New Results on the β - delayed α – Decay of ^{16}N

K. E. Rehm

Argonne National Laboratory

Why another ^{16}N decay experiment?

Previous Measurements

			S(E1) [keVb]
Mainz (1969-1974)	Si	35 μ	-
TRIUMF (1993-1997)	Si	11-16 μ	57- 82
Yale (1993-1997)	Si	50 μ	95
Seattle (1994-1995)	Si	? μ	-

- All experiments use Si detectors
- Still a large variation in S(E1)

Systematic Uncertainties (PRC 50, 1194(94))

TRIUMF: $S_{E1}(300)=79\pm 16$ (stat) $\pm$ 14(sys) keVb	
Energy calibration	± 10 keVb
β-branching ratio (1^-)	± 6 keVb
^{17}N subtraction	± 5 keVb
Systematic differences between data sets	± 4 keVb
Coincidence efficiency	± 3 keVb
Uncertainty in Γ_γ (7.12 MeV)	± 3 keVb
Uncertainty in energy resolution	± 2 keVb
Normalization of $^{12}C(\alpha,\gamma)^{16}O$	± 2 keVb
^{18}N subtraction	± 1 keVb
Noise events	± 1 keVb

Goals of new experiment:

- Setup with different detectors (different systematic uncertainties)
- Minimize sensitivity to the strong β-background
- Eliminate contributions from $^{17,18}N$ beams
- Improve energy calibration
- Better value for the branching ratio of the 7.116 MeV 1^- state

Outline

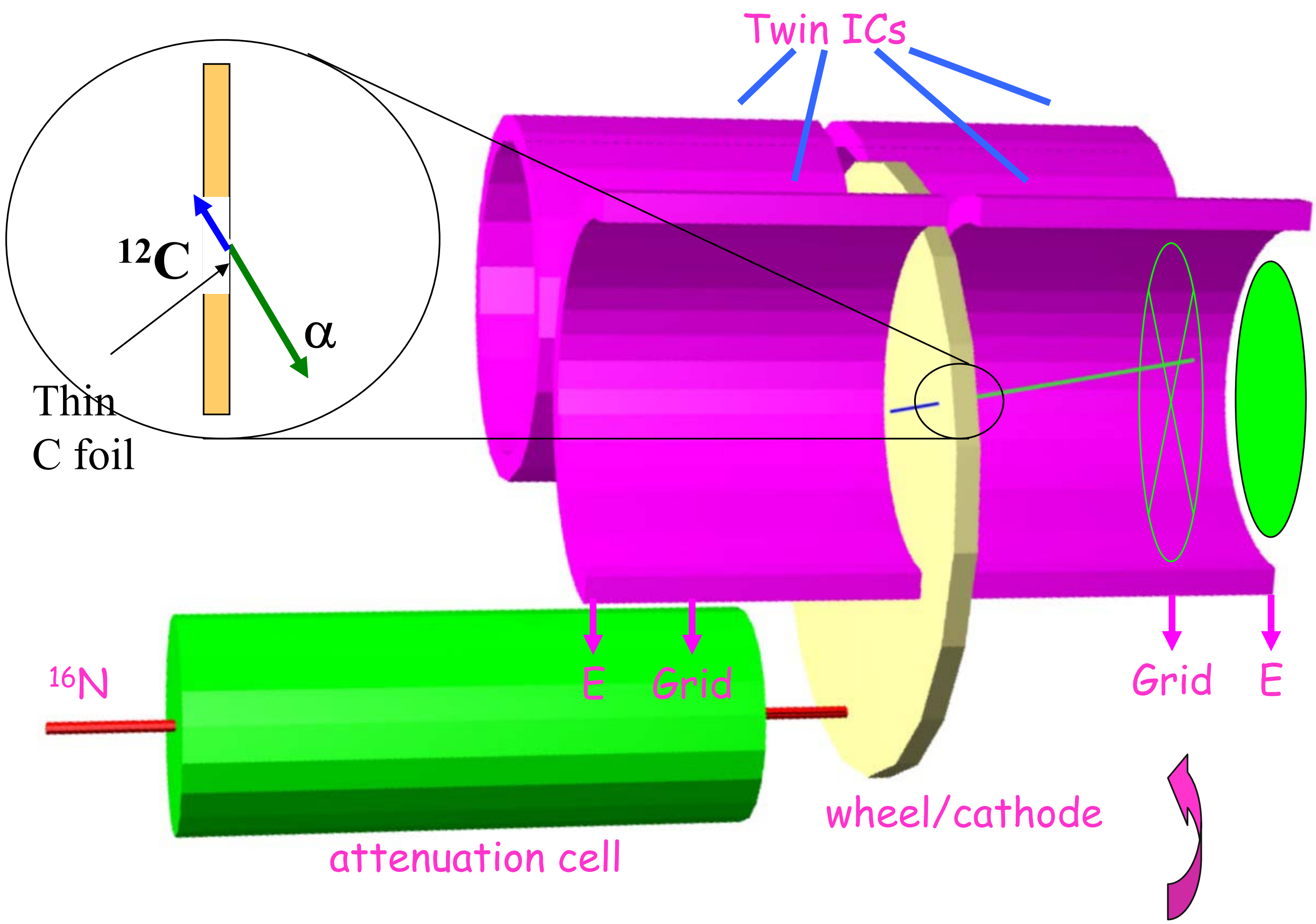
- Twin-ionization chamber
- ^{16}N beam production technique
- Branching ratio experiment at Gammasphere
- Results

Advantages of gas over solid-state detectors

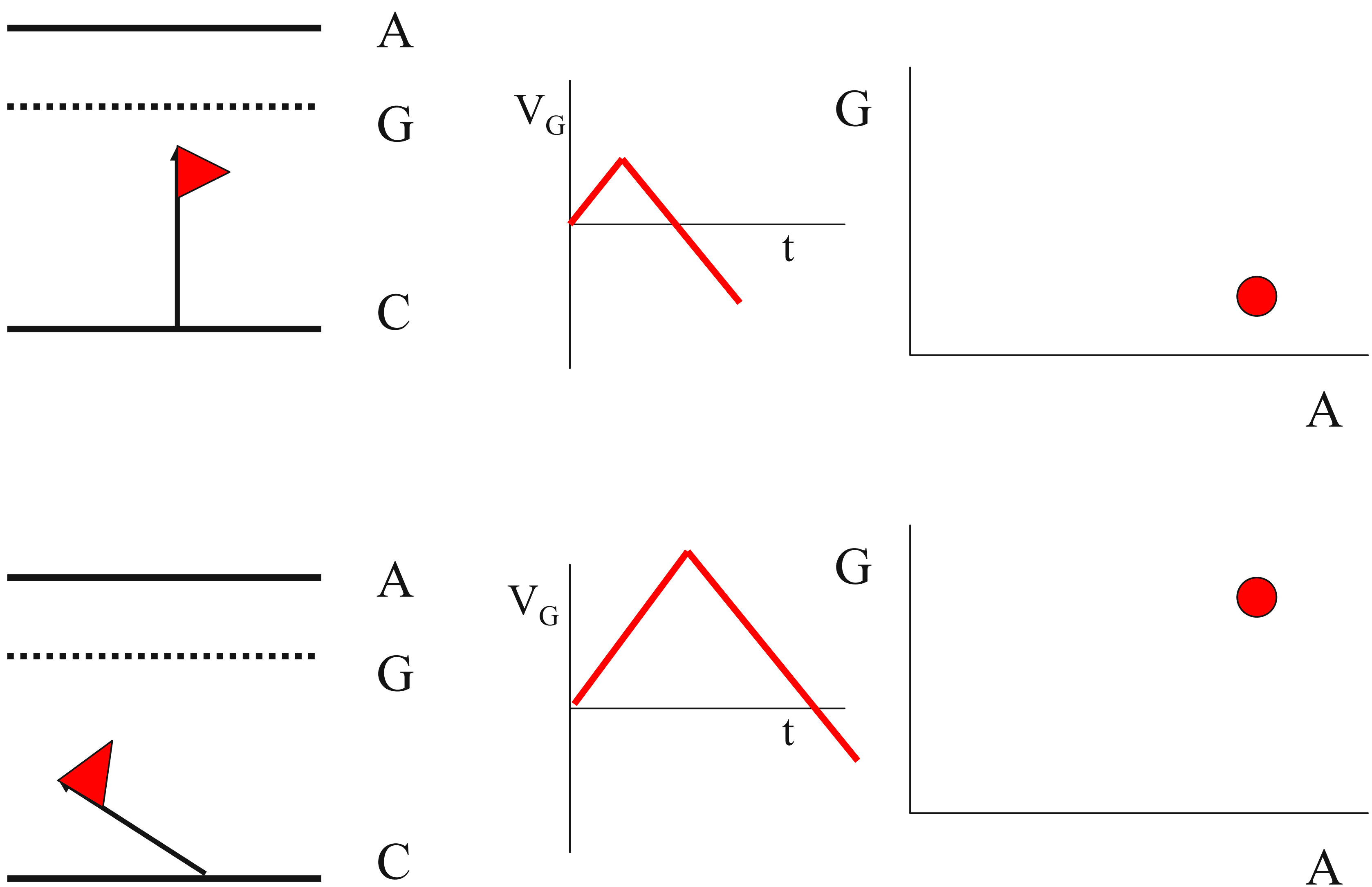
- Choose the thickness exactly as needed.
- This limits β sensitivity to a minimum.
- No radiation damage
- Available with large areas
- Improved homogeneity
- No dead layer
- Smaller pulse height defects
- Provides signal of emission angle (back-to back)

The twin ionization chambers

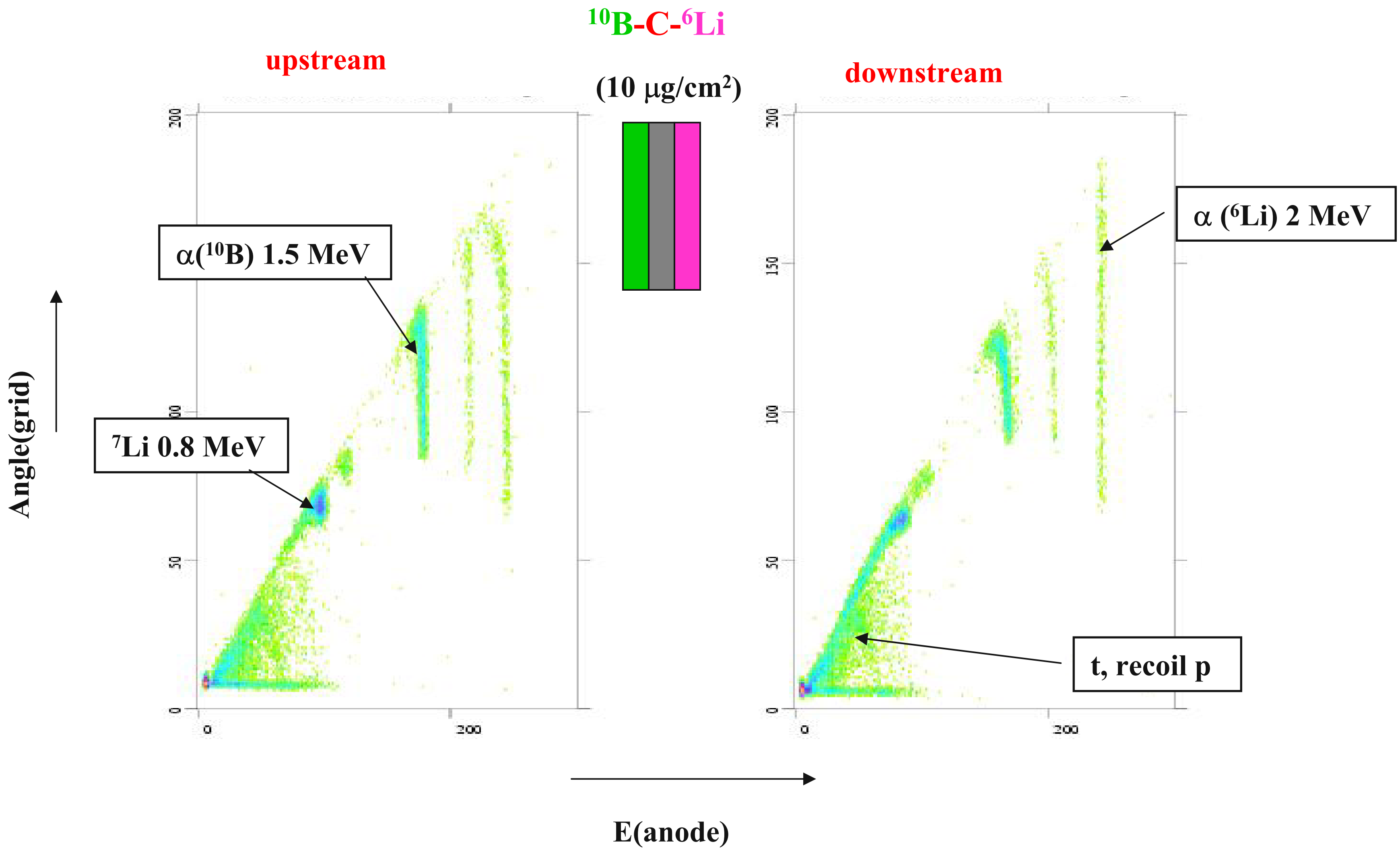
(NIMA 258, 209(1987))



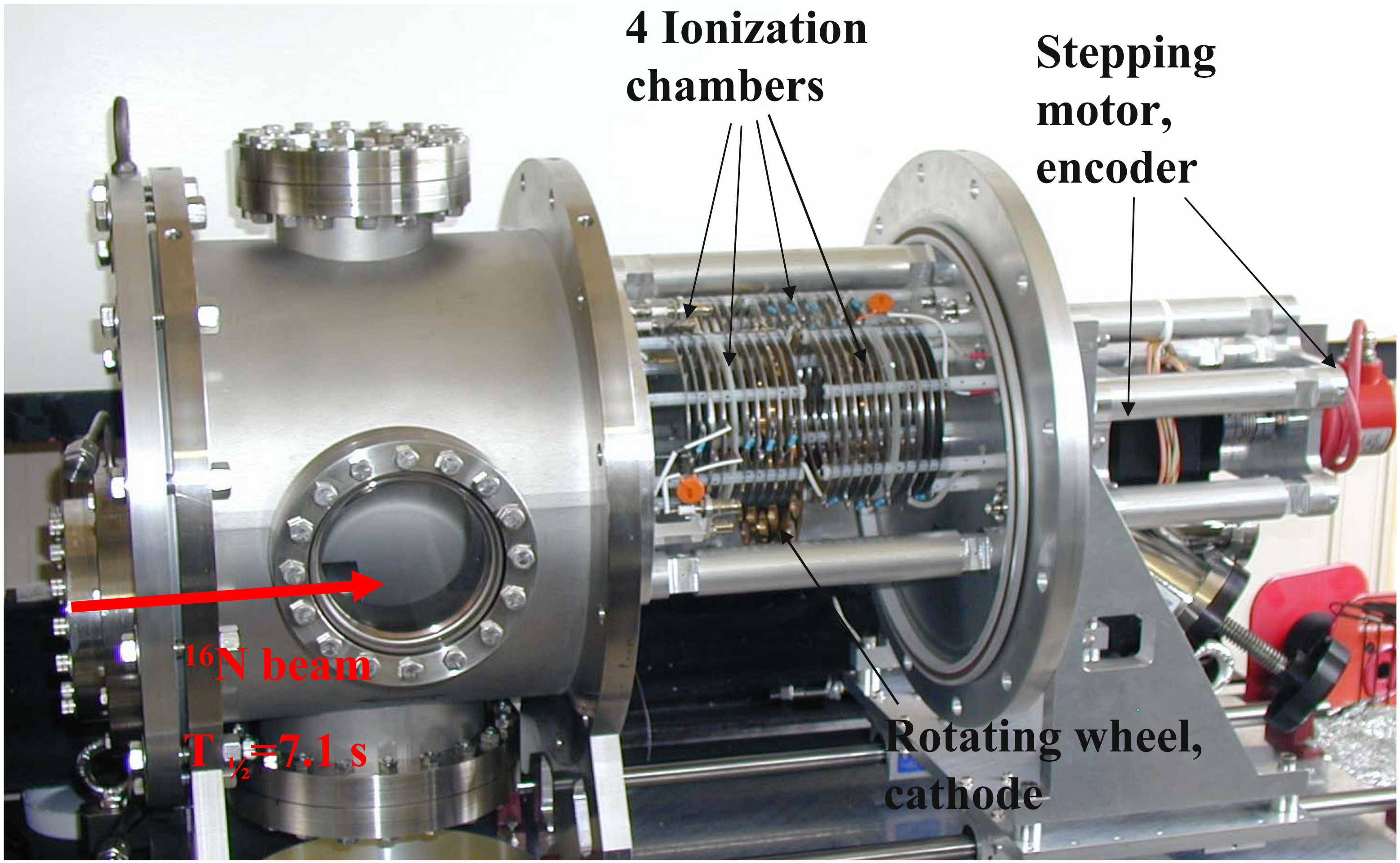
Emission angle dependence of the Frisch grid signal



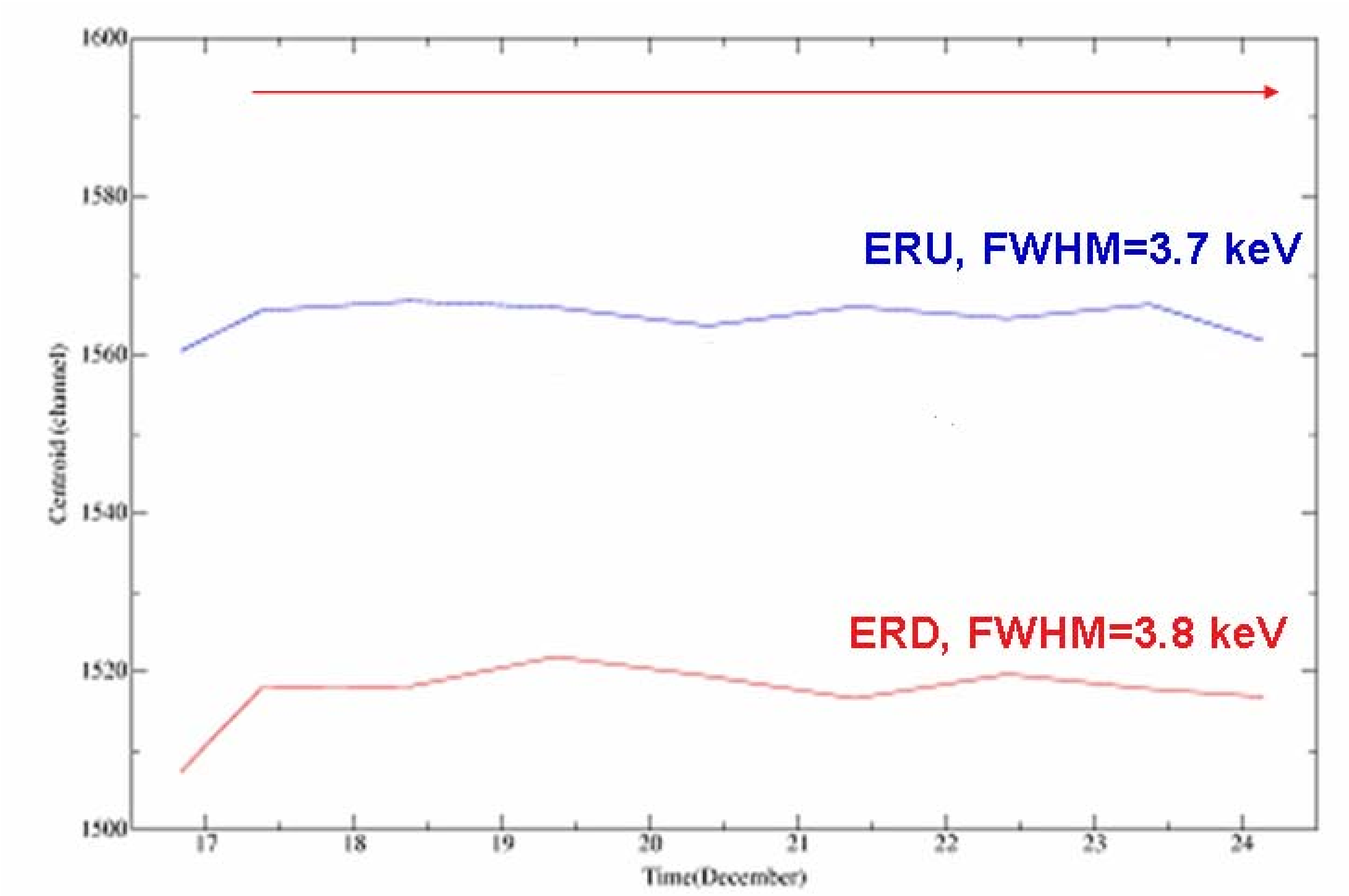
Energy calibration with a mixed ^{10}B-^{6}Li source ($^{10}B(n,\alpha)^{7}Li$, $^{6}Li(n,\alpha)t$)



Experimental setup for the study of the β-delayed α decay of ^{16}N



Long-term stability of Ionization Chambers



What are the backgrounds ?

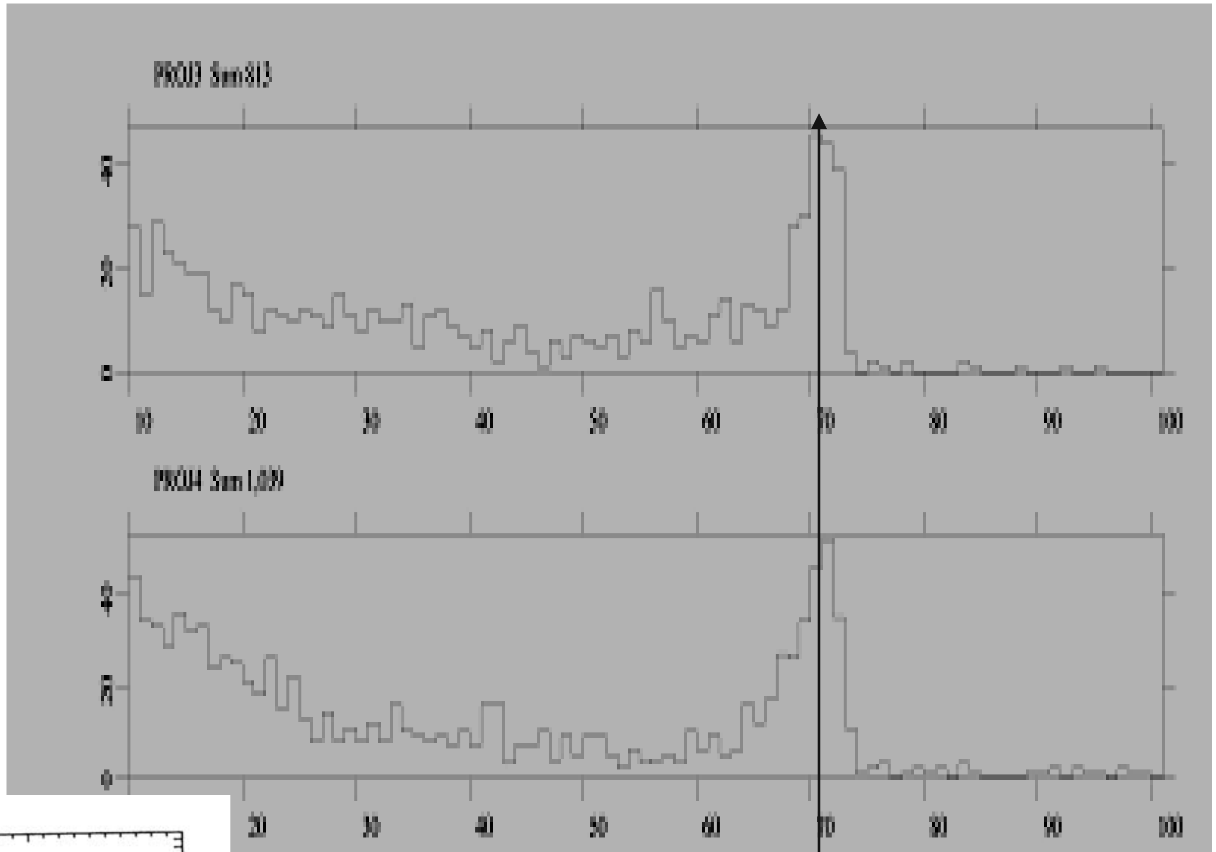
P=760 Torr

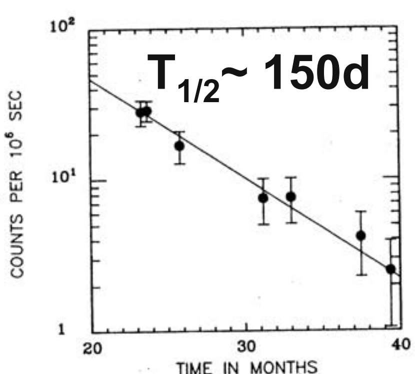
ELU

130/hr

ELD

170/hr

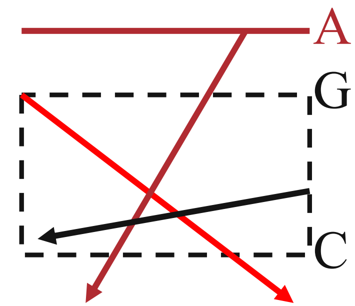




→ ~ 5.3 MeV

^{210}Po!!

