Study of the beta-delayed alpha decay of ^{16}N

M.J.G. Borge[1], L.M. Fraile[2], H.O.U. Fynbo[3], A. Heinz[4], A.M. Howard[3], J.S. Johansen[3], H.T. Johansson[4], B. Jonson[4], O.S. Kirsebom[3], M.V. Lund[3], I.M. Alonso[5], M. Munch[3], E. Nacher[5], T. Nilsson[4], A. Perea[5], J. Refsgaard[3], K. Riisager[3], O. Tengblad[5], R. Thies[4] and V. Vedia[2]

[1] ISOLDE, CERN
[2] Universidad Complutense de Madrid, Madrid, Spain
[3] Aarhus University, Denmark
[4] Chalmers University of Technology, Göteborg, Sweden
[5] CSIC, Madrid, Spain

Spokesperson: O. S. Kirsebom

Astrophysical motivation

$^{12}C(\alpha,\gamma)^{16}O$

Nucleosynthesis

- intermediate mass (A=16-40)
- s-process only (^{70}Ge, ^{76}Se, ^{80}Kr, ^{82}Kr, ^{86}Sr, ^{87}Sr)
- gamma-ray emitters (^{26}Al, ^{44}Ti, ^{60}Fe)
- ν-process nuclei (^{7}Li, ^{11}B, ^{19}F, ^{138}La, ^{180}Ta)

West, Heger and Austin, Ap. J. **769**:2 (2013)
Woosley and Heger, Phys. Rep. **442** (2007) 269-283
Tur, Heger and Austin, Ap. J. **718** (2010) 357
Austin, West and Heger, Phys. Rev. Lett. **112** (2014) 111101

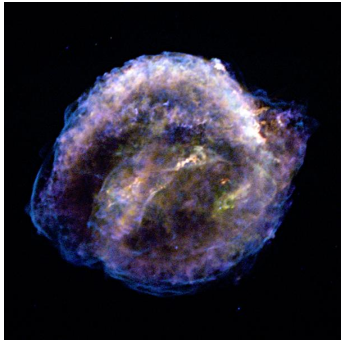
Stellar evolution and cosmology

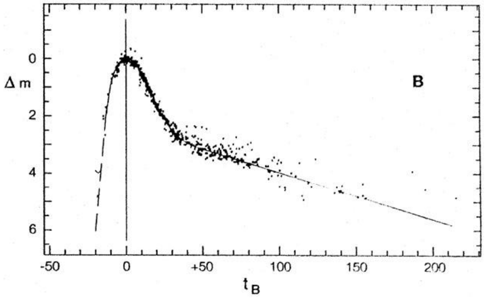
- CCSN remnant mass

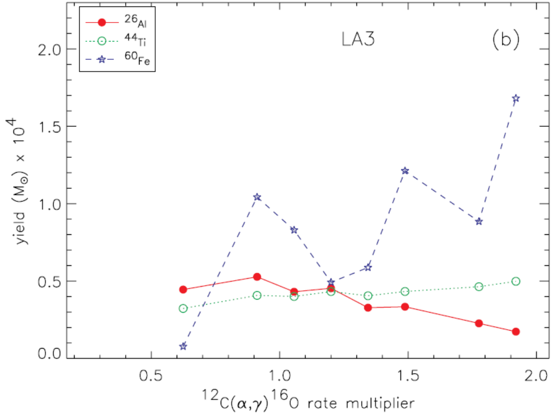
Woosley *et al.* Nuclear Physics **A718** (2003) 3c-12c

- SN-Ia light curve

Thielemann *et al.* New Astron. Rev. **48** (2004) 605–610



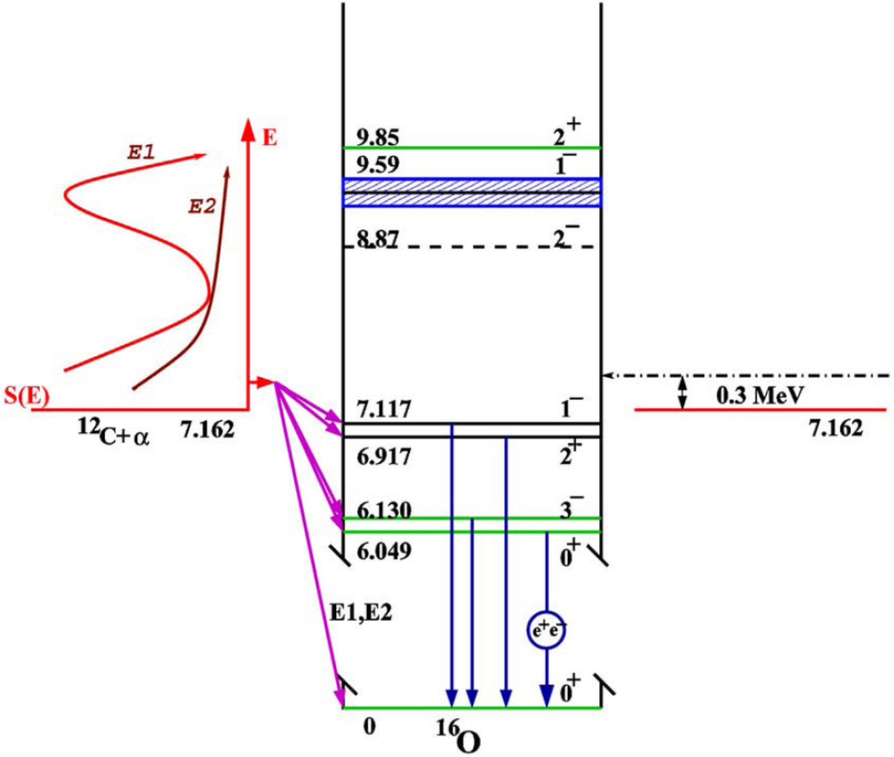




Experimental techniques

T=0.2 GK
Gamow energy ≈ 300 keV
σ ≈ 10^{-17} barn

- ^{12}C(α,γ)
  - normal or inverse kinematics
  - γ-array and/or recoil separator
  - γ angular distribution used to separate E1 and E2
  - lowest energy = 0.98 MeV



Indirect methods to determine **reduced alpha widths (γ_α)**:

- ^{12}C(α,α)
- $^{16}N \xrightarrow[\beta\nu]{} {}^{16}O^* \rightarrow \alpha + {}^{12}C$
- α-transfer reactions (^{6}Li,d), (^{7}Be,^{3}He), (^{11}B,^{7}Li)

Current status

18%

NACRE-II:

S(300) = 148 ± 27 keV b

Xu *et al.* Nucl. Phys. **A918** (2013) 61–169

15%

Most optimistic:

S(300) = 161 ±19 (stat) +8-2 (syst) keV b

Schürmann *et al.* Phys. Lett. B **711** (2012) 35–40

factor of ~3

Most pessimistic:

$S_{E1}(300) \approx 10-80$ keV b

$S_{E2}(300) \approx 60-154$ keV b

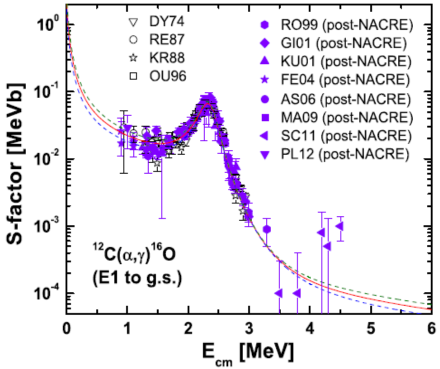
Gai, Phys. Rev. C **88**, 062801(R) (2013)

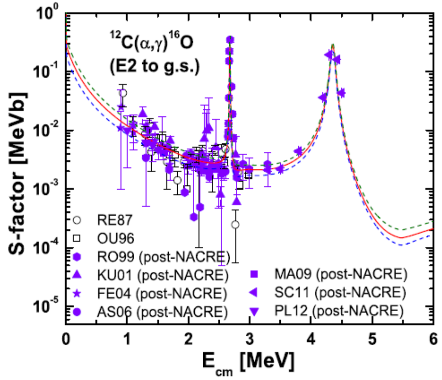
12%

Constraint from astrophysics:

S(300) ≈ 170 ± 20 keV b

Weaver & Woosley, Phys. Rep. **227** (1993) 65





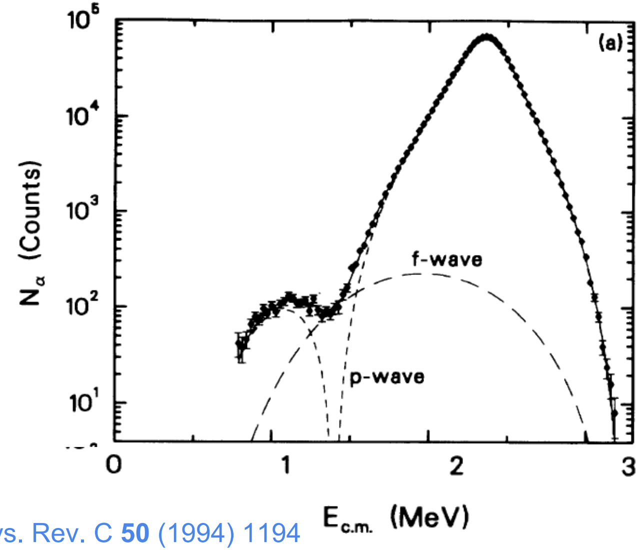
$S_{E1}(300) = 80 \pm 18$ keV b

$S_{E2}(300) = 61 \pm 19$ keV b

$S_{casc}(300) = 6.5_{-2.2}^{+4.7}$ keV b

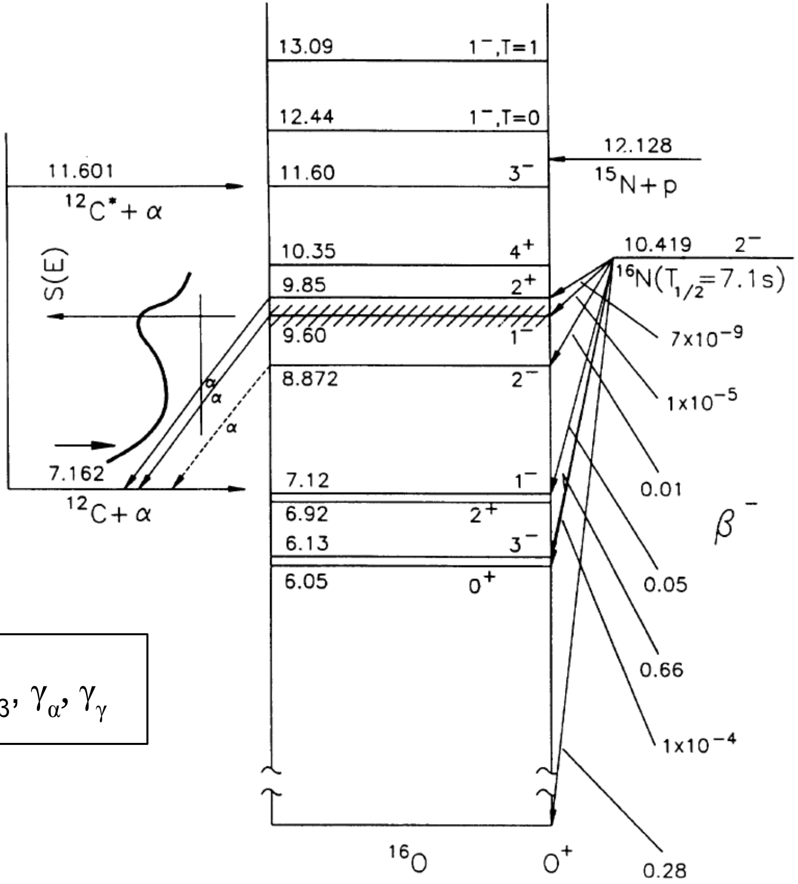
β-delayed α-decay of ^{16}N

- Allowed GT transitions ⇒ 1^-, 2^-, 3^-
- Influence of subthreshold 1^- state at 7.12 MeV amplified by large br_β.
- γ_α(7.12) determined via *R*-matrix fit:



Azuma *et al.* Phys. Rev. C **50** (1994) 1194

E_0, br_β, γ_α, γ_γ



br_β for the 9.60 MeV state

Previous measurements:

- $(1.19 \pm 0.10) \times 10^{-5}$ and $(1.13 \pm 0.08) \times 10^{-5}$
  Hättig, Hünchen, and Wäffler, Phys. Rev. Lett. **25** (1970) 941
  Neubeck, H. Schober, and Wäffler, Phys. Rev. C **10** (1974) 320.
- $(1.3 \pm 0.3) \times 10^{-5}$
  Zhao et al. Phys. Rev. C **48** (1993) 429.

⇓

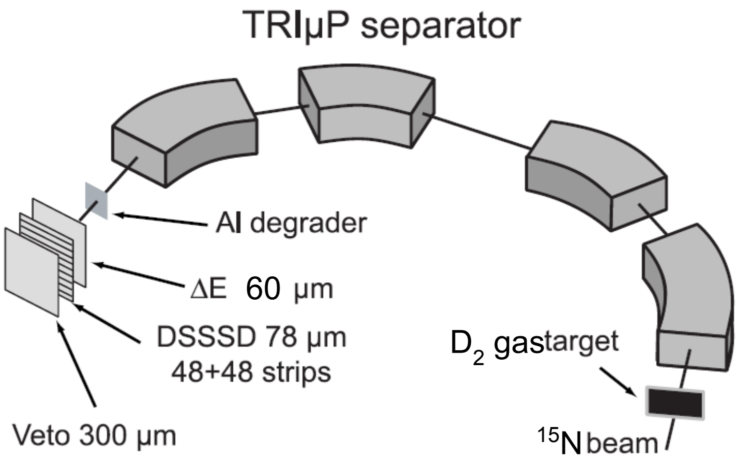
"The origin of the error is unknown to us."
"A revised measurement with improved errors of this branching ratio is desirable."
Buchmann, Ruprecht and Ruiz, Phys. Rev. C **80** (2009) 045803

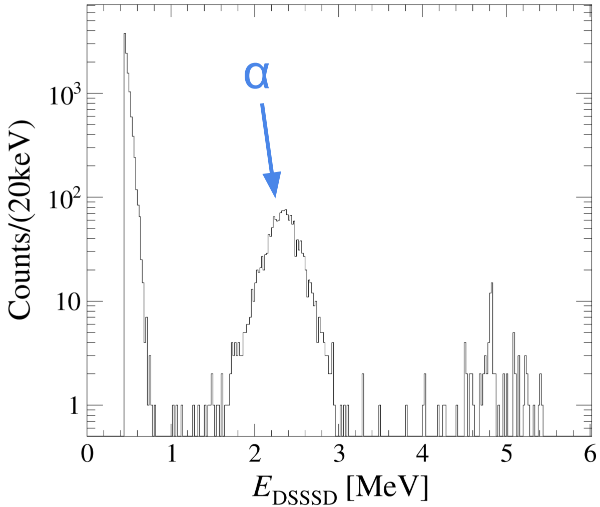
TUNL (1993)

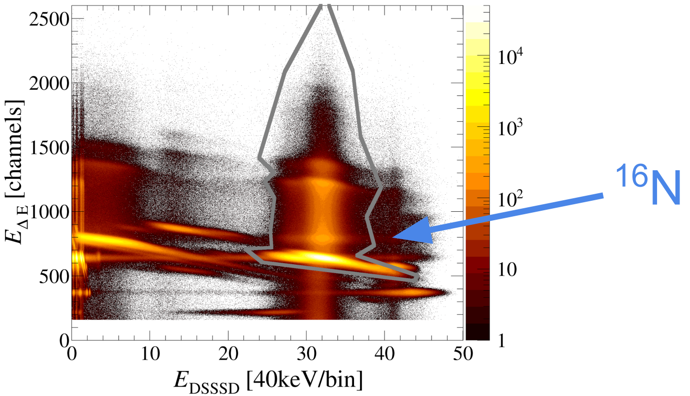
Final State		Branch (%)
$^{16}O^*$ (MeV)	J^π	
0	0^+	28.0 ± 0.5 [a]
6.05	0^+	$(1.2 \pm 0.4) \times 10^{-2}$
6.13	3^-	66.2 ± 0.6 [b]
7.12	1^-	4.8 ± 0.4
8.87	2^-	1.06 ± 0.07 [c]
9.59	1^-	$(1.20 \pm 0.05) \times 10^{-3}$
9.84	2^+	$(6.5 \pm 2.0) \times 10^{-7}$

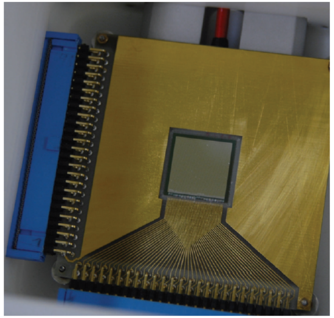
KVI experiment (2013)

- Normalised by counting no. of implanted ^{16}N
- Preliminary result: $(1.54 \pm 0.08) \times 10^{-5}$
- 30% change in br_β ⇒ ~30% change in $S_{E1}(300)$
- Deadtime correction ~45%





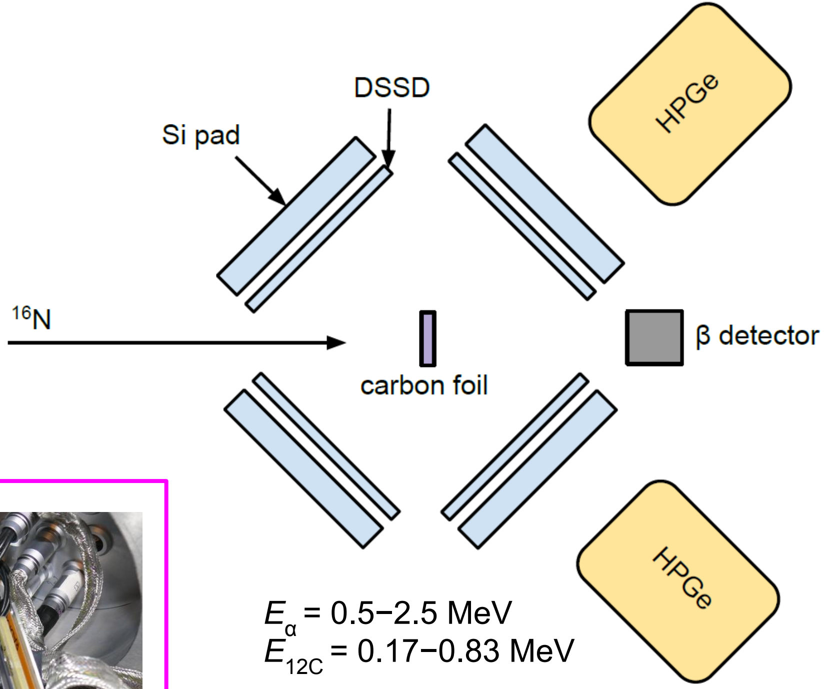




ISOLDE proposal

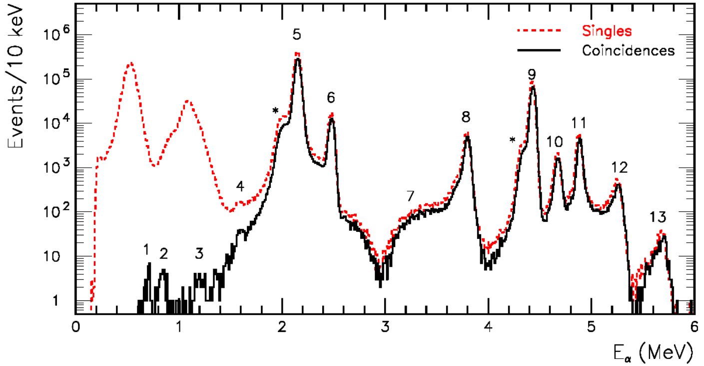
Method:

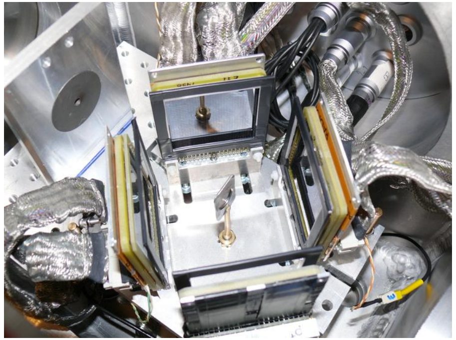
- Detect α+^{12}C coincidences with high efficiency using array of DSSDs (26% of 4π)
- $\beta\gamma$ lines 2.74 and 6.13 MeV used for normalisation



E_α = 0.5−2.5 MeV
E_{12C} = 0.17−0.83 MeV

Similar setup used to study $\beta\alpha$ decay of ^{8}B and ^{20}Na at IGISOL in 2008:





Kirsebom *et al.* Phys. Rev. C **83** (2011) 065802
Laursen *et al.* Eur. Phys. J. A **49** (2013) 1-13

Calibration and normalisation

ENERGY CALIBRATION:

- On-line: βα lines of ^{18}N ($t_{1/2}$=620 ms) at 1.081(1) and 1.409(1) MeV.
- Off-line: 3.182 MeV α-decay line of ^{148}Gd.

NORMALISATION:

Method 1: Efficiency calibration of γ-detectors

- Off-line: Absolutely calibrated sources (E_γ=0−1.5 MeV).
- On-line: βγ lines of ^{34}Ar known with < 3% precision (E_γ=0.67, 2.58 and 3.13 MeV).
- Normalisation: βγ line of ^{16}N at 2.74 MeV (known with 7% precision).

Method 2: βγ/β ratio method

- Normalisation: βγ line ^{16}N at 6.13 MeV (known with 0.9% precision).

^{34}Ar → ^{34}Cl*+β+ν ($t_{1/2}$=845 ms)

Eγ†	E(level)	Iγ†§
460.8 *10*	460.8	36.5 *36*
665.8 *10*	665.8	100
2579.4 *14*	2579.5	34.5 *10*
3129.0 *10*	3129.2	52.1 *12*

Beam production

Same target and same ion source for all three beams: ^{16}N, ^{18}N, ^{34}Ar

- CaO target
- Cooled plasma ion-source
- ^{16}N and ^{18}N released as N_2 and N_2H

^{16}N on *A*=30

$t_{1/2}$=7.13 s

Yields:
In 2009 at 500ºC: 1.5×10^3 μC^{-1} (*)
In 2014 at 500ºC: 2.0×10^3 μC^{-1}
In 2014 at 800ºC: 50×10^3 μC^{-1}

No β background expected.
^{14}C ($t_{1/2}$=5700 y)

^{18}N on *A*=32

$t_{1/2}$=620 ms

Yield in 2009 at 500ºC: 5 μC^{-1}

β*α* background (br~10^{-5}):
^{16}N ($t_{1/2}$=7.1 s) and ^{18}N ($t_{1/2}$=4.2 s)

β*p* background: ^{32}Ar ($t_{1/2}$=100 ms)

^{34}Ar on *A*=34

$t_{1/2}$=845 ms

Yield database: >10^6 μC^{-1}

(*) Deduced from yield at A=31 (2.2×10^3 μC^{-1})

Beam times

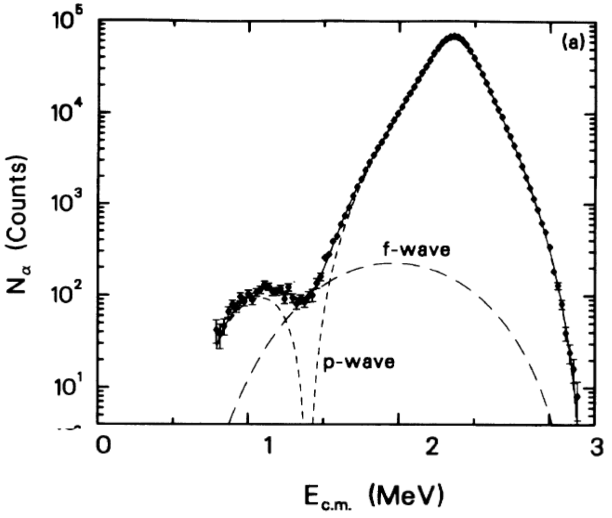
^{16}N

Best-case scenario

- Characterise low-energy part of βα spectrum (0.5−1.0 MeV) and determine br_β with high precision
- ⇒ 10^5 α-decays ⇒ 3×10^{10} implantations
- ⇒ Beam time needed(*) @ 50×10^3 μC^{-1} = 11 shifts

Worst-case scenario

- Determine br_β with statistical precision of 2%
- ⇒ 2.5×10^3 α-decays ⇒ 0.8×10^9 implantations
- ⇒ Beam time needed(*) @ 1.5×10^3 μC^{-1} = 10 shifts



(*) Assuming a proton current of 2 μA

Beam request

- 3 shifts for the ^{18}N energy calibration
  (1.5 at the beginning and 1.5 at the end)
- 1 shift for the ^{34}Ar efficiency calibration
  (0.5 at the beginning and 0.5 at the end)
- 11 shifts for the ^{16}N measurement
  (1 shift to explore the temperature dependence of the production rate and 10 shifts for the actual measurement)

Total: 15 shifts

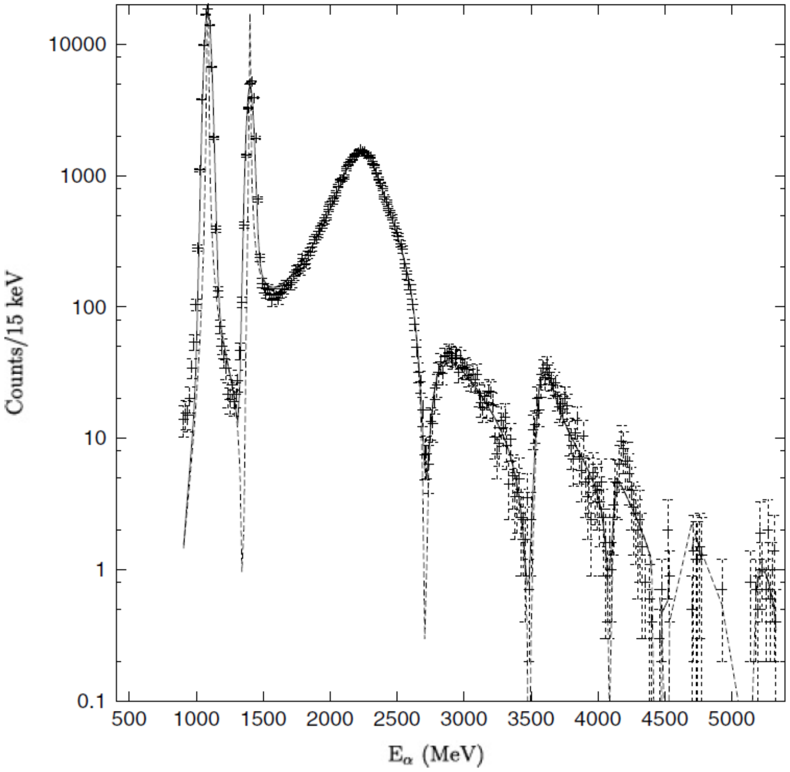
The end

Thank you for your attention!

Beam times

^{18}N

- 1σ energy resolution: δ*E* ≈ 20 keV
- Centroid statistical precision ≈ δ*E*/√*N*
- ⇒ *N* ≈ 1600 needed to reach ±0.5 keV precision
- $br_{\beta\alpha}$ = 6.8% and 1.8%
- ⇒ 3.4 × 10^5 implantations
- ⇒ Beam time needed(*) @ 5 μC^{-1} = 1.5 shifts



Buchmann *et al.* Phys. Rev. C **75** (2007) 012804(R)

(*) Assuming a proton current of 2 μA

Readiness

- Detectors
  - DSSDs and Si pads: Aarhus+Madrid
  - HPGe detectors: ISOLDE
  - β detector (Si or plastic): Aarhus
- Electronics and DAQ: Aarhus+Madrid
- Chamber: Aarhus+Madrid
- Catcher foil: Aarhus