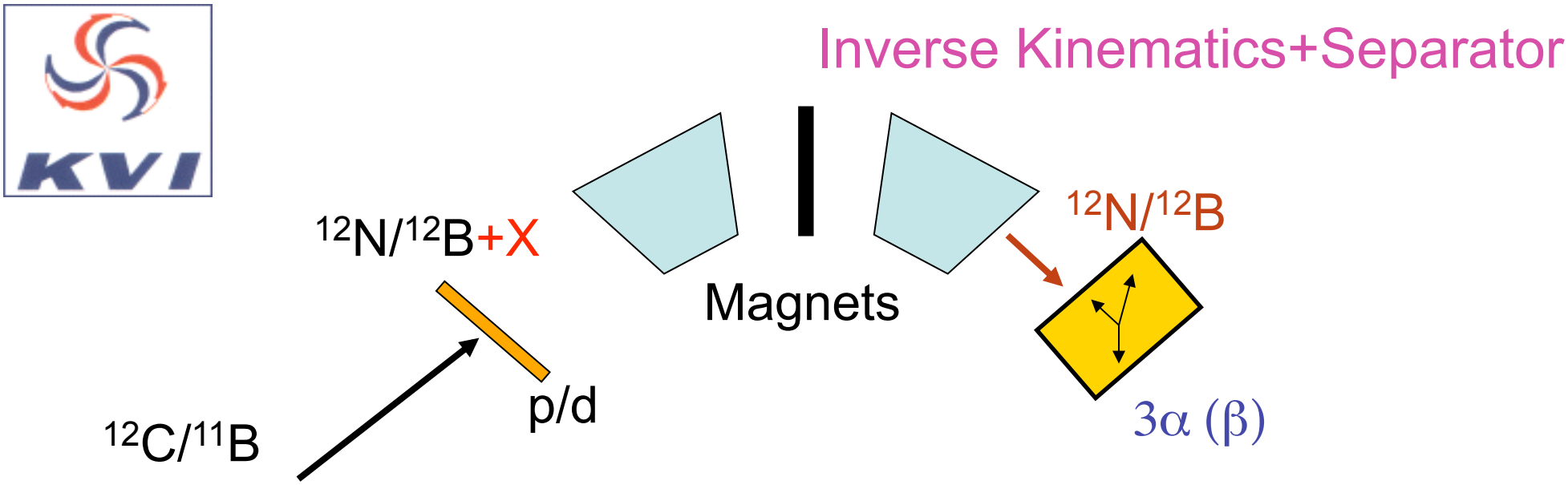
Deuteron angular distributions

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} = A_1^2[j_{L_1}(sqR)]^2 + A_2^2[j_{L_2}(sqR)]^2 + 2A_1A_2\cos(\psi_{12})j_{L_1}(sqR)j_{L_2}(sqR)$$

$$q^2 = k_\alpha^2 + k_\beta^2 - 2k_\alpha k_\beta \cos\theta$$

$$\text{Background} = c_1 + c_2 \sin^2\theta$$


JYFL
Direct Kinematics+ISOL
12C/11B
p/d
12N/12B+X
Magnet
12N/12B
3α (β)


KVI
Inverse Kinematics+Separator
12N/12B+X
Magnets
12N/12B
12C/11B
p/d
3α (β)