Background run – 0.925×10^6 s (257 hr) (p=150 Torr)



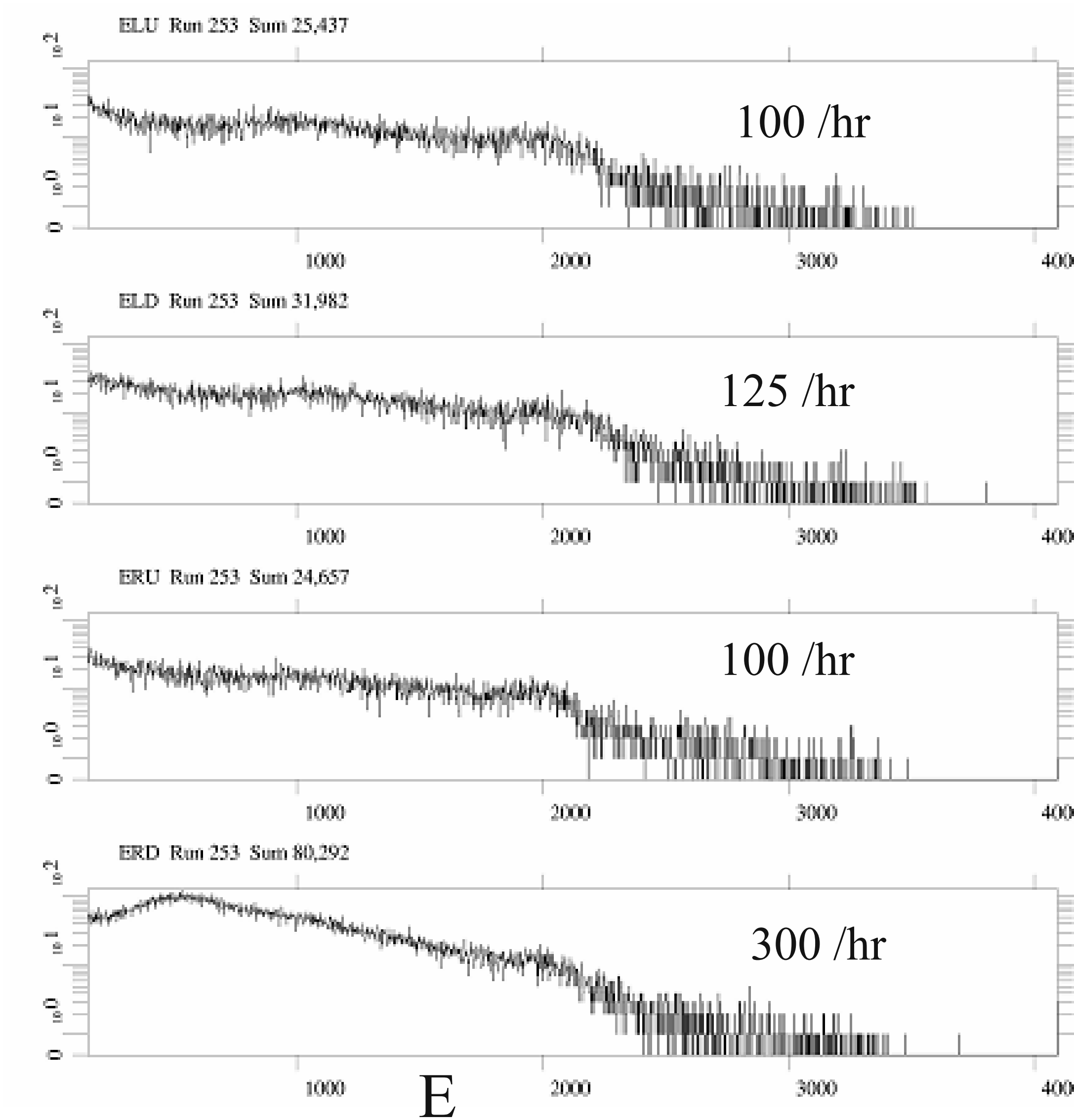
ELU

ELD

ERU

ERD (resoldered)

counts



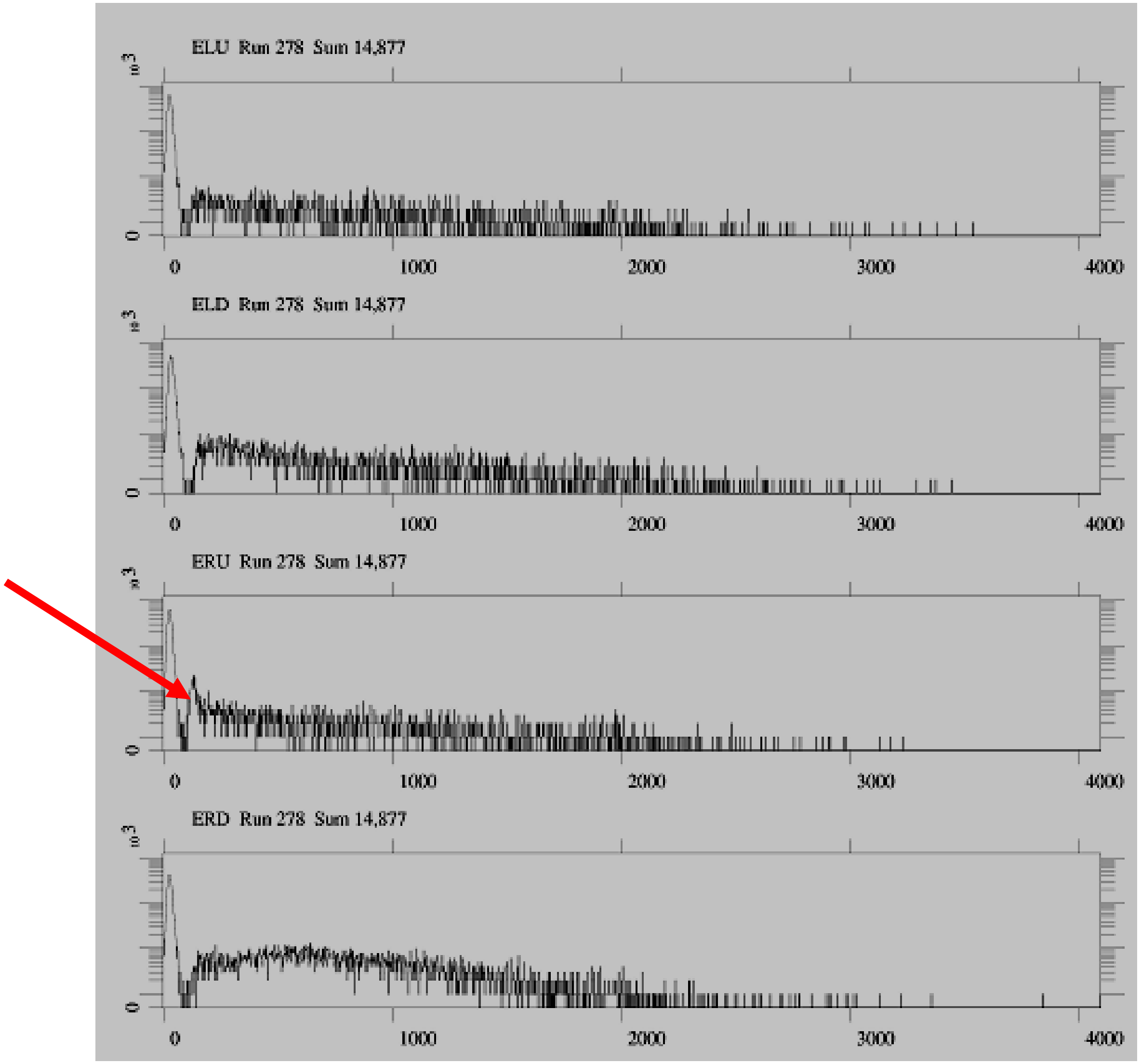
Al: ~16/hr/100cm^2

SS: ~12/hr/100cm^2

Solder: ~2400/hr/100cm^2

(~fempto-g of ^{210}Po)

Sensitivity to β's from a 10^5/sec ^{22}Na source



Background rates

115/hr

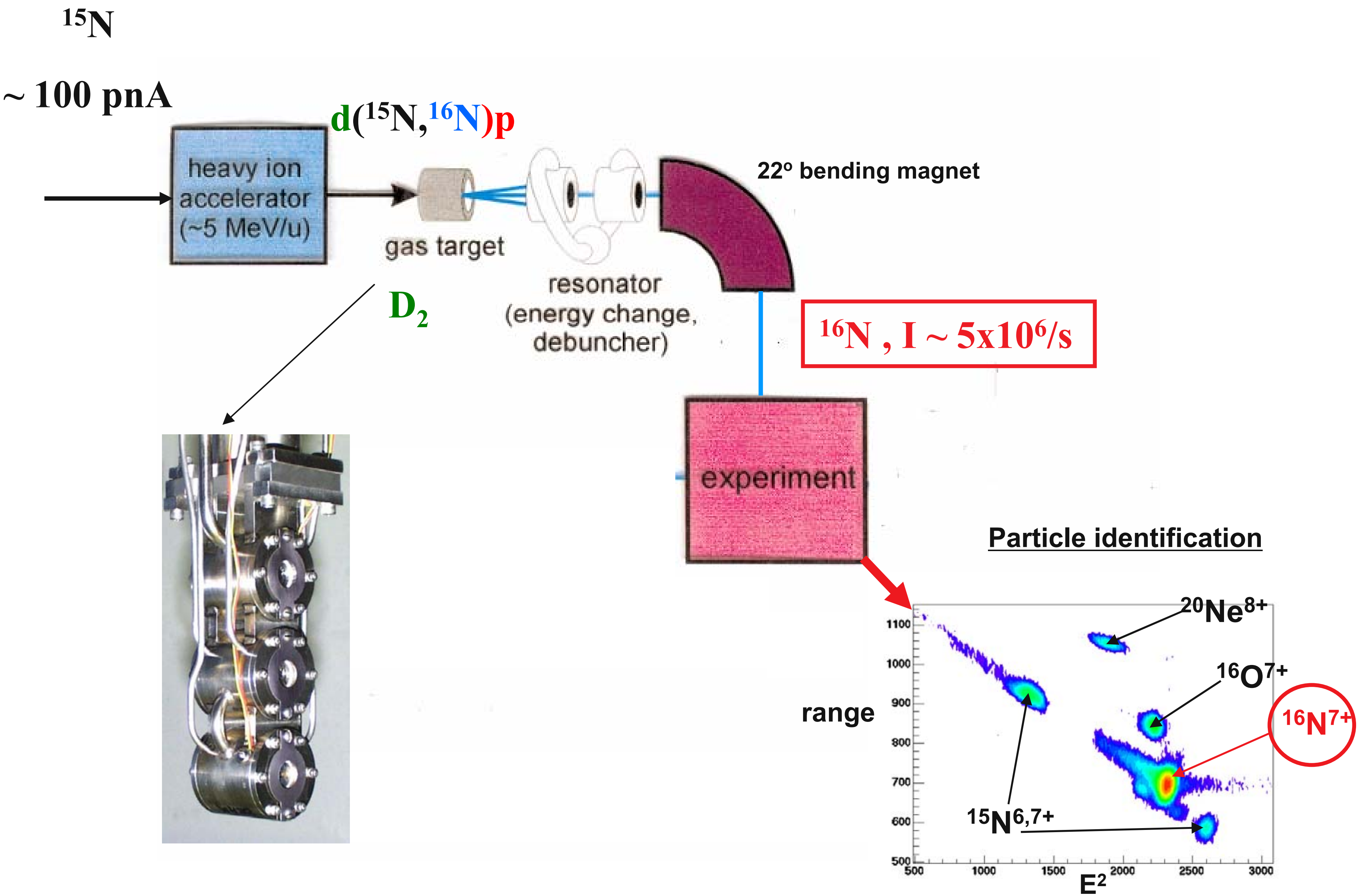
185/hr

160/hr

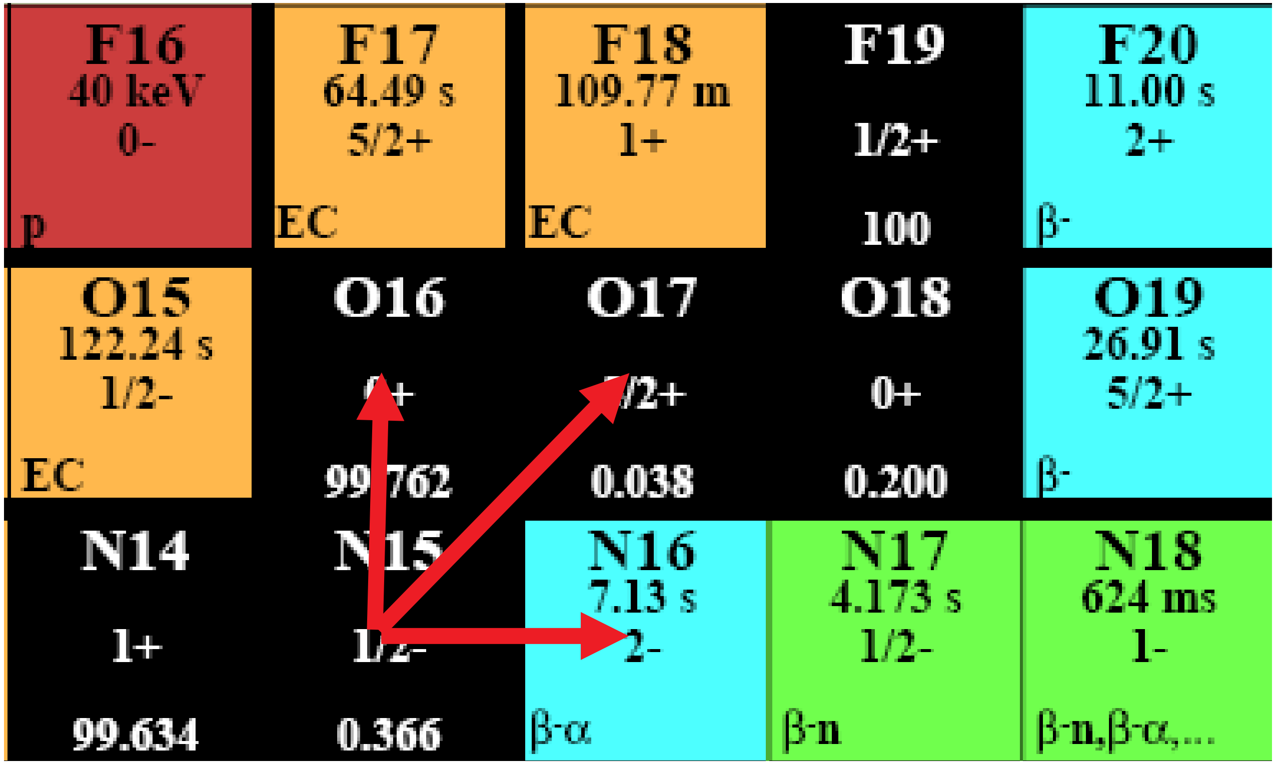
345/hr

^{16}N beam production technique

How do we produce the ^{16}N beam?



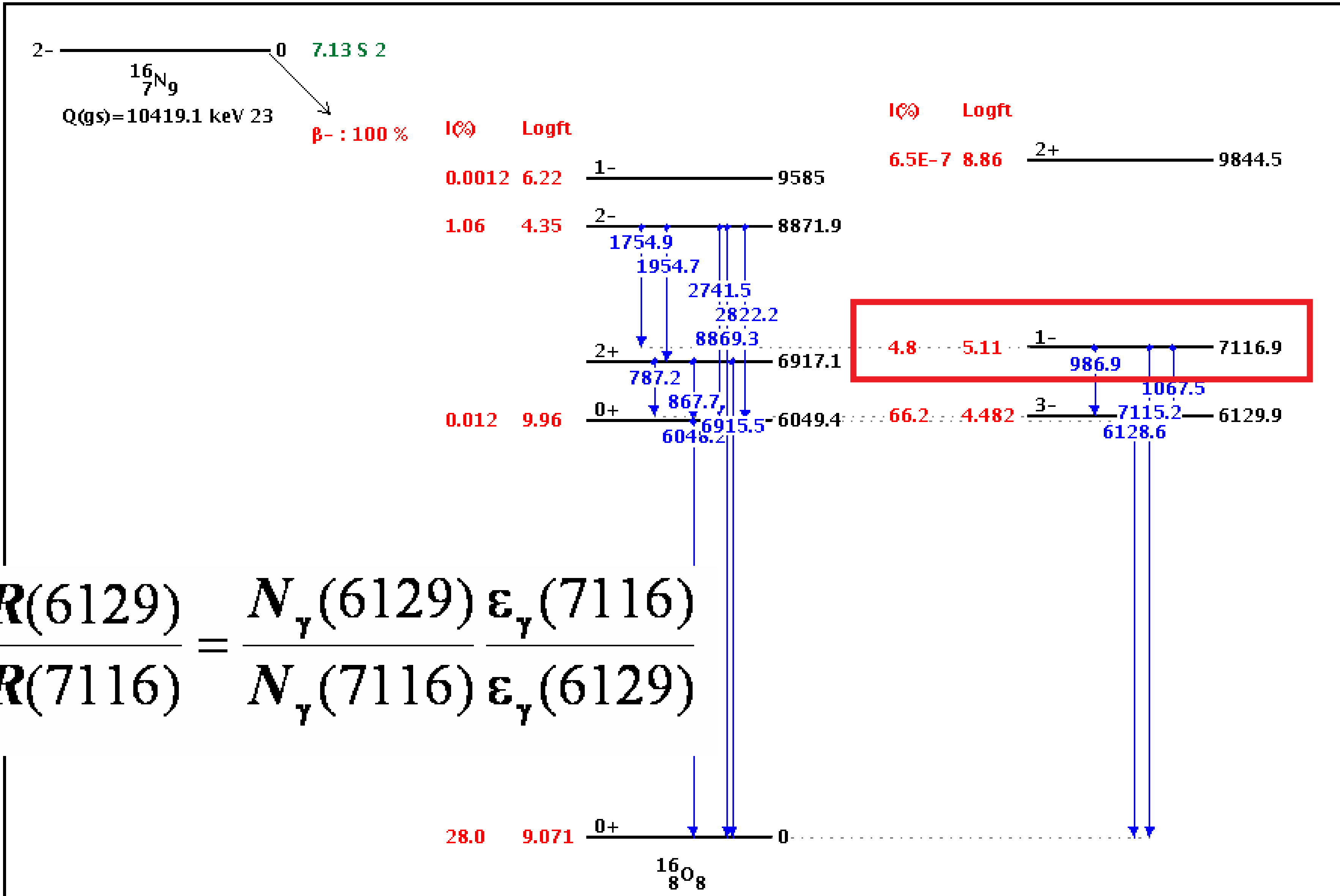
Possible reactions for $^{15}N + d$



→ **No ^{17}N or ^{18}N to subtract**

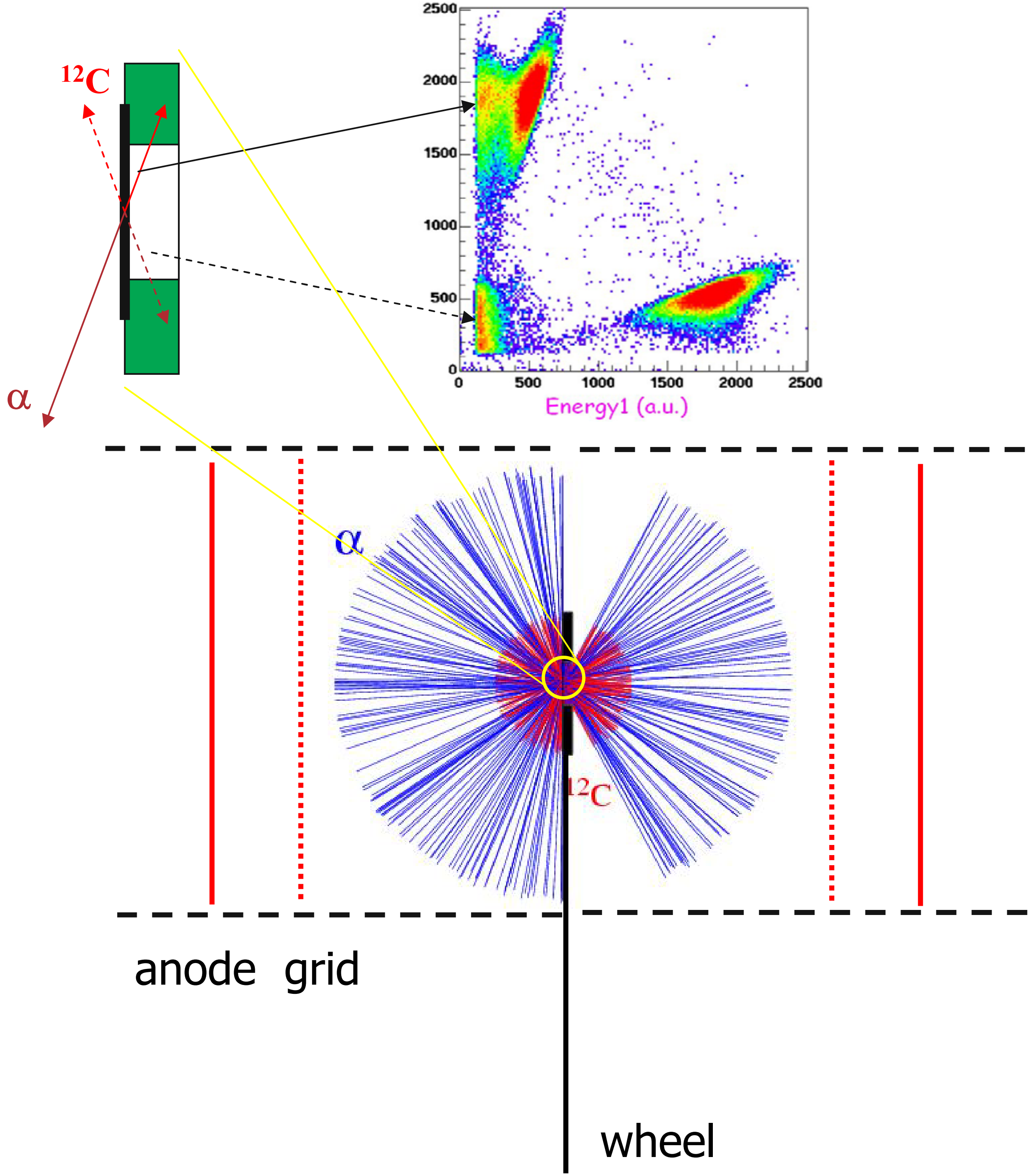
β-branching ratio measurement

β-branching ratio of the 1⁻ sub-threshold state

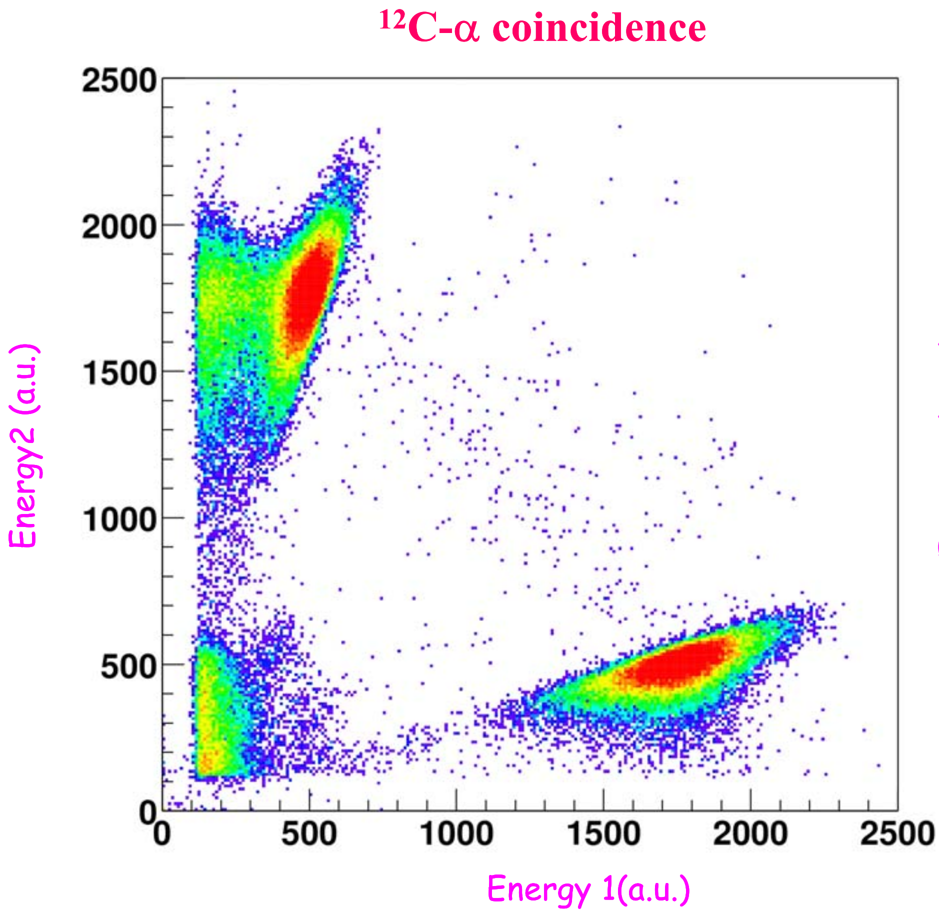


$$\frac{BR(6129)}{BR(7116)} = \frac{N_\gamma(6129)}{N_\gamma(7116)}\frac{\varepsilon_\gamma(7116)}{\varepsilon_\gamma(6129)}$$

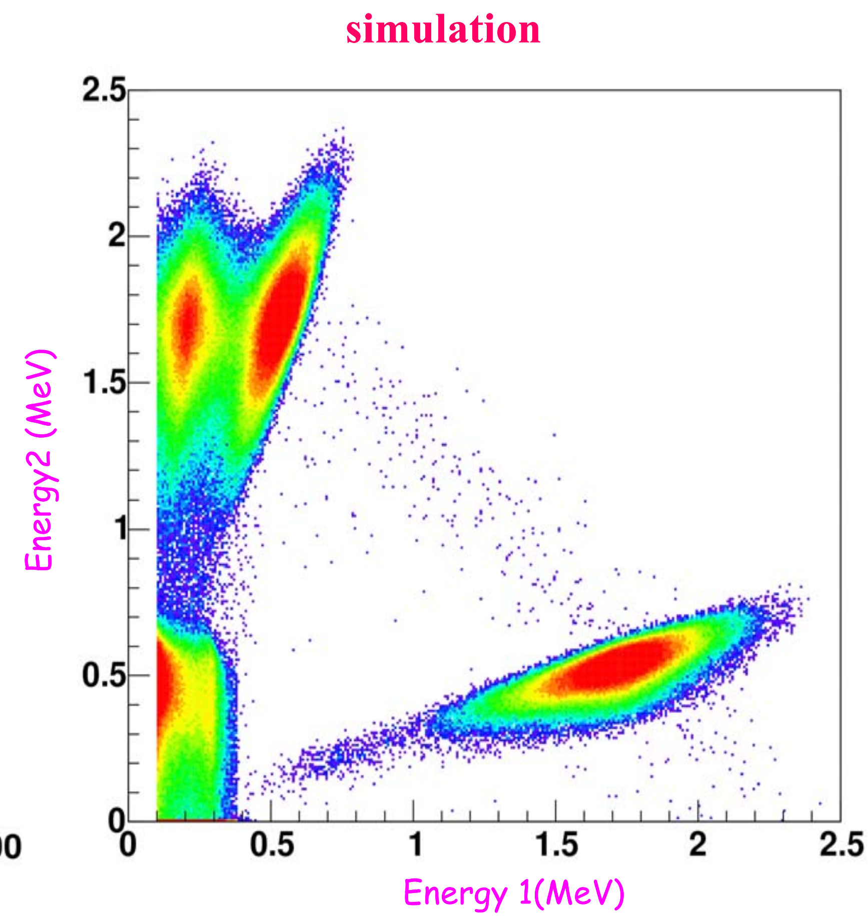
Branching ratio of the 1^- sub-threshold state



12C
α
2500
2000
1500
1000
500
0
0 500 1000 1500 2000 2500
Energy1 (a.u.)
α
12C
anode grid
wheel

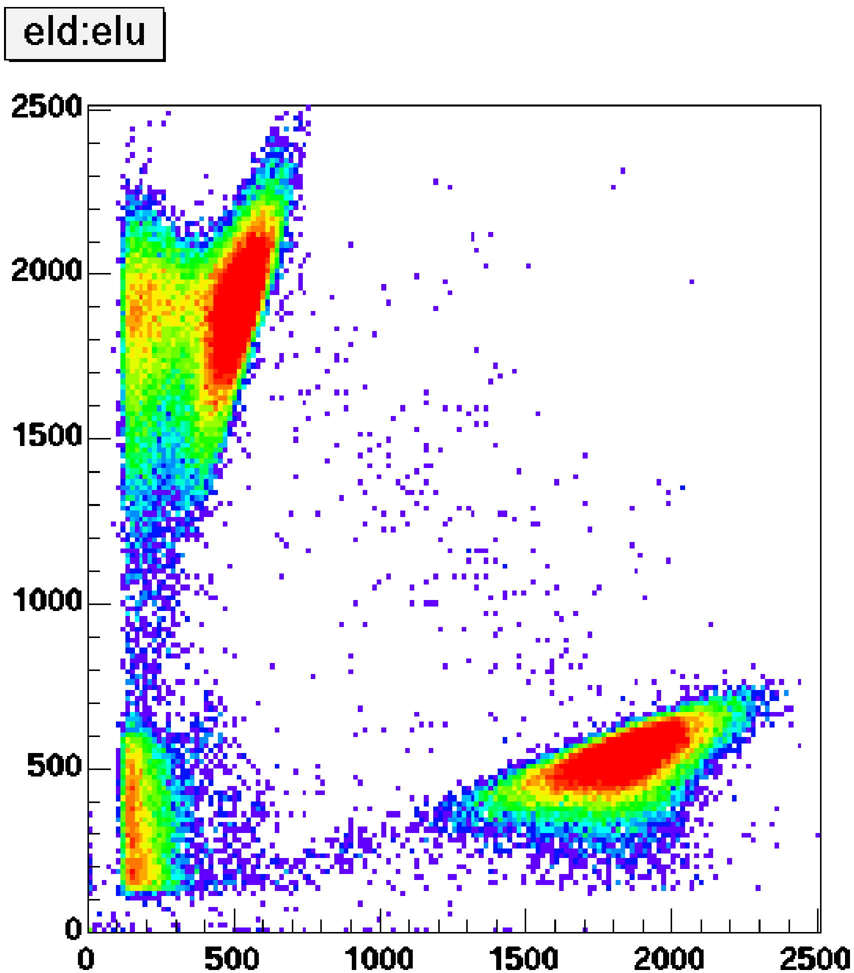


^{12}C-α coincidence
Energy2 (a.u.)
Energy 1(a.u.)
0
500
1000
1500
2000
2500

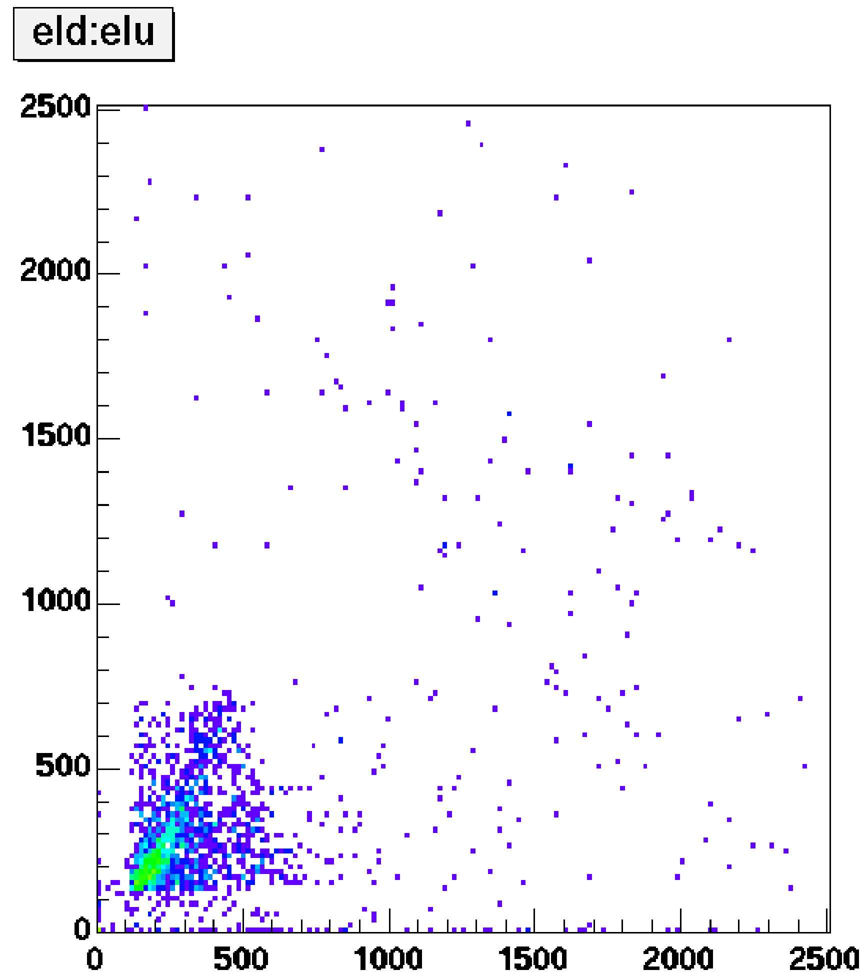


simulation
Energy2 (MeV)
Energy 1(MeV)
0
0.5
1
1.5
2
2.5

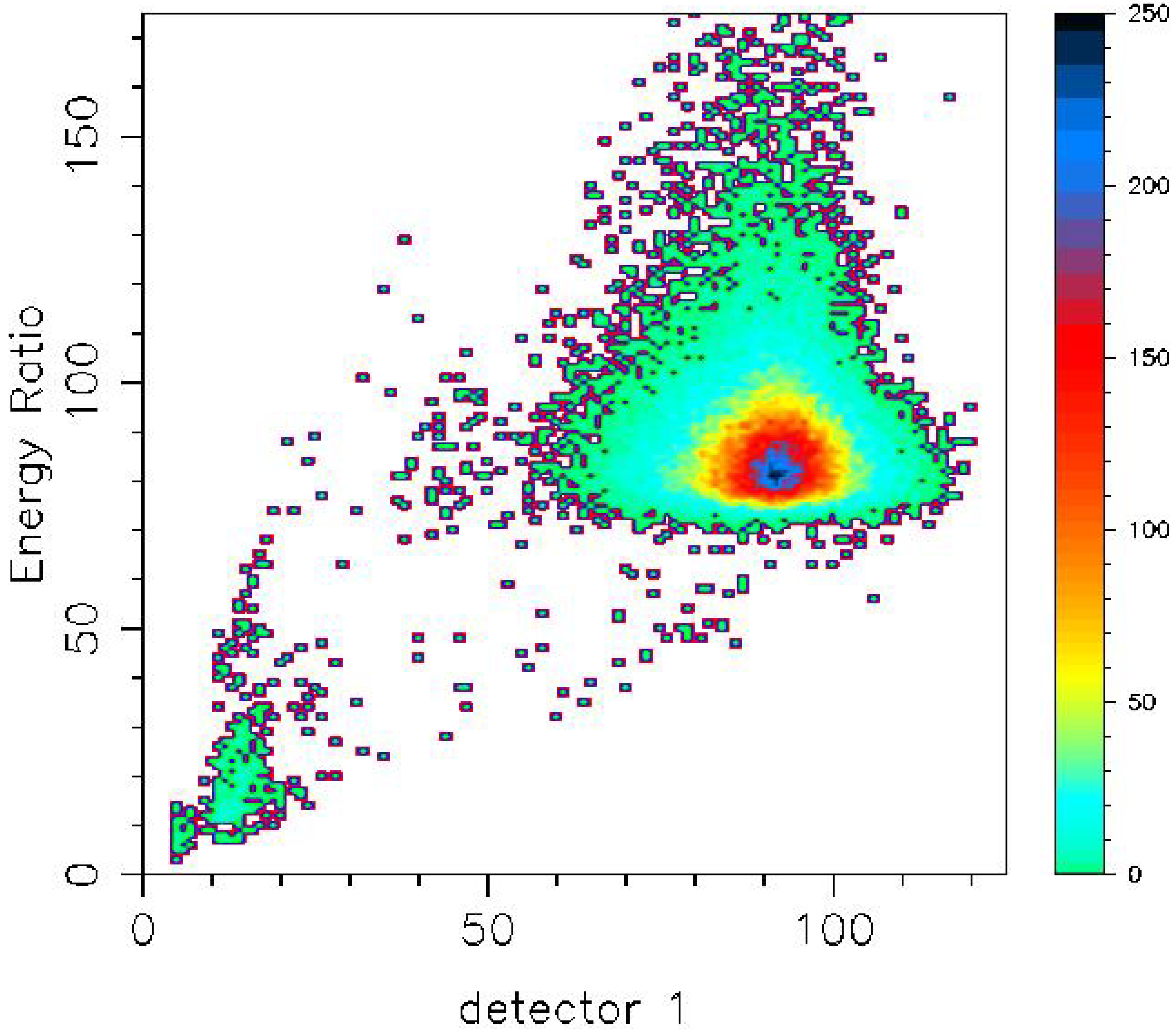
^{16}N irradiated foil



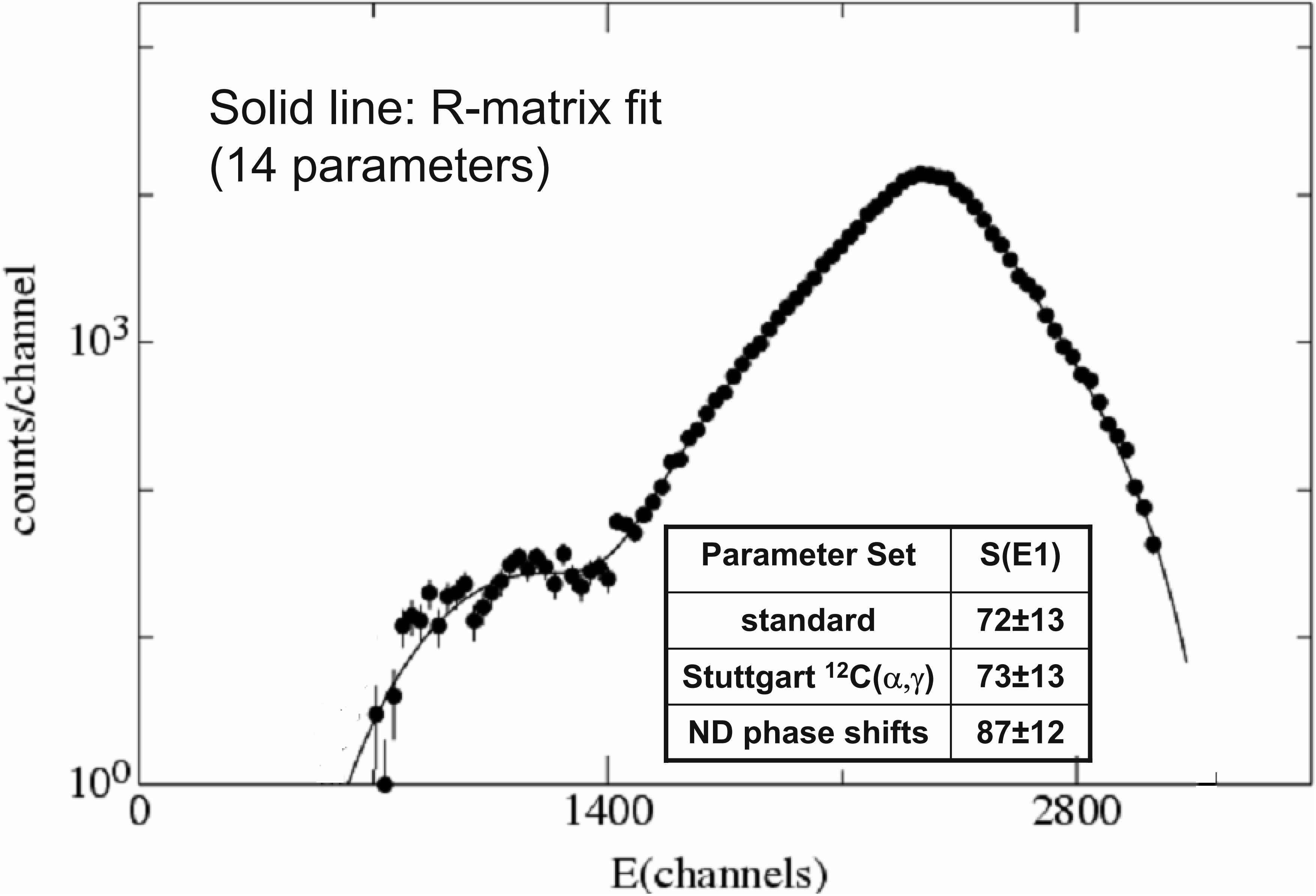
non-irradiated foil



Energy Ratio E_α/E_C



+ back-to-back condition



Parameter Set	S(E1)
standard	72±13
Stuttgart $^{12}C(\alpha,\gamma)$	73±13
ND phase shifts	87±12

Summary

New experiment for the $^{12}C(\alpha,\gamma)^{16}O$ reaction

- **Very clean ^{16}N beam**
- **High efficiency detectors**
- **No sensitivity to β's**
- **Reduced systematic uncertainities**

- **$S(E1)_{prel} = 72 \pm 13_{(stat)} \pm 8_{(systematic)}$ keVb**

Collaborators

ANL: X. D. Tang, J. Greene, A. Hecht, D. Henderson, R. V. F. Janssens, C. L. Jiang, D. Kahn, C. Lister, E. F. Moore, M. Notani*, N. Patel, R. C. Pardo, K. E. Rehm, G. Savard, J. P. Schiffer, D. Seweryniak, S. Sinha, B. Shumard, S. Zhu

Hebrew University: M. Paul

Northwestern University: L. Jisonna, R. E. Segel

Ohio University: C. Brune

University of North Carolina: A. Champagne

Western Michigan University: A. Wuosmaa

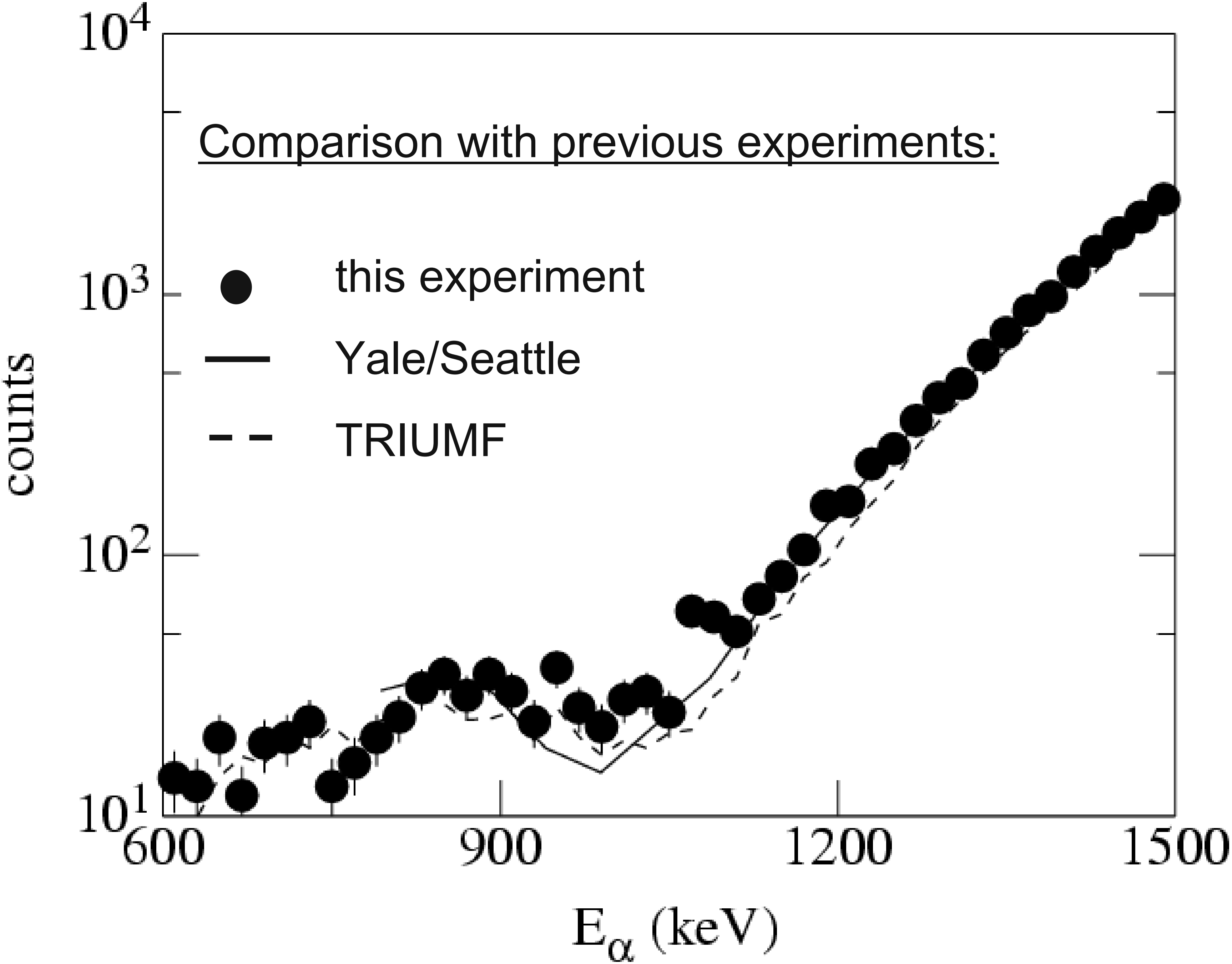
* supp. by JINA

Without side-feeding corrections:

$$\frac{BR(6129)}{BR(7116)} = \frac{N_{\gamma}(6129)}{N_{\gamma}(7116)} \frac{N_{\gamma\gamma}(7116-1754)}{N_{\gamma\gamma}(6129-2741)} \frac{N_{\gamma}(2741)}{N_{\gamma}(1754)}$$

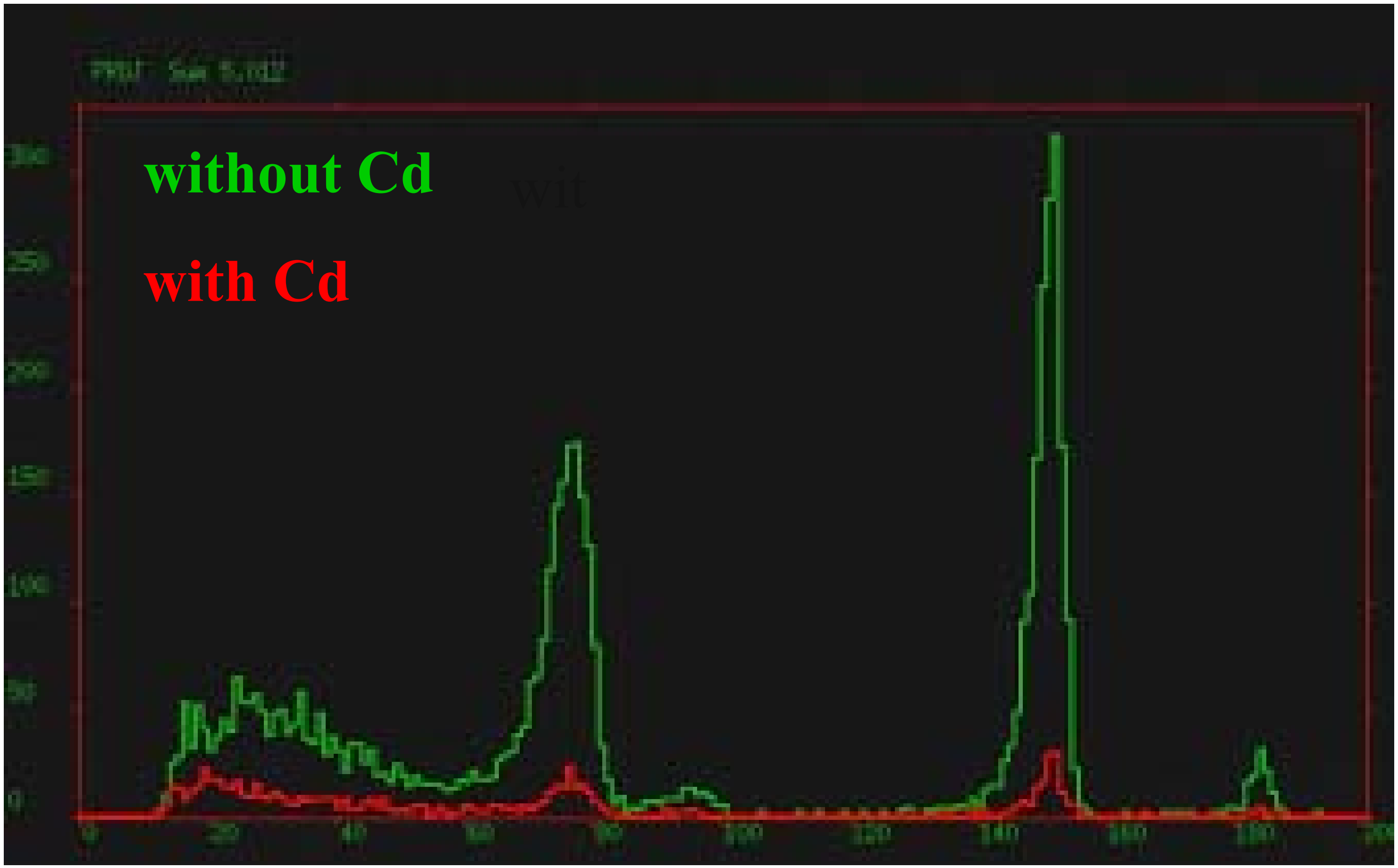
Old β-branching ratio: 4.8 ± 0.4 %

New ratio (preliminary) 5.3 ± 0.1 %



Comparison with previous experiments:
this experiment
Yale/Seattle
TRIUMF
counts
10^4
10^3
10^2
10^1
600
900
1200
1500
E_α (keV)

Reaction induced by thermal neutrons



Energy and efficiency calibration:

Energy of ^{16}N alphas ~ 1.75 MeV

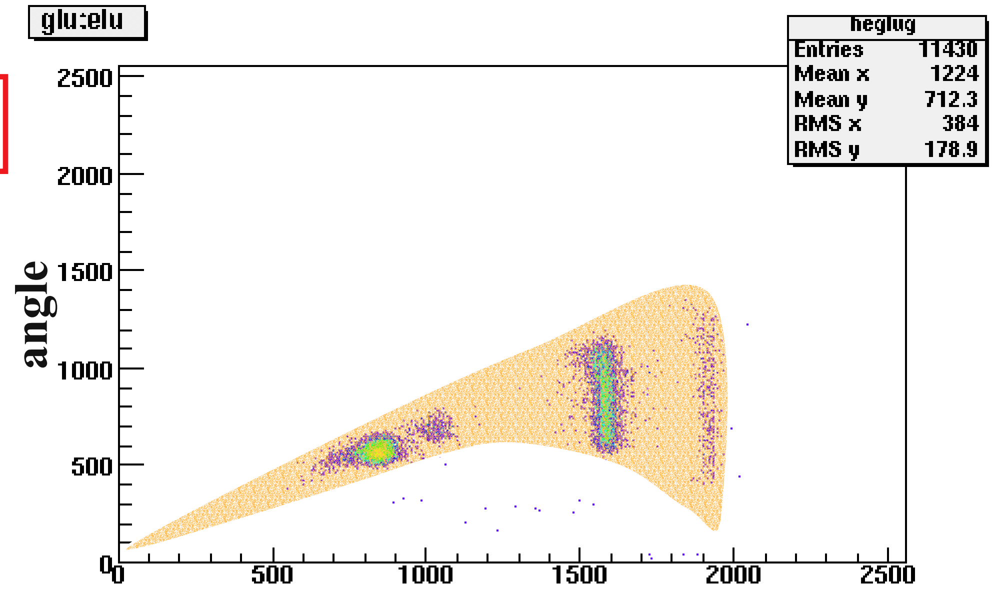
$^{10}B + n \rightarrow \alpha + {}^{7}Li$

$E_{\alpha} =$ 1.789 MeV

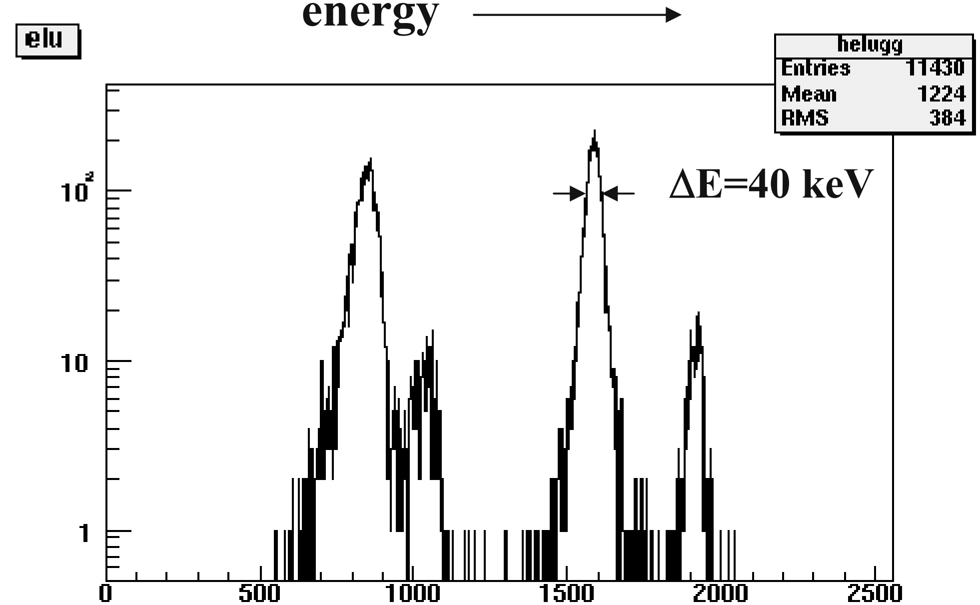
1.483 MeV

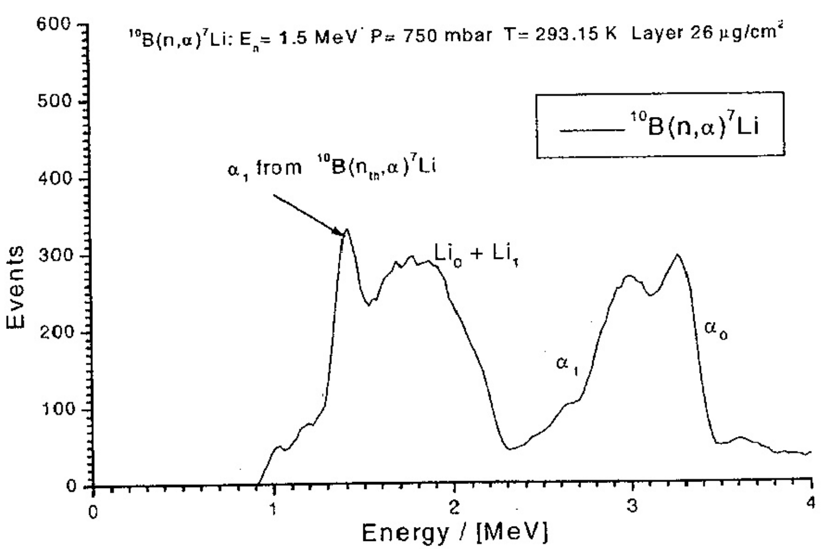
$E_{Li} =$ 1.022 MeV

0.847 MeV



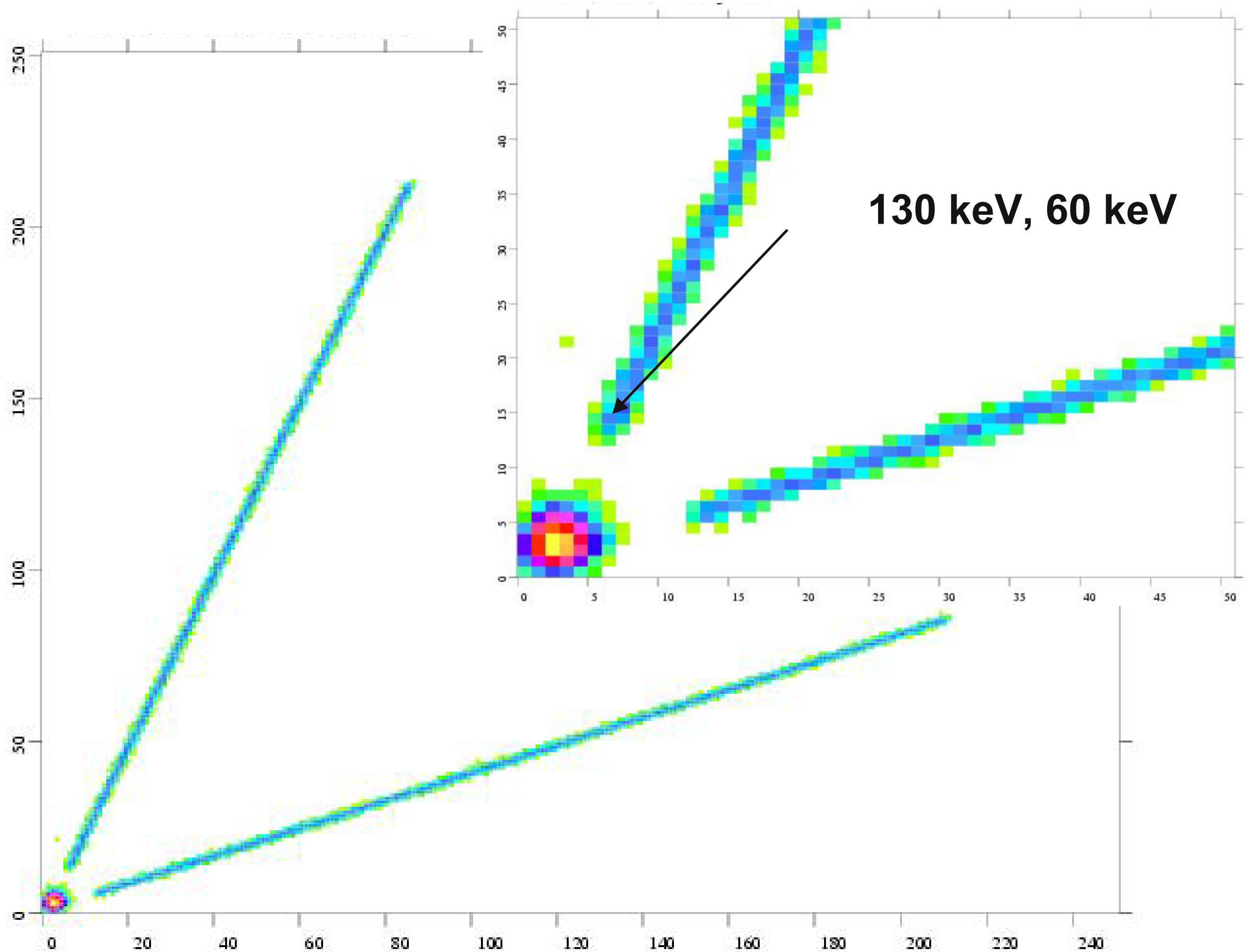
energy →

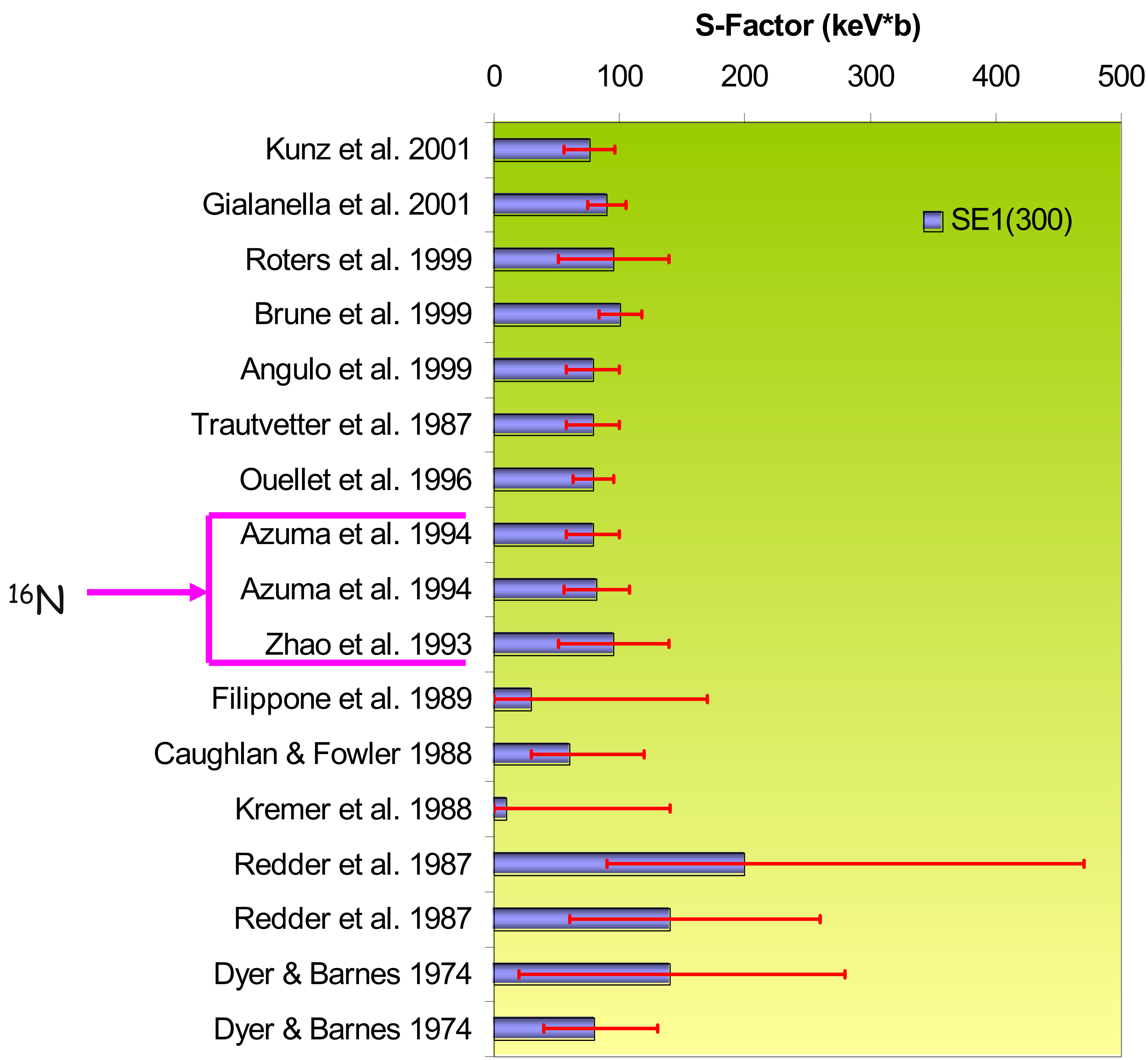


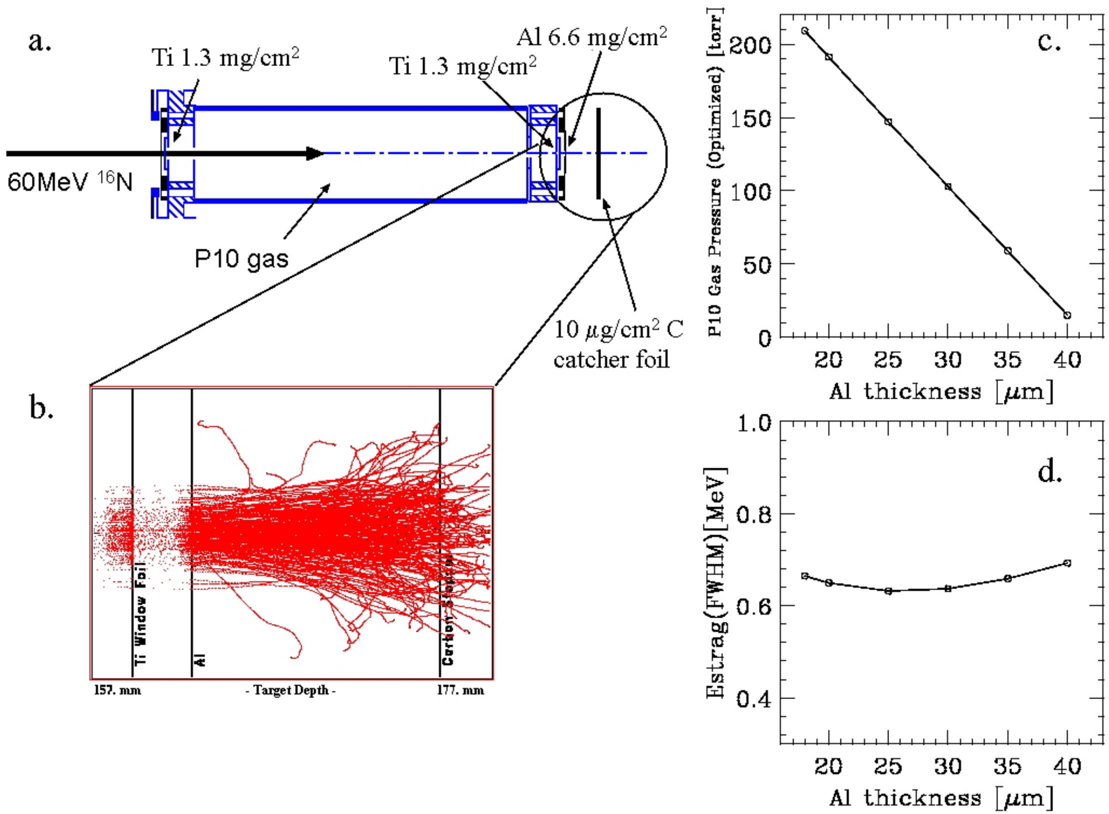


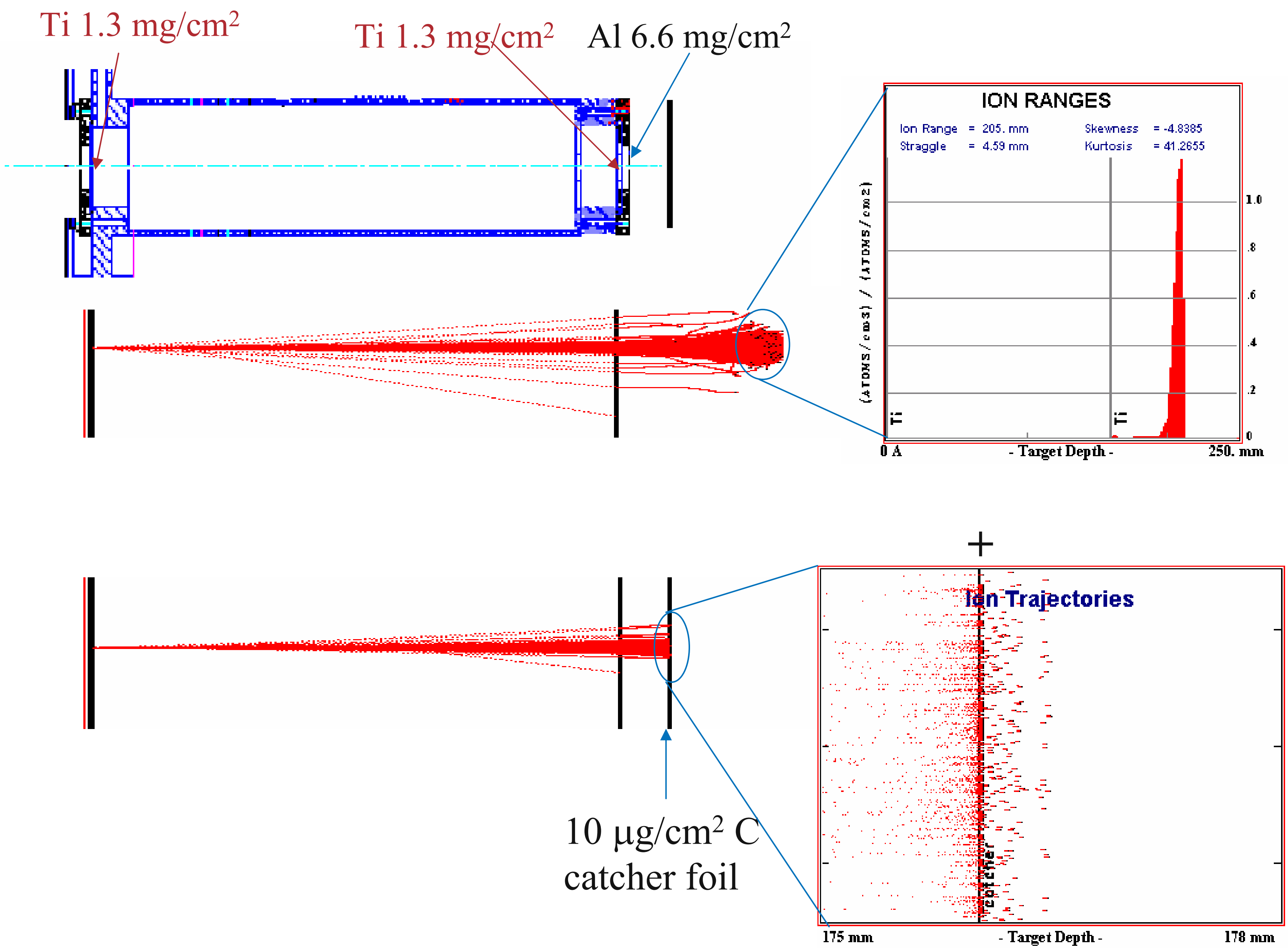
Low-energy cutoffs

(no dead layers)



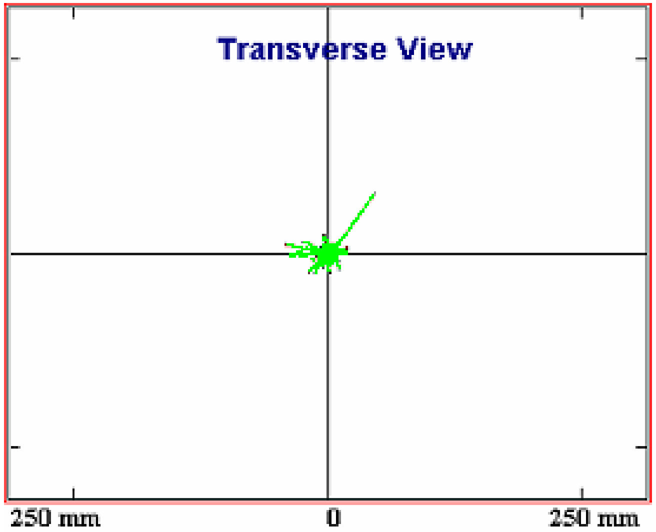

S-Factor (keV*b)
0
100
200
300
400
500
SE1(300)
Kunz et al. 2001
Gialanella et al. 2001
Roters et al. 1999
Brune et al. 1999
Angulo et al. 1999
Trautvetter et al. 1987
Ouellet et al. 1996
Azuma et al. 1994
Azuma et al. 1994
Zhao et al. 1993
Filippone et al. 1989
Caughlan & Fowler 1988
Kremer et al. 1988
Redder et al. 1987
Redder et al. 1987
Dyer & Barnes 1974
Dyer & Barnes 1974
16N


a.
Ti 1.3 mg/cm2
Ti 1.3 mg/cm2
Al 6.6 mg/cm2
60MeV 16N
P10 gas
10 μg/cm2 C
catcher foil
b.
Ti Window Foil
Al
157. mm
- Target Depth -
177. mm
c.
P10 Gas Pressure (Optimized) [torr]
Al thickness [μm]
d.
Estrag(FWHM)[MeV]
Al thickness [μm]

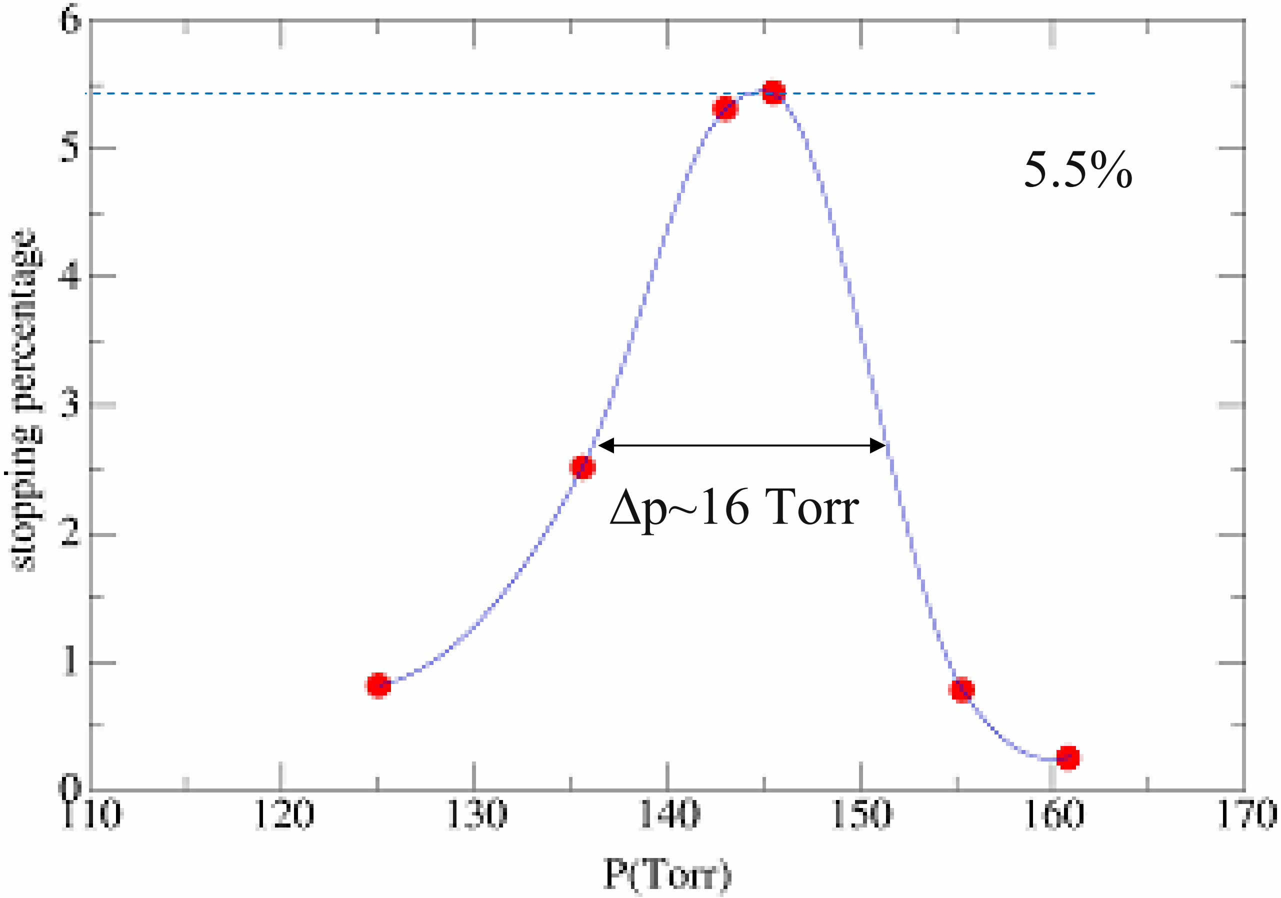


Ti 1.3 mg/cm²
Ti 1.3 mg/cm²
Al 6.6 mg/cm²
ION RANGES
Ion Range = 205. mm
Straggle = 4.59 mm
Skewness = -4.8385
Kurtosis = 41.2655
(ATOMS/cm3) / (ATOMS/cm2)
Ti
Ti
0 A
- Target Depth -
250. mm
+
Ion Trajectories
catcher
175 mm
- Target Depth -
178 mm
10 µg/cm² C
catcher foil

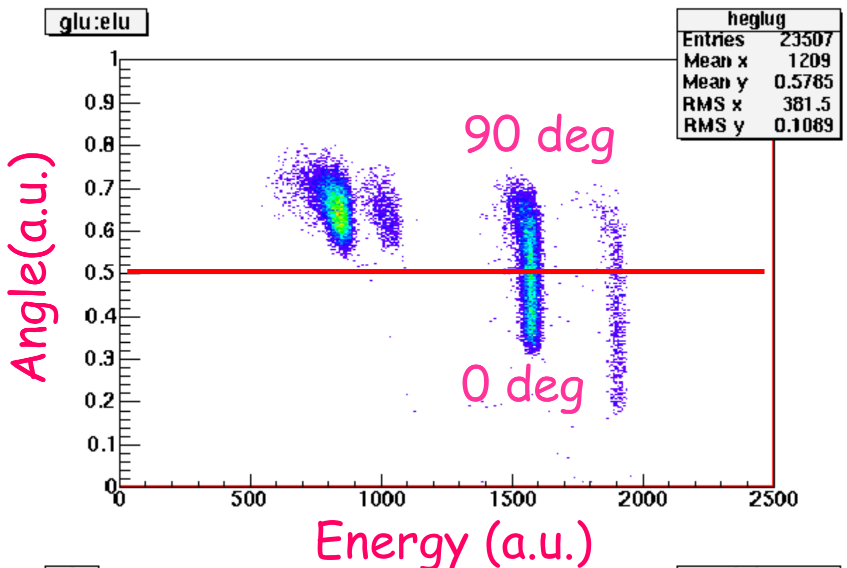
Beam diameter

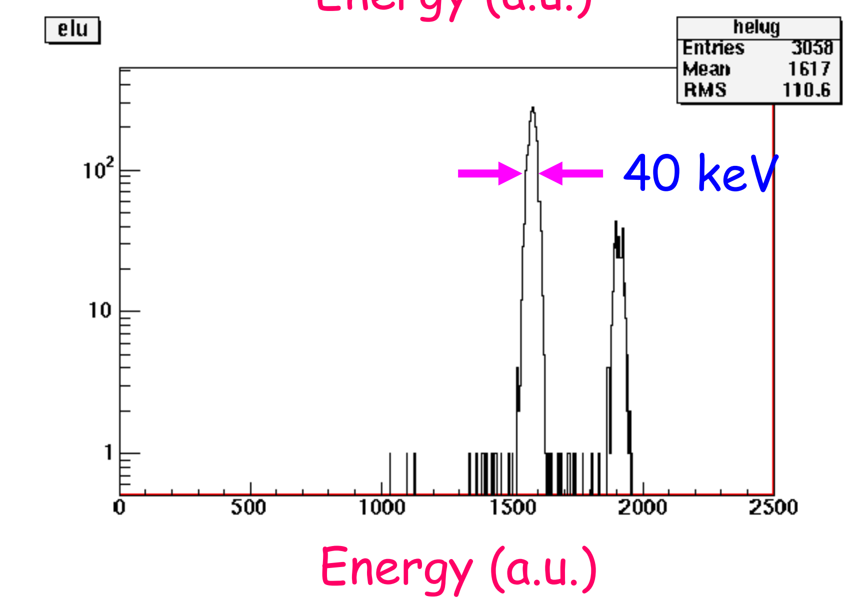


Choosing the optimum pressure

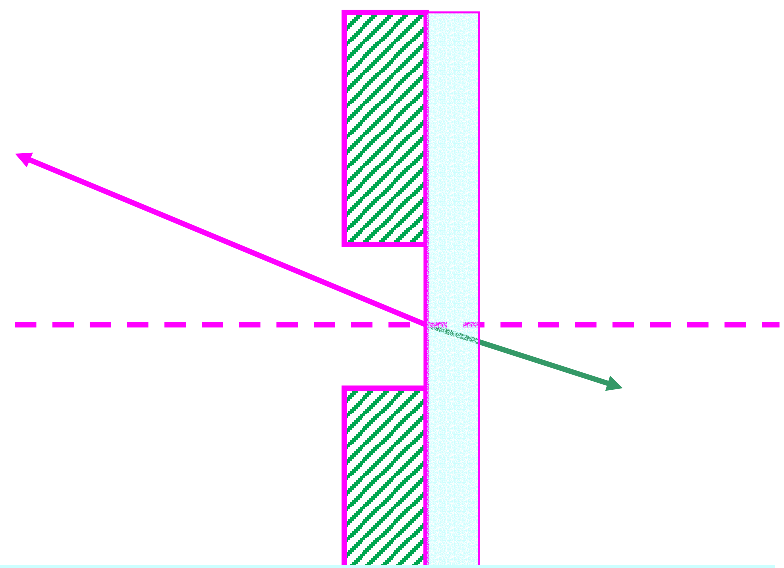


Energy Calibration

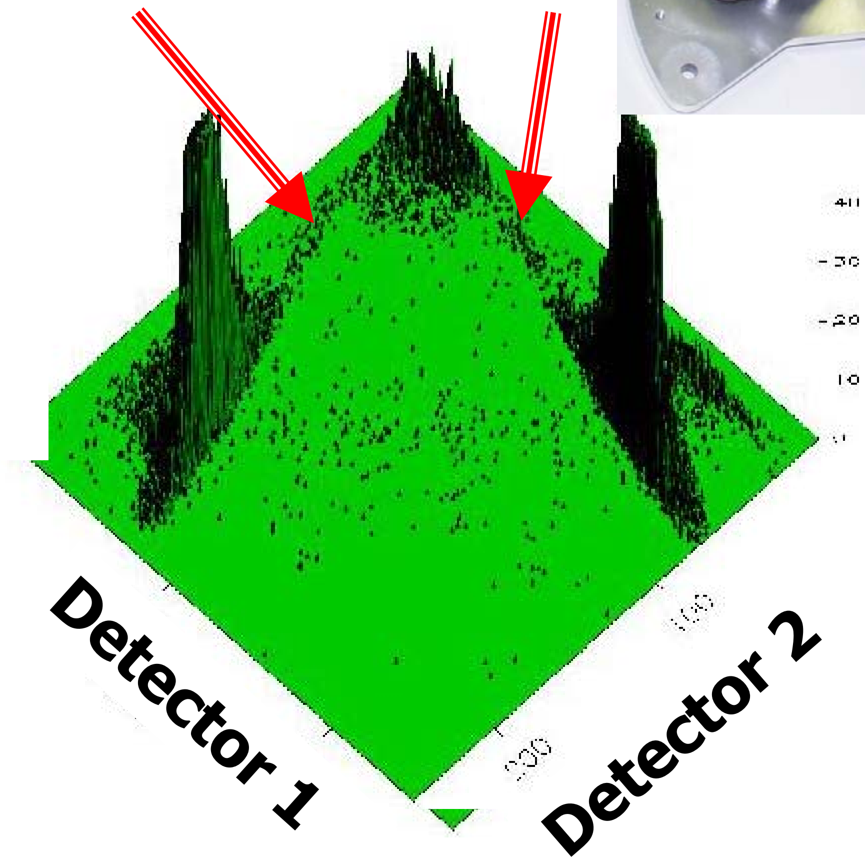


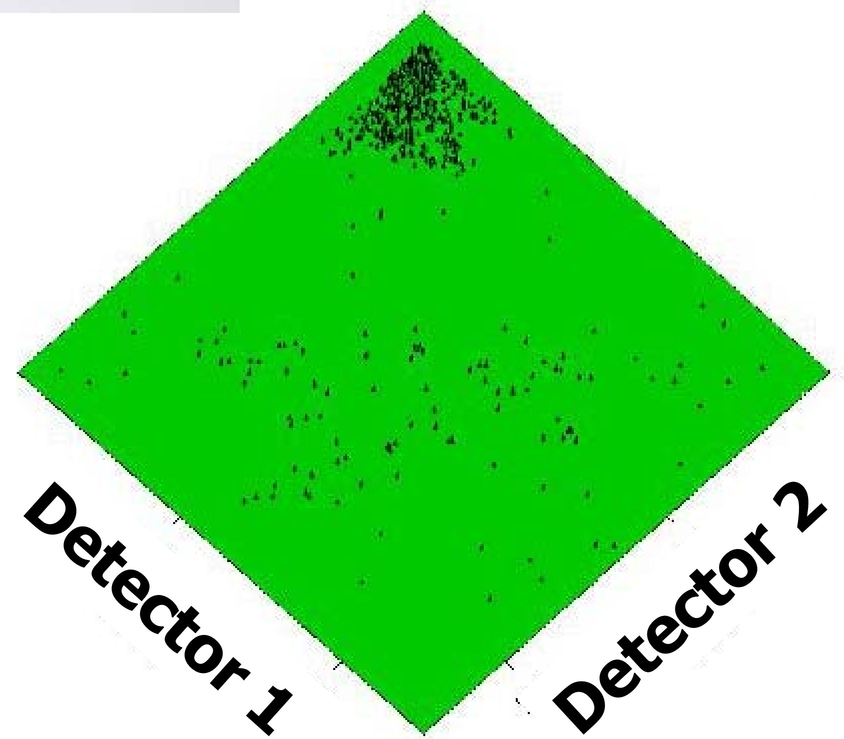


$^{10}B(n,\alpha)^{7}Li$
($10\mu g/cm^2$ ^{10}B on
$10\mu g/cm^2$ ^{12}C)
$E_{\alpha 0}$=1.7891 MeV
$E_{\alpha 1}$=1.4832 MeV

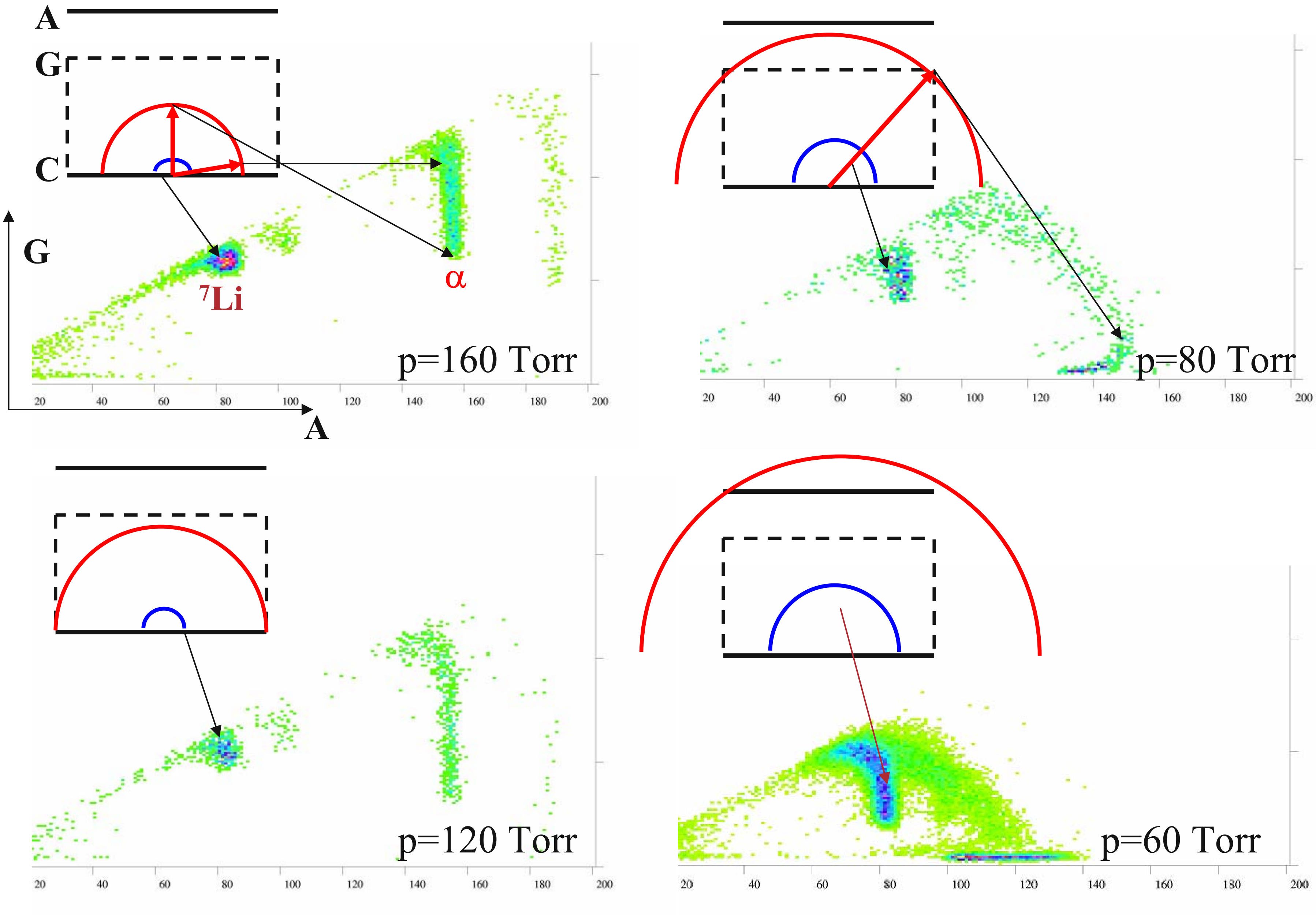


Angle=Grid/E=C(1-R(E)/D*cos(θ))


Detector 1
Detector 2


Detector 1
Detector 2

Pressure dependence



“Direct Measurements”:

$^{12}C(\alpha,\gamma)^{16}O$:	^{4}He Beam	Stuttgart, Karlsruhe
$\alpha(^{12}C,\gamma)^{16}O$	^{12}C beam	Bochum
$\alpha(^{12}C,^{16}O)\gamma$	^{12}C beam	Bochum, TRIUMF

“Indirect Measurements”:

^{16}N β decay	^{16}N beam	ANL
$^{16}O(\gamma,\alpha)^{12}C$	FEL	TUNL
Coulomb Breakup of ^{16}O	^{16}O	KVI

Others:

$^{12}C(^{6}Li,d)^{12}C$, $^{12}C(\alpha,\alpha)^{12}C$	^{6}Li	Caltech, Notre D.
^{17}Ne β decay	^{17}Ne	RIA!

Theoretical Methods:

Solar abundances		UCSC
Pulsating White Dwarfs		UT

Summary:

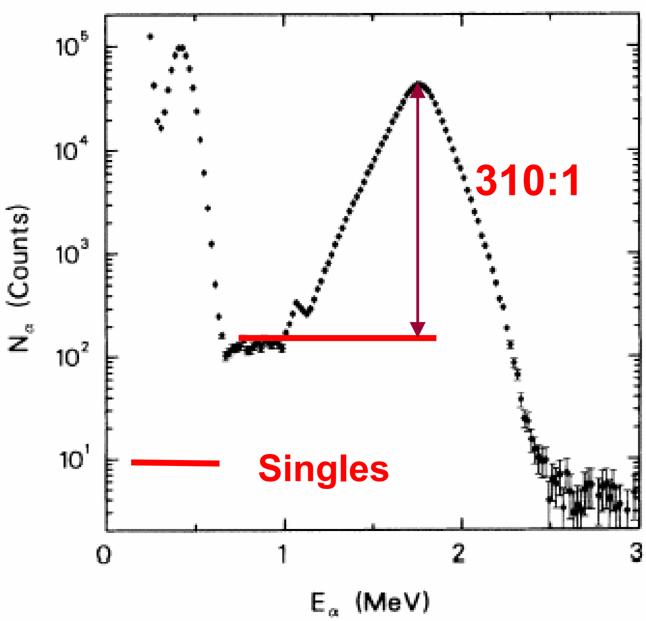
Still a big uncertainty for S[$^{12}C(\alpha,\gamma)^{16}O$] (in keVb):

Compilations:	1985		240	
	1988		100^{+100}_{-50}	
	1999		200 ± 80	
Most recent experiment:		Triumf	146^{+124}_{-84}	(^{16}N)
		Kunz	165 ± 50	
(α,γ)				
		Fey	162 ± 40	
(α,γ)				
		Tischh.	150 ± 30	
(α,α)				
Element abundances:			170	
Pulsating white dwarfs:			290 ± 15	

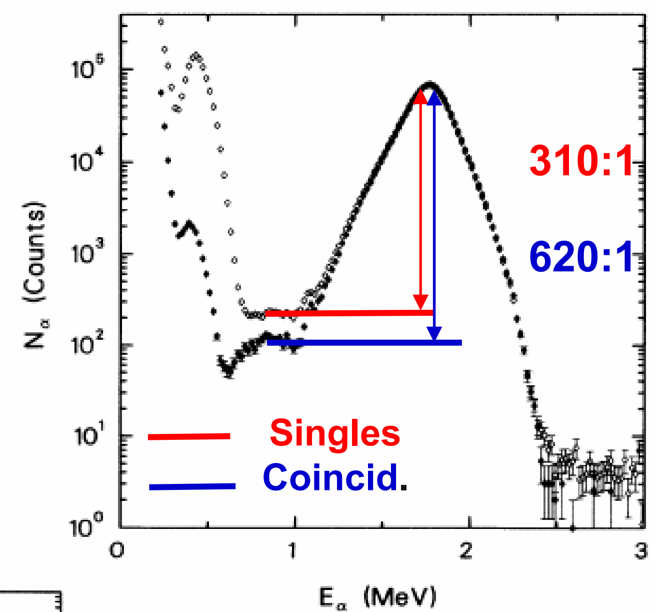
Experiment	*Coincidence (Detector)*	*Contamination*	*Cut off Energy (MeV)*	*Statistics*
Mainz 1971	Single (Si 35μ)	N/A	1.08	$2x10^6$
Yale-UConn 1994	$\beta+\alpha$(Si 50μ)	N/A	0.8	$6x10^4$
TRIUMF 1994	$\alpha+{}^{12}C$ (Si 10-15μ)	$^{17,18}N$	0.59	$1x10^6$
Seattle 1995	$\alpha+{}^{12}C$(Si ?)	N/A	0.63	$1x10^5$
Yale-UConn 1996	$\beta+\alpha$(Si 50μ)	N/A	0.73	$2.8X10^5$

- **N_β/N_α~1x10^5**
- **Huge β background** (noise)/**A high energy tail in β-ray response function/ Radiation damage/ Dead layer correction/Pulse height correction**

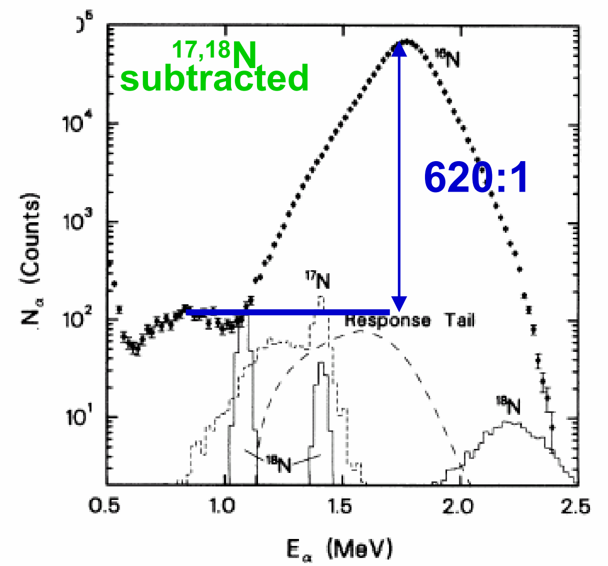
TRIUMF 93



10^5
10^4
10^3
10^2
10^1
N_α (Counts)
310:1
Singles
0
1
2
3
E_α (MeV)

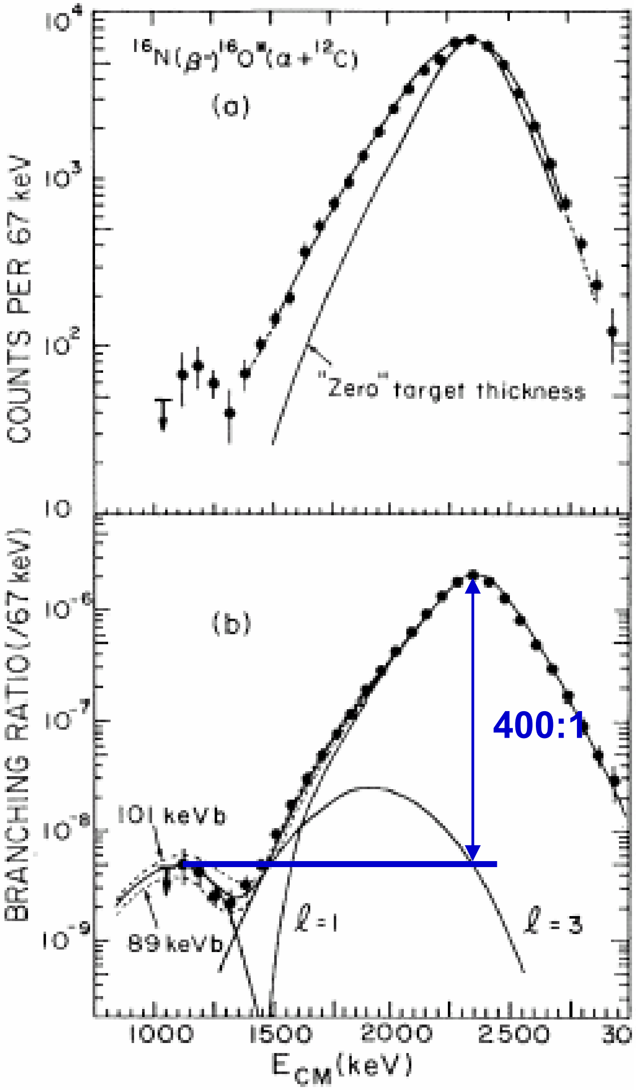


10^5
10^4
10^3
10^2
10^1
10^0
N_α (Counts)
310:1
620:1
Singles
Coincid.
0
1
2
3
E_α (MeV)

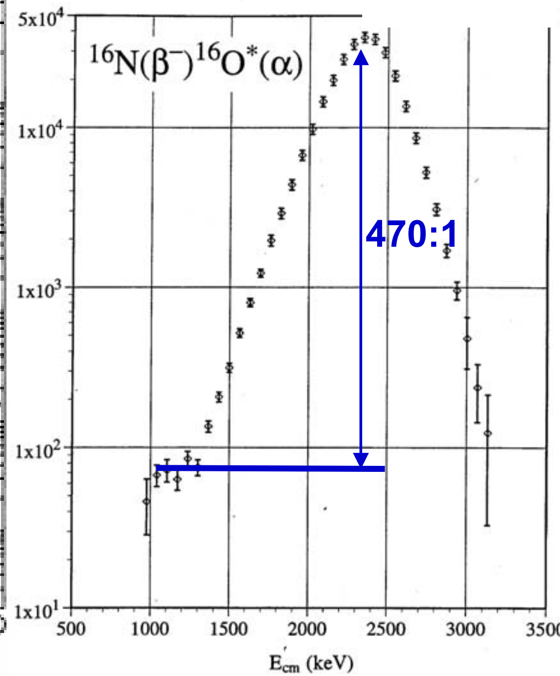


^{17,18}N
subtracted
^{16}N
620:1
^{17}N
Response Tail
^{18}N
^{18}N
10^4
10^3
10^2
10^1
N_α (Counts)
0.5
1.0
1.5
2.0
2.5
E_α (MeV)

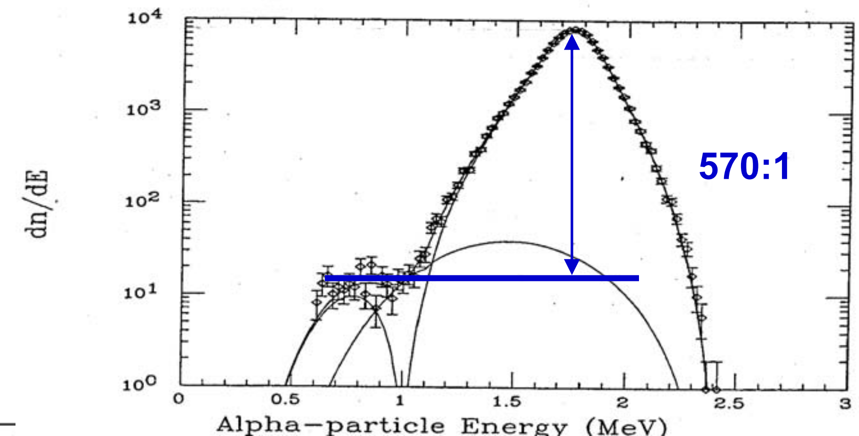
Yale 1993

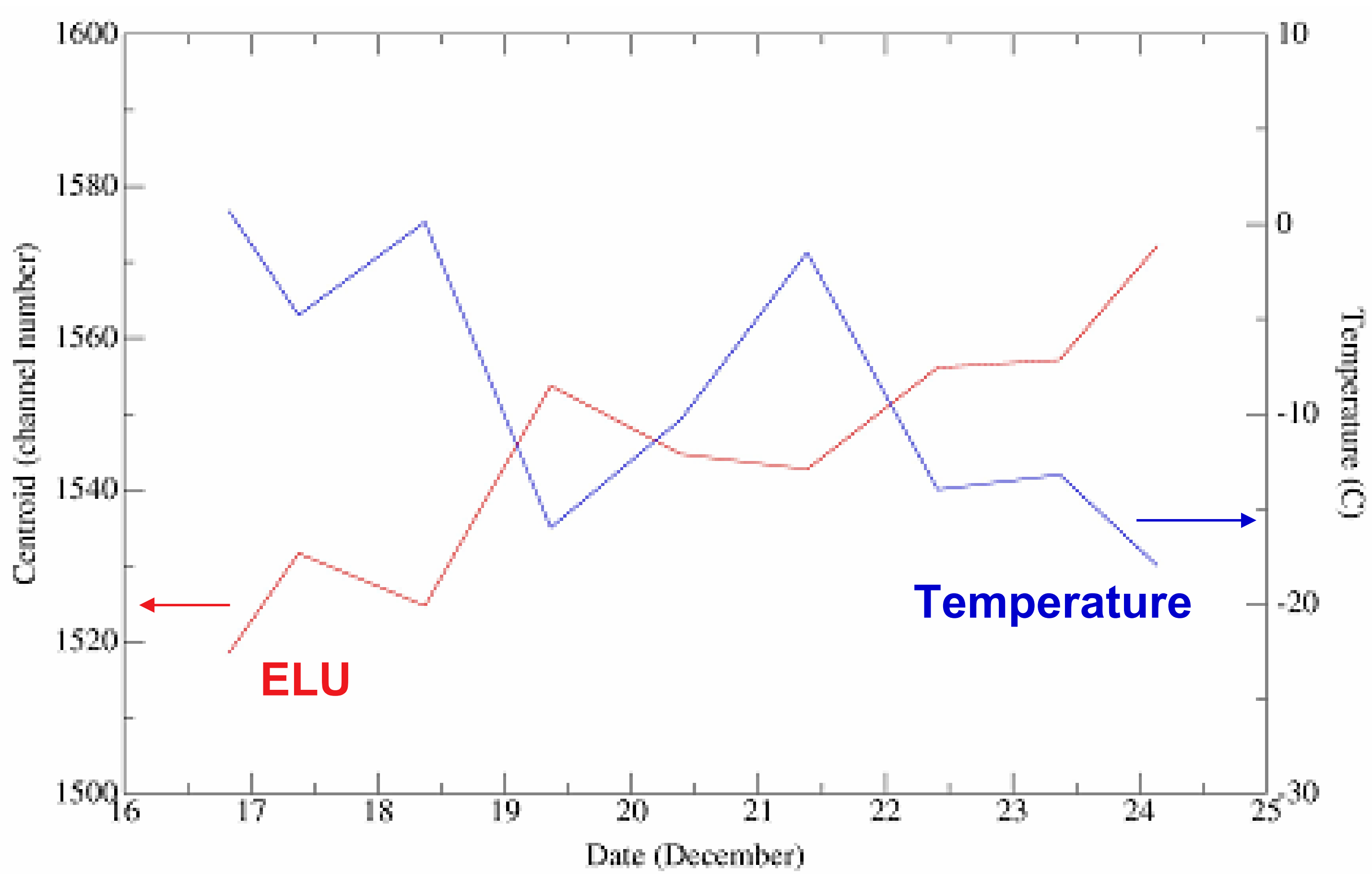


Yale 1997

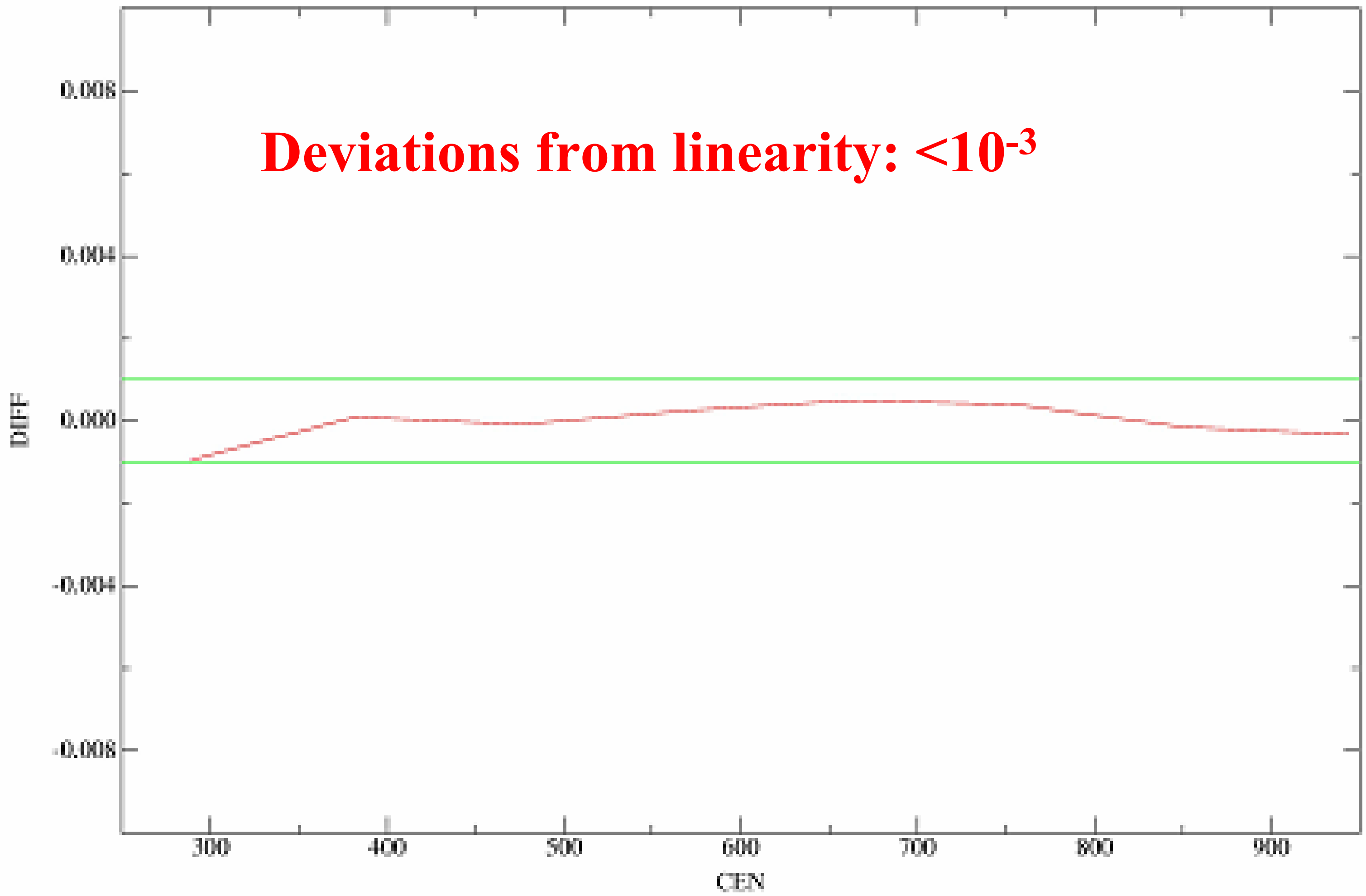


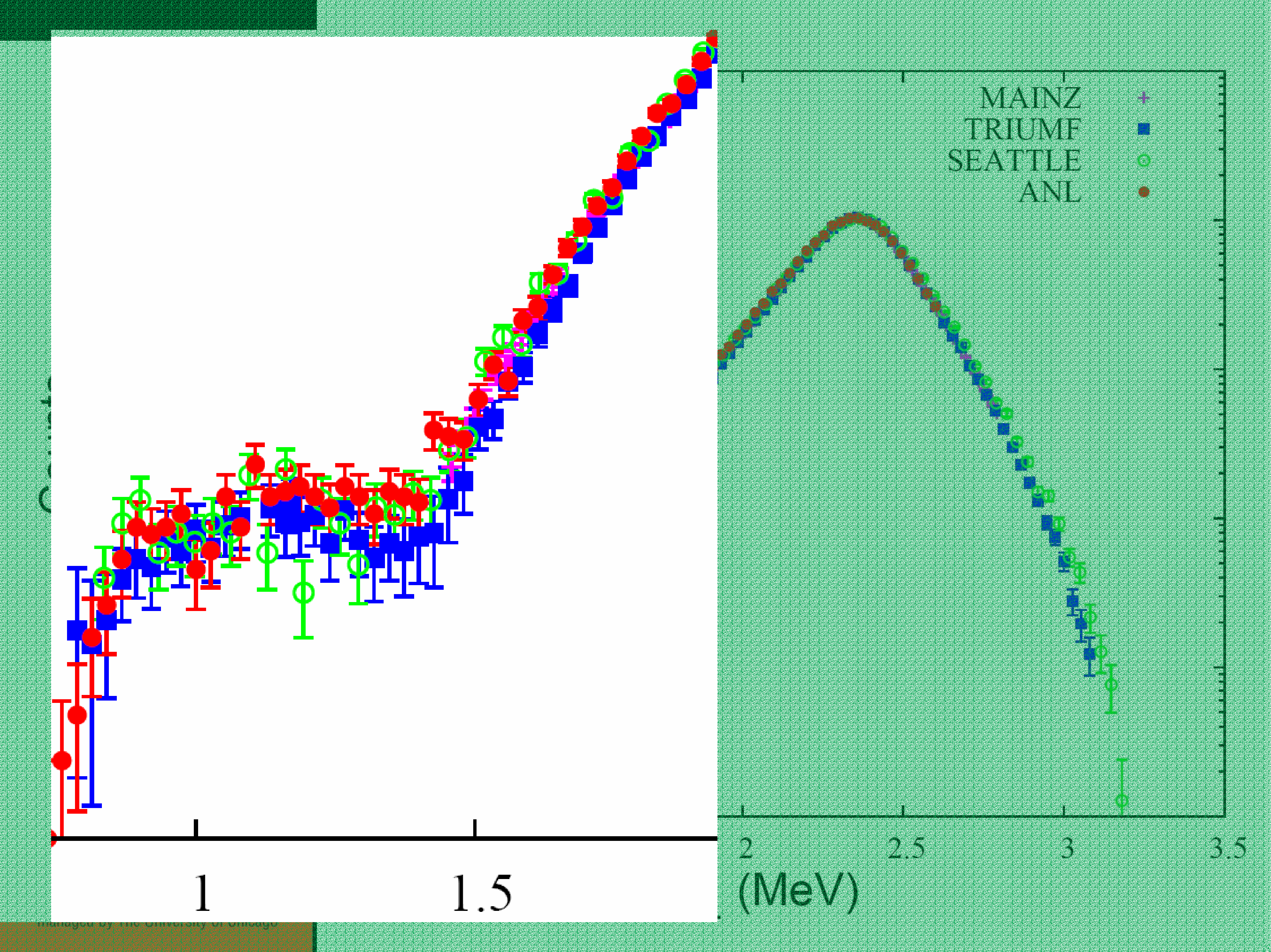
Seattle 1995





- 2.18 channel/(deg C)


Deviations from linearity: <10-3
0.008
0.004
0.000
-0.004
-0.008
DIFF
300
400
500
600
700
800
900
CEN

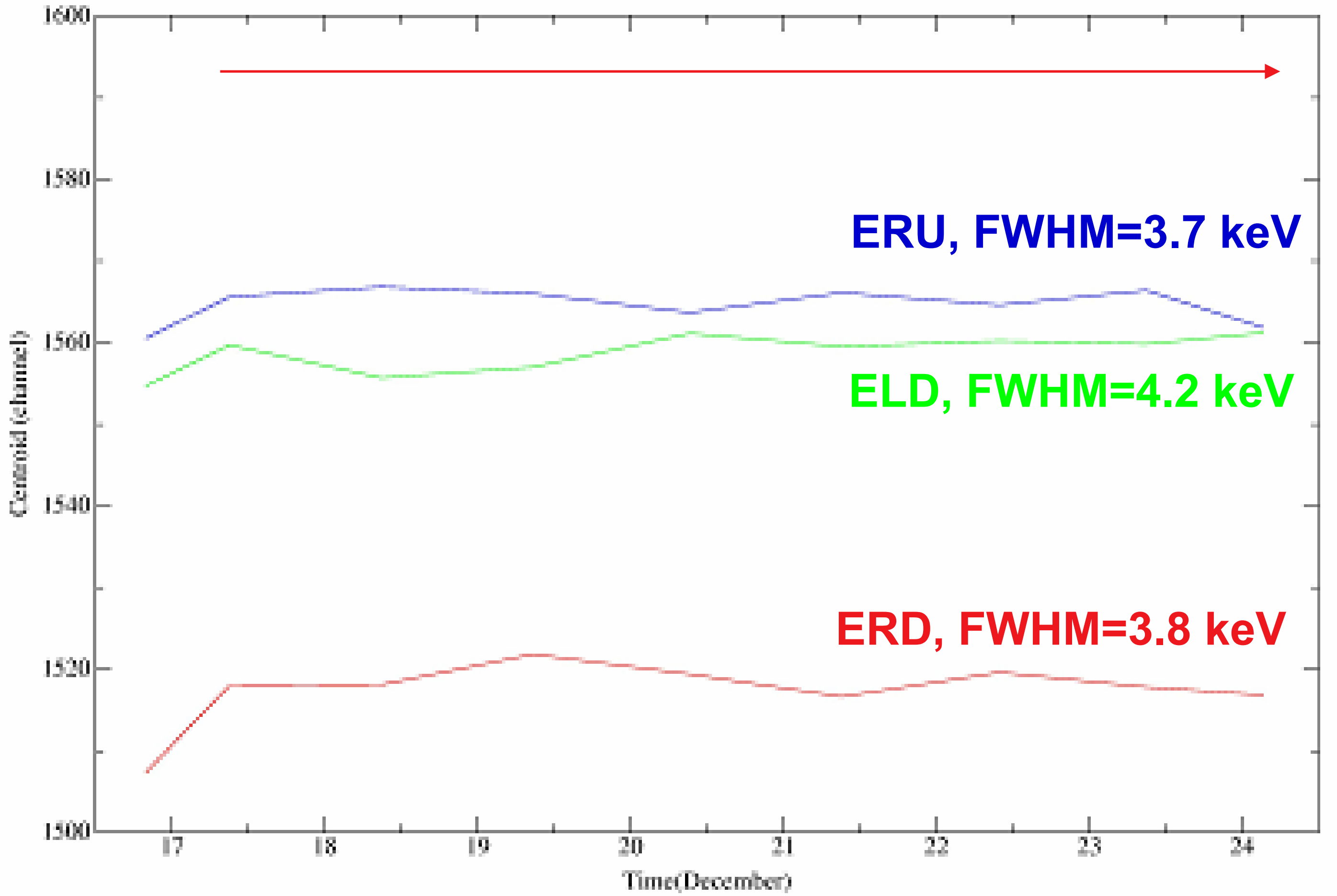

MAINZ
TRIUMF
SEATTLE
ANL
1
1.5
2
2.5
3
3.5
(MeV)

*Problems in Previous Experiments**

- Thin Si detectors (10-15 μm(T), 50 μm(Y))
- Huge β background (noise)
- Radiation damage (diff. detector response)
- Pulse height defect
- Dead layer correction

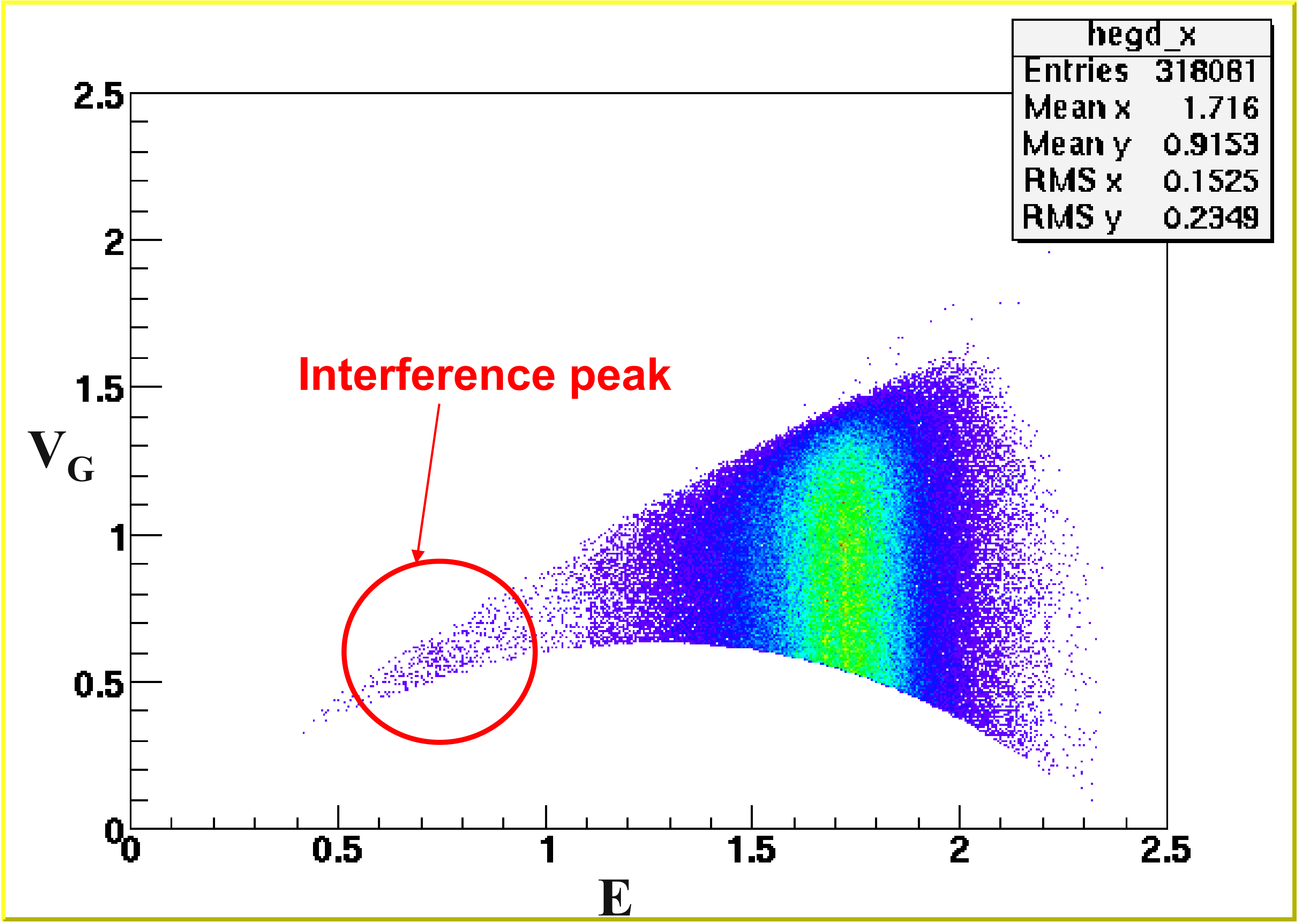
Gas detector would be the best choice.

* Yale: Z. Zhao et al., PRL 70(1993)2066 [S(E1,300keV)=95±6±28 keV•b]
TRIUMF: L. Buchmann et al., PRL 70(1993)726 [S(E1,300keV)=57 ±13 keV•b]
R.Azuma et al., PRC 50(1994)1194 [S(E1,300keV)=82±26 keV•b]



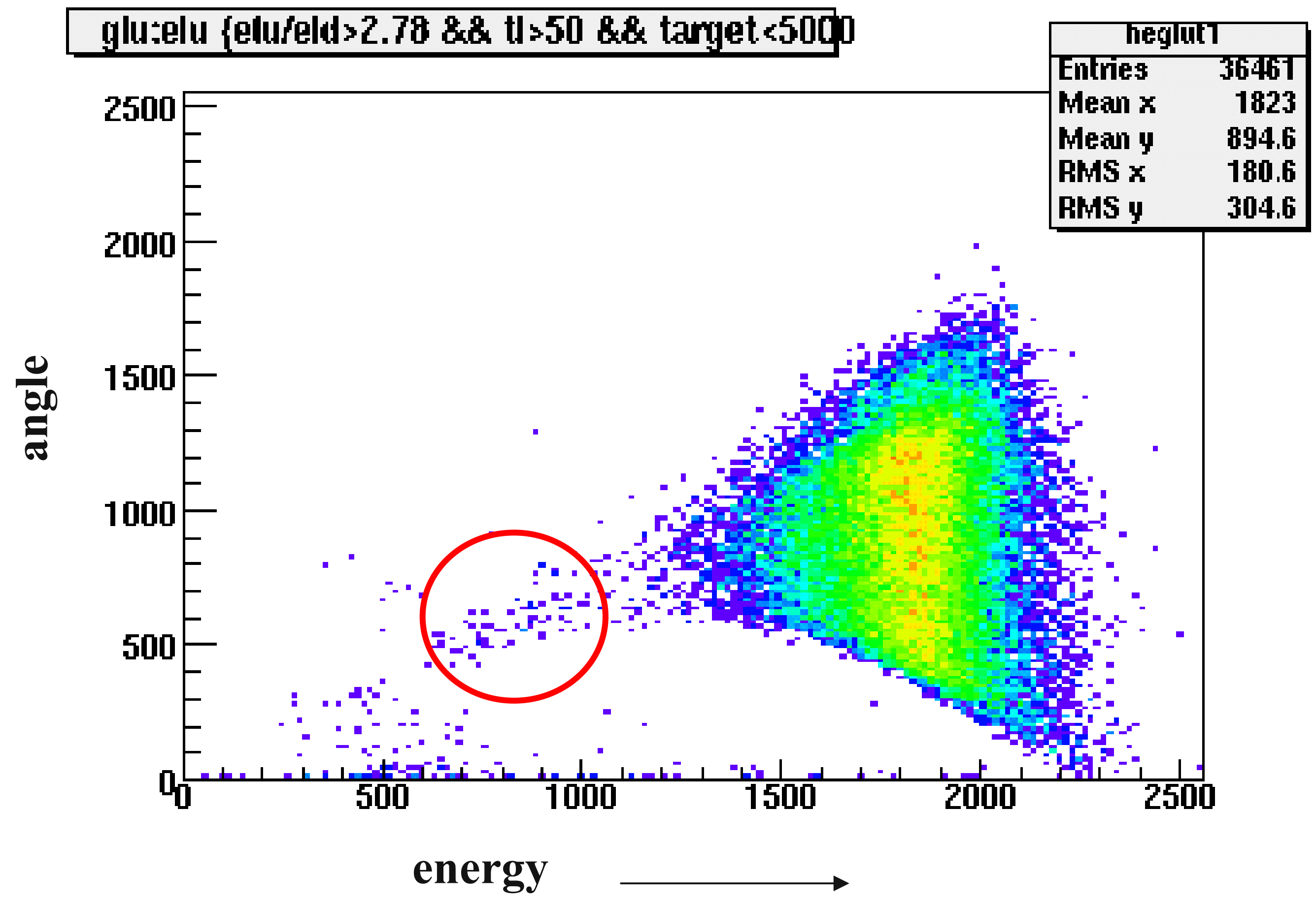
1600
1580
1560
1540
1520
1500
Centroid (channel)
17
18
19
20
21
22
23
24
Time(December)
ERU, FWHM=3.7 keV
ELD, FWHM=4.2 keV
ERD, FWHM=3.8 keV

Simulation



hegd_x
Entries 318081
Mean x 1.716
Mean y 0.9153
RMS x 0.1525
RMS y 0.2349
Interference peak
V_G
E
0
0.5
1
1.5
2
2.5

$^{16}N \rightarrow {}^{16}O \rightarrow {}^{12}C + \alpha$ first test results



Alpha background (2.5×10^4 s)

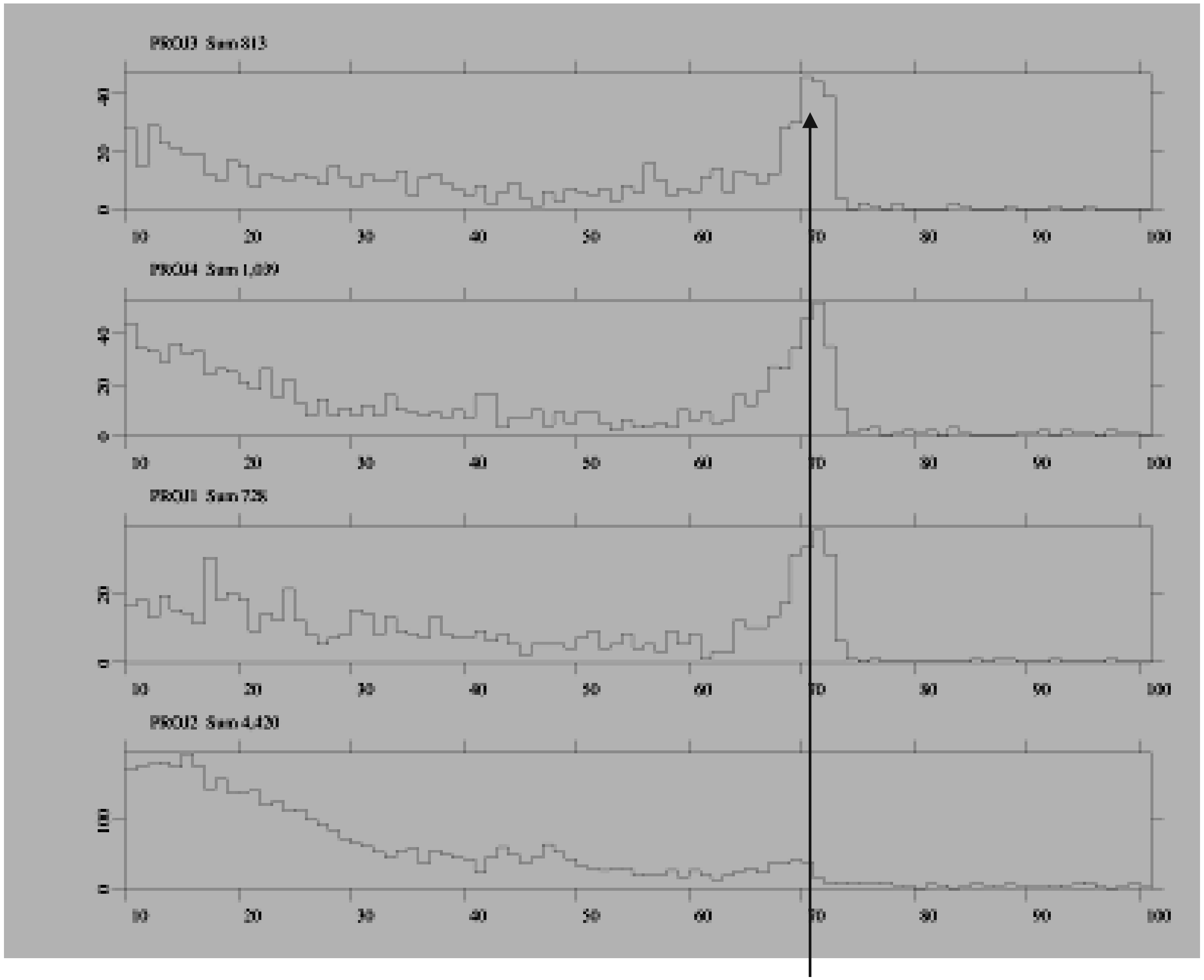
P=760 Torr

ELU — 130/hr

ELD — 170/hr

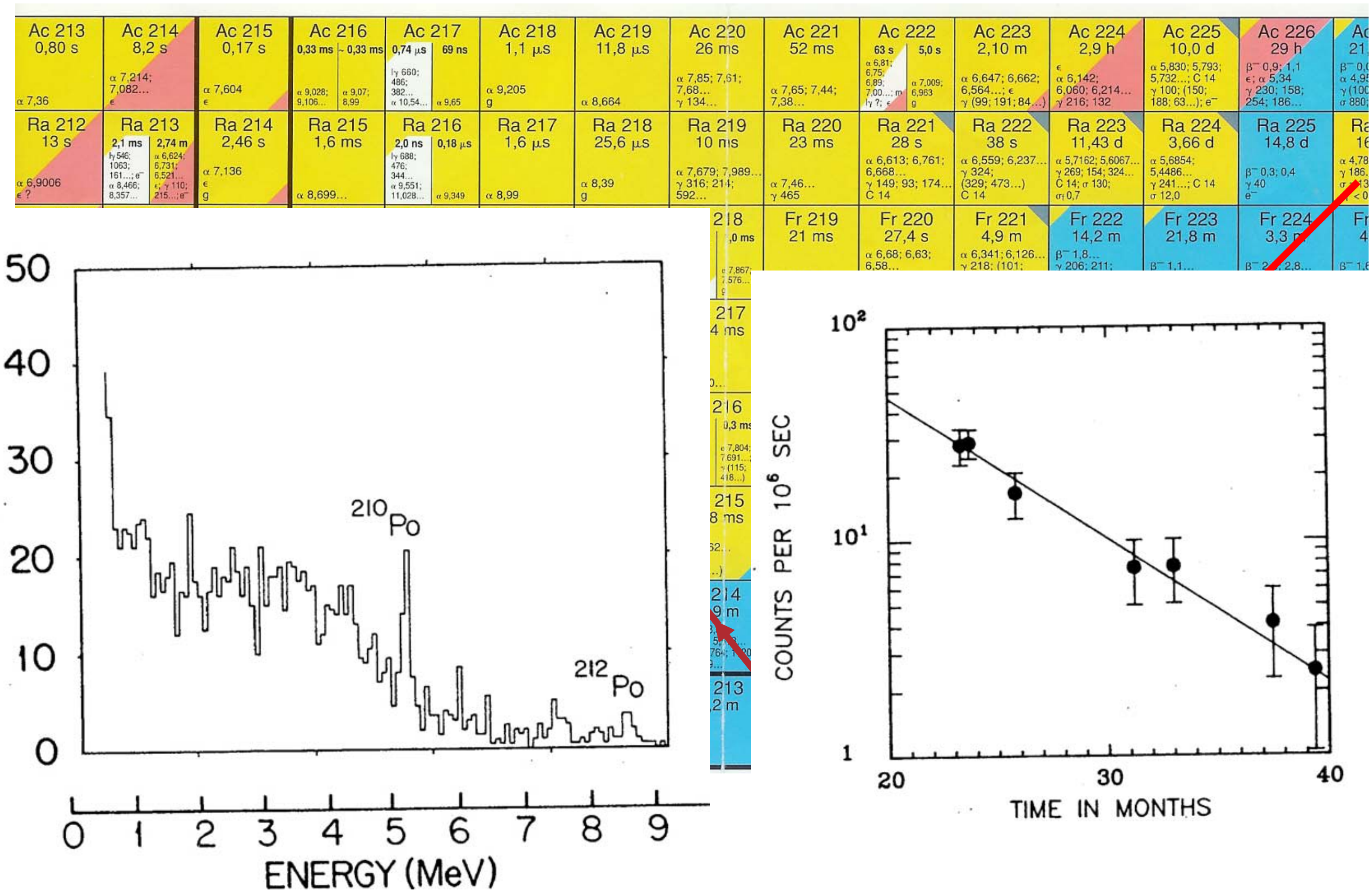
ERU — 110/hr

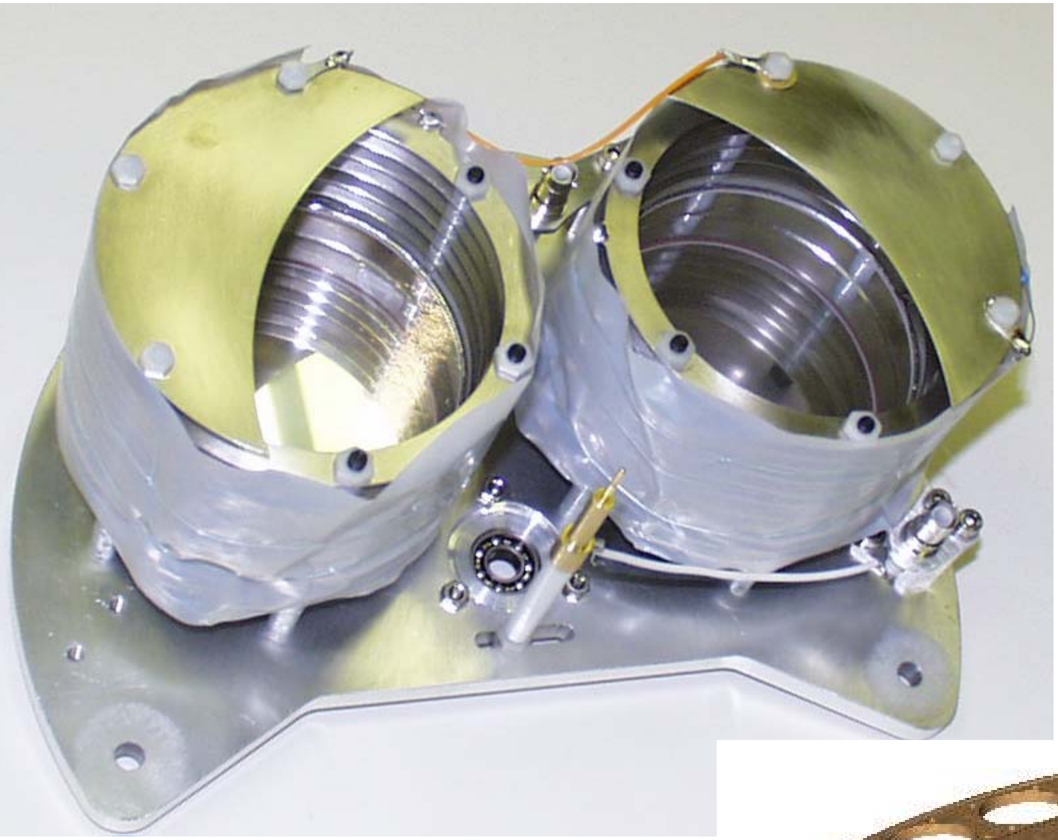
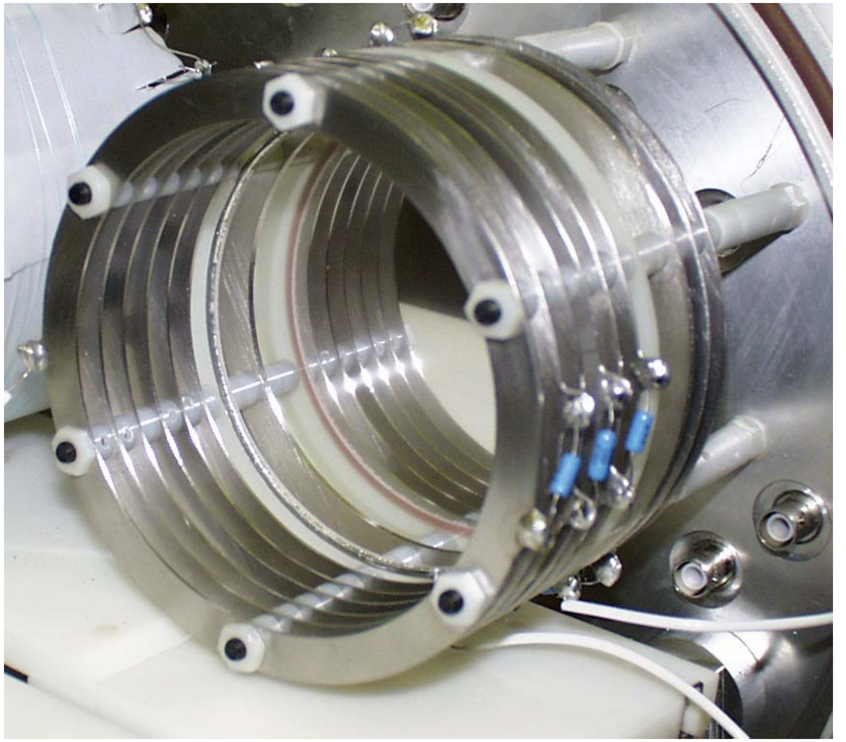
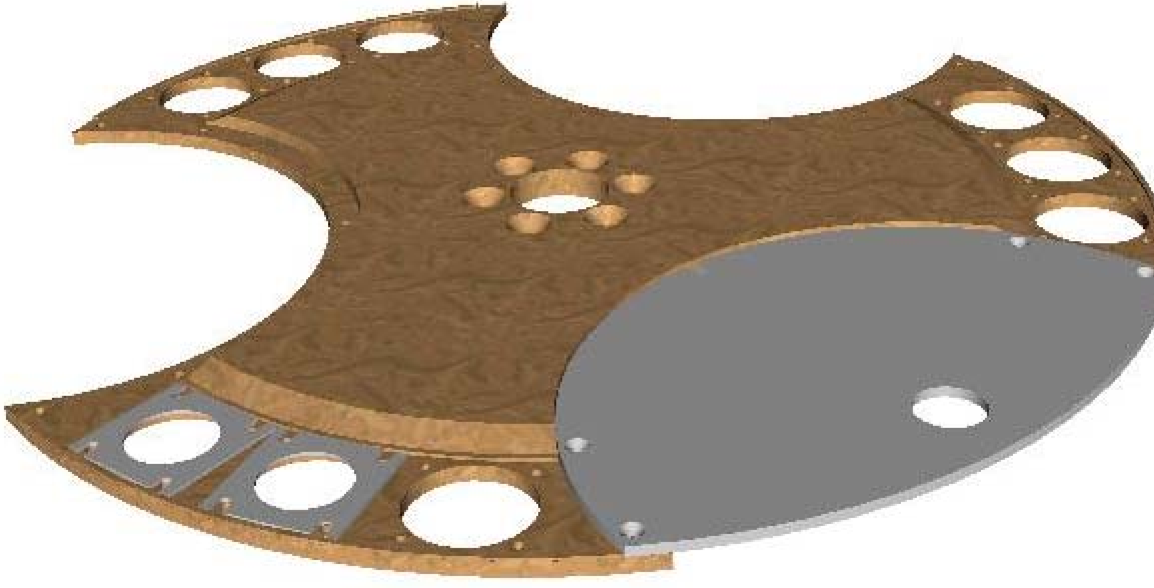
ERD — 700/hr

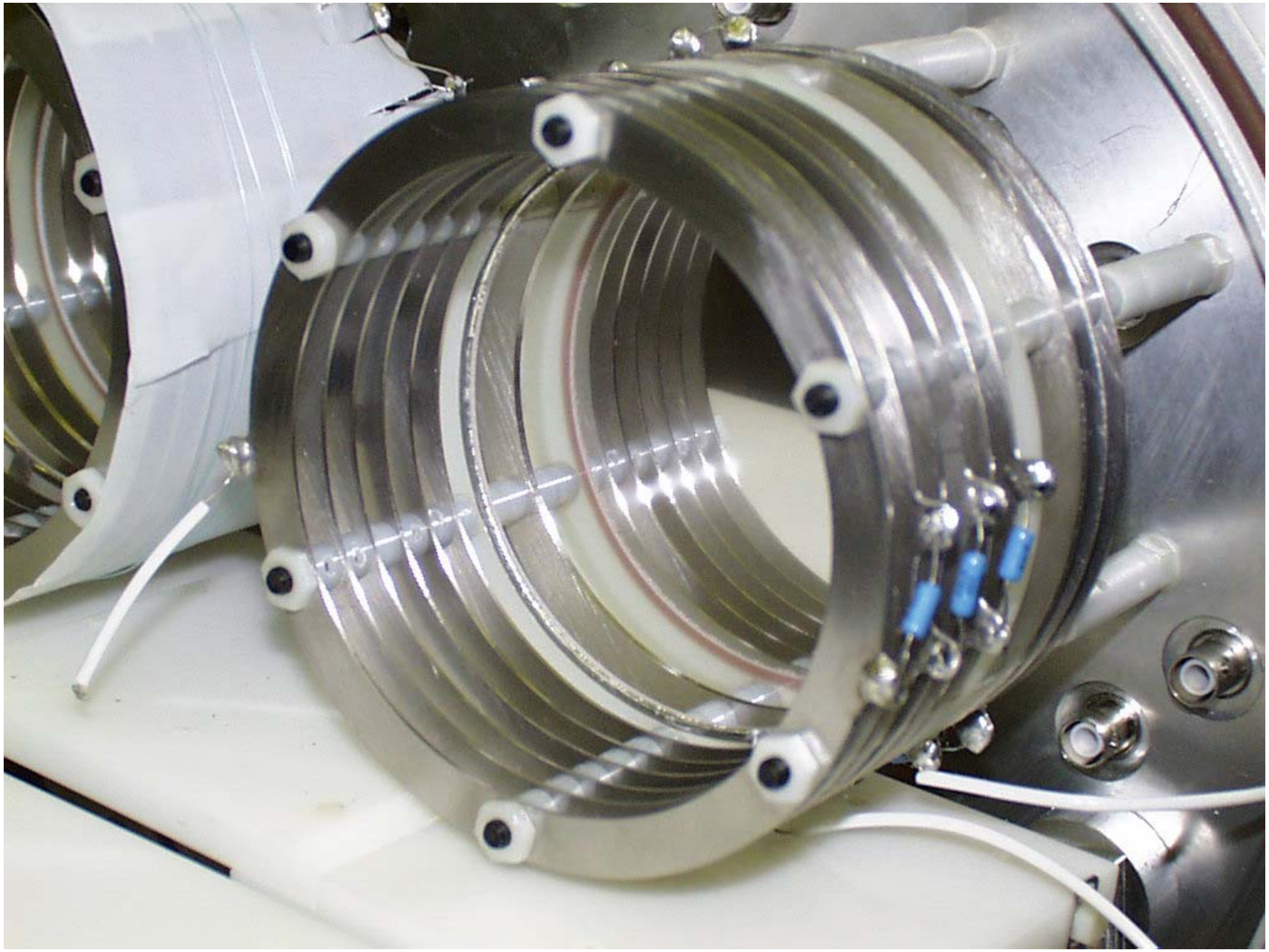


~5.2 MeV

^{210}Po background



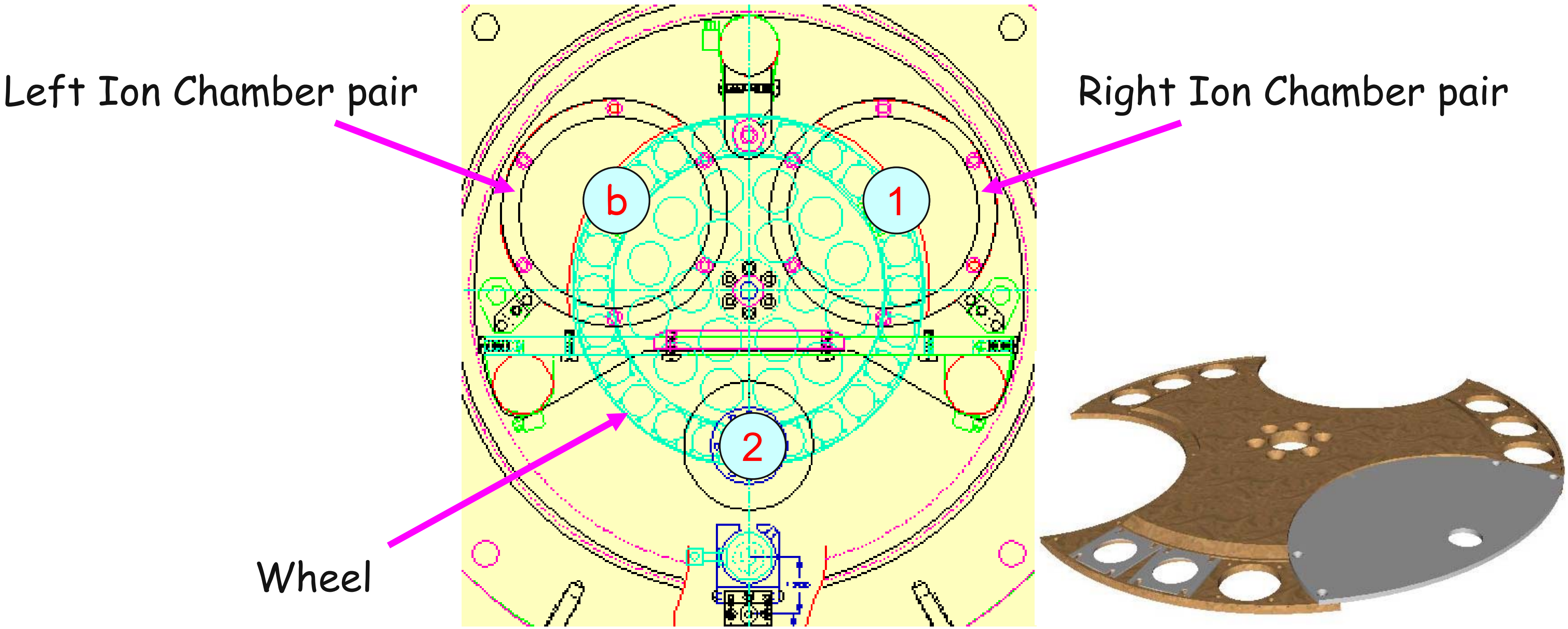


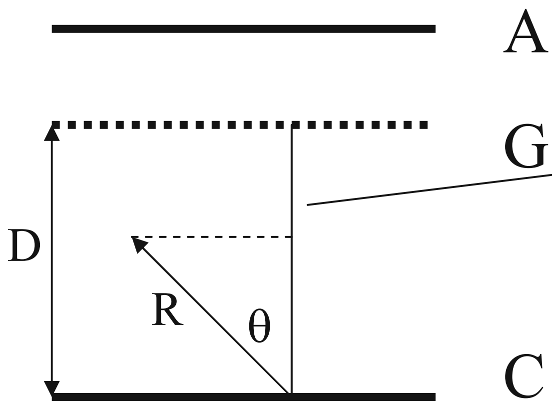
Background in double β decay

We have discovered a broad peak at 5.2 MeV with its leading edge at 5.3 MeV followed by a significant continuum. A similar peak has been observed in the UCSB-LBL detector[31] at 5.1 MeV and has been attributed to a Doppler broadened line produced by the reaction $^{28}Si(n,n\gamma)^{28}Si$. We have been successful in reproducing our line at 5.2 MeV in a simple laboratory experiment. When soft solder is melted, the ^{210}Po, from the sequential decays of ^{210}Pb and ^{210}Bi, concentrates on the surface of the bead. After melting and solidifying several beads of solder, α spectra from their surfaces observed with a surface barrier detector were also found to contain this peak. The same phenomenon was observed in the UCI (University of California, Irvine) time projection chamber, and

T. Avignone et al. PRC 34,666(1986)

Measure the α spectrum





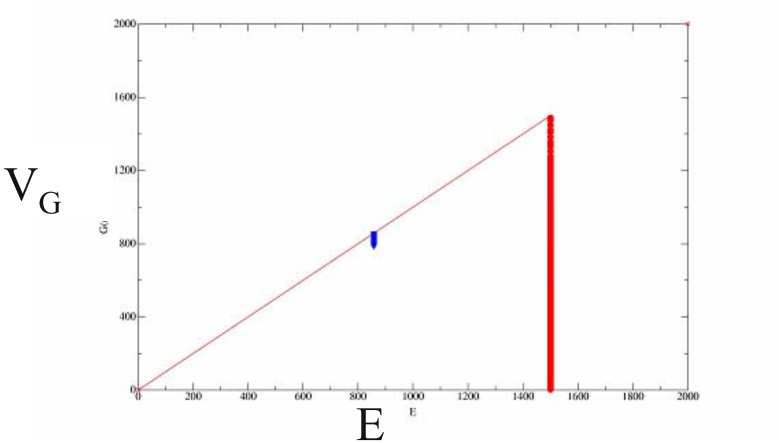
$$V_G \sim E \cdot (D - R\cos\theta)$$

$$V_G \sim E \cdot \left(1 - \lambda \frac{E^2}{mZ^2} \cos\theta\right)$$

For $^{10}B(n,\alpha)^{7}Li$

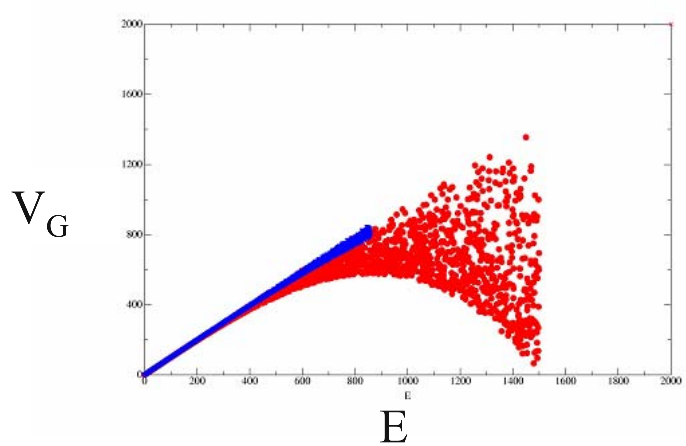
E_α=1.5 MeV, random θ

$E_{Li}=4/7*E_\alpha$



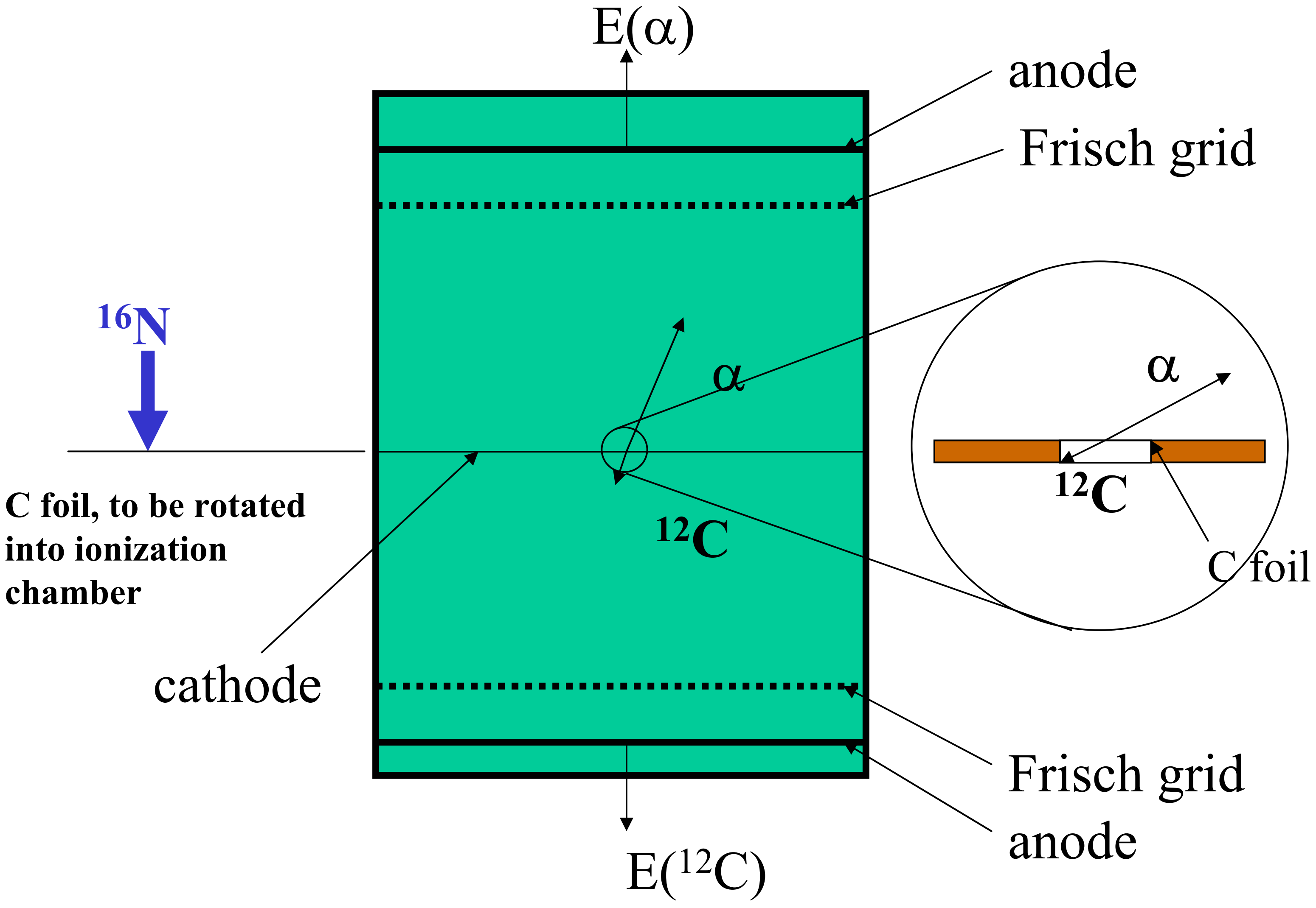
random E_α, random θ

$E_{Li}=4/7*E_\alpha$

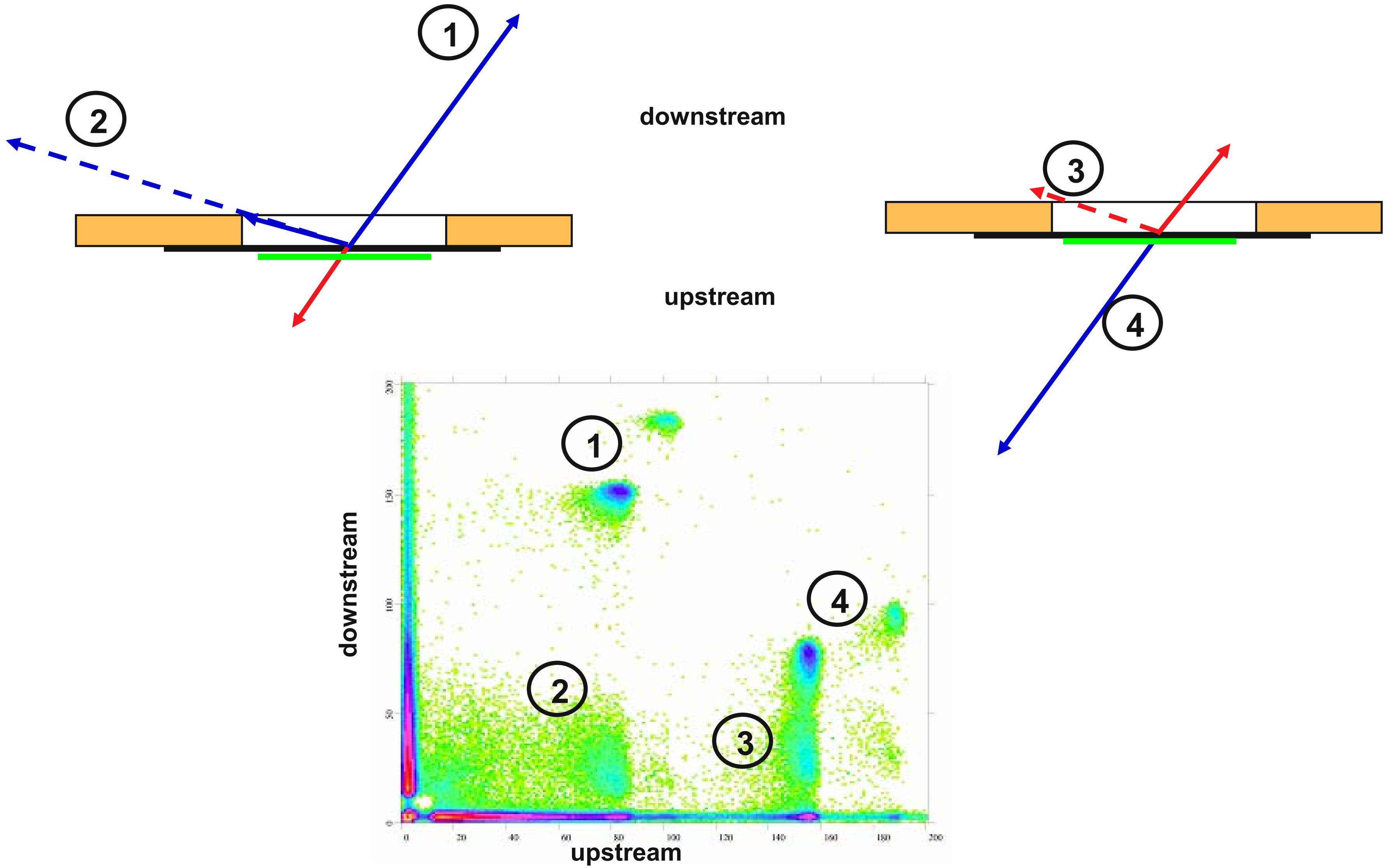


Response of a Si detector to the $^{10}B(n,\alpha)^{7}Li$ reaction

Twin-Ionization Chamber

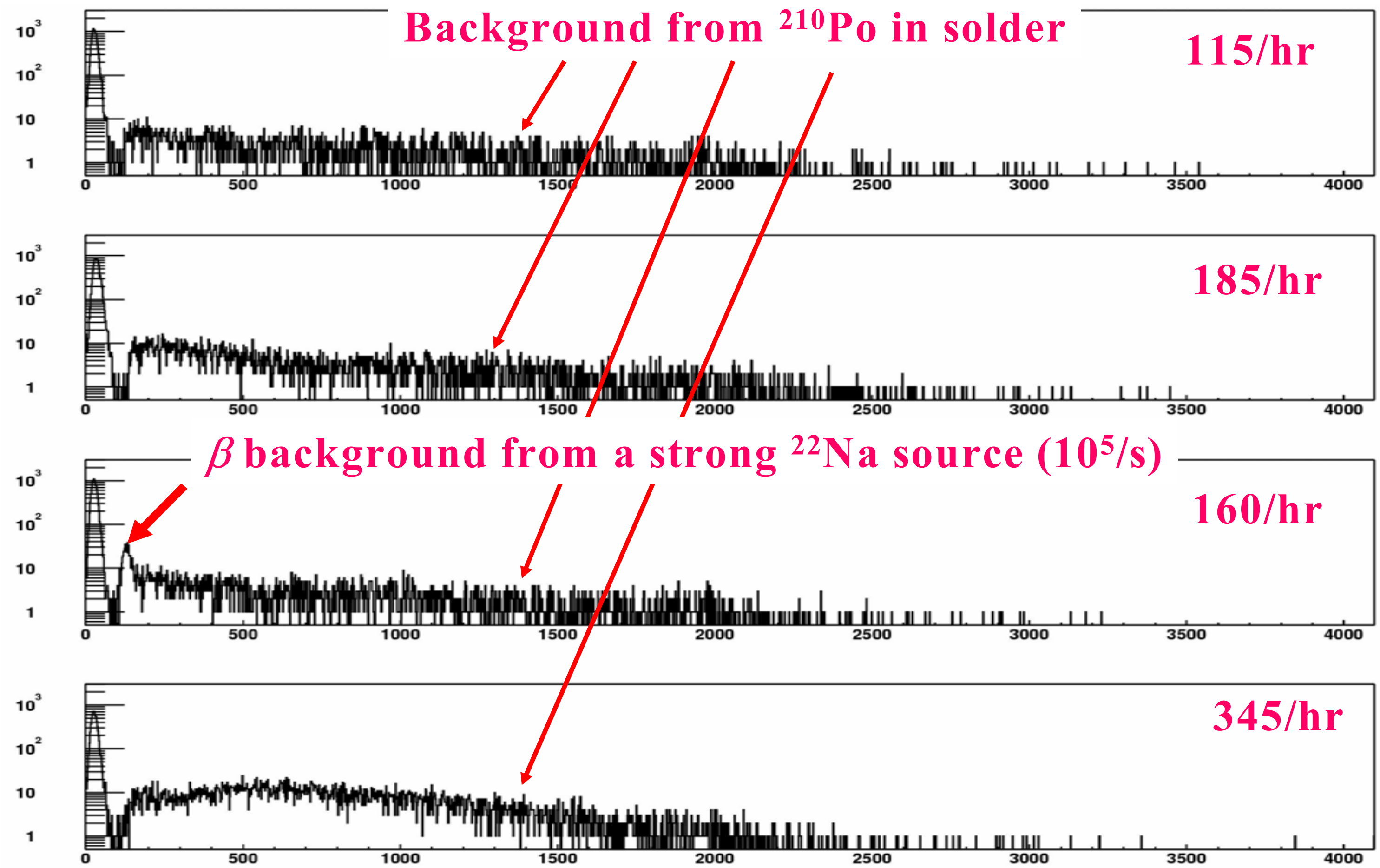


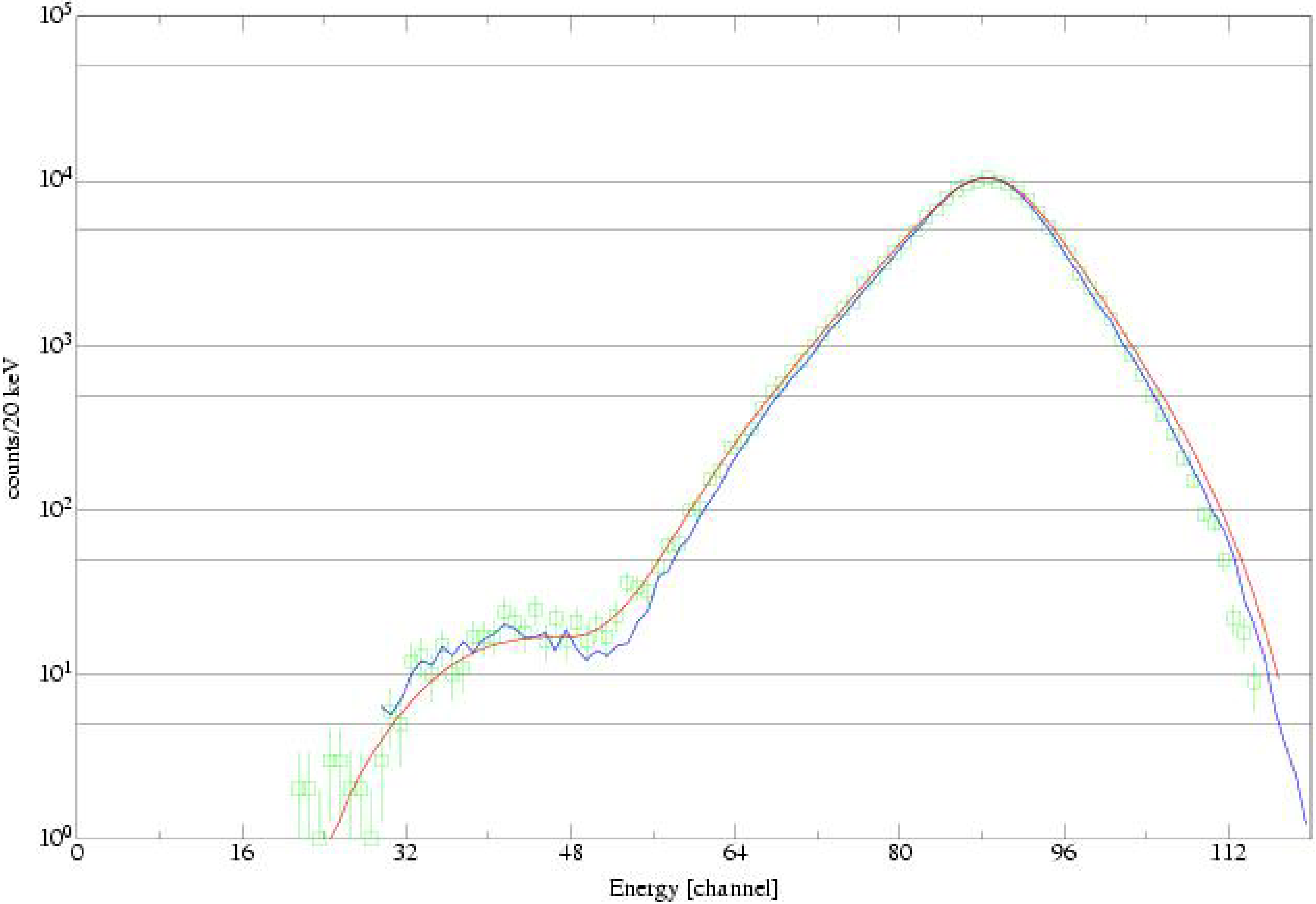
Used GAMMASPHERE



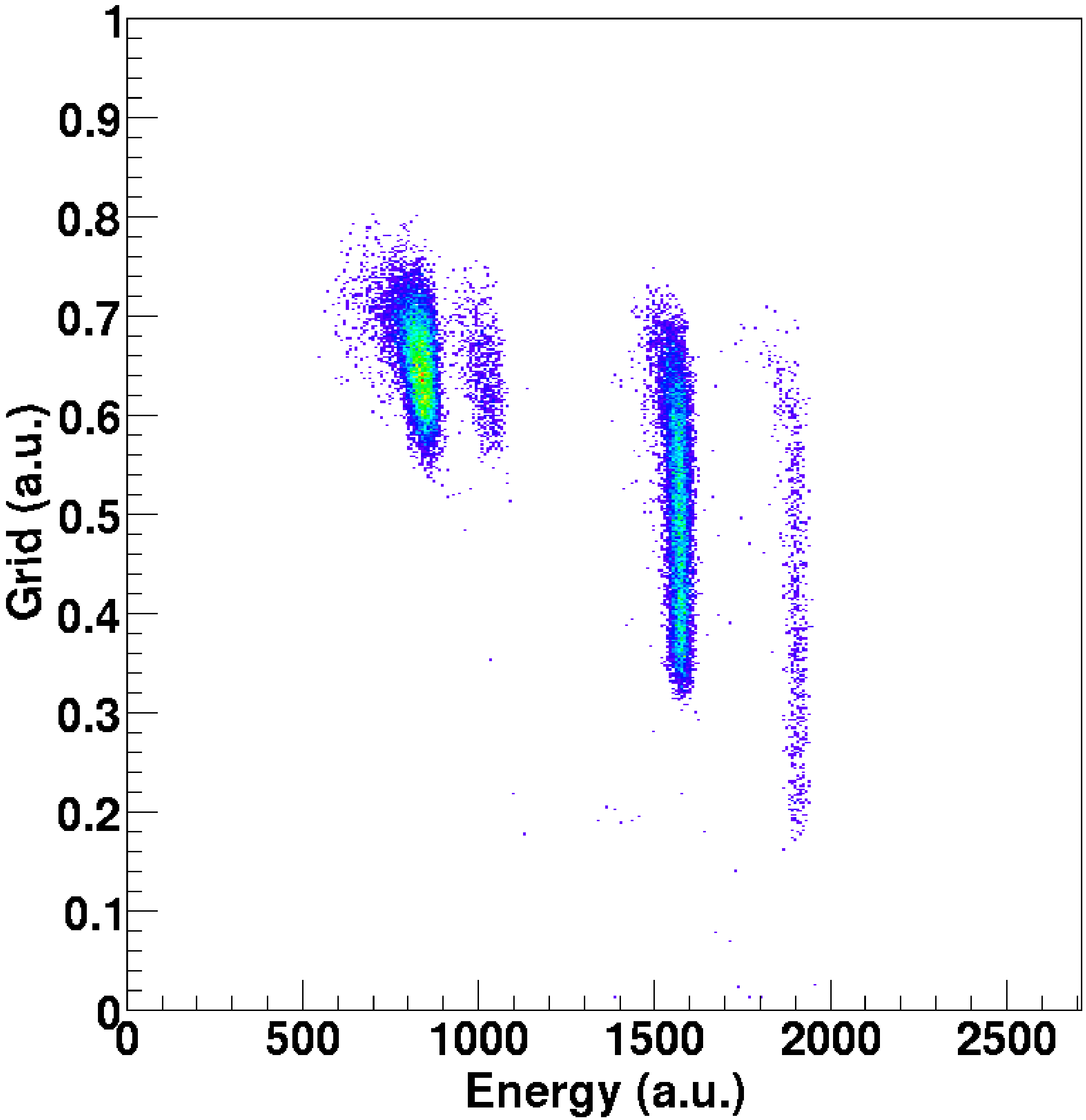
1
2
downstream
3
upstream
4
1
4
downstream
2
3
upstream

What is the β-sensitivity?





10^5
10^4
10^3
10^2
10^1
10^0
counts/20 keV
0
16
32
48
64
80
96
112
Energy [channel]



1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Grid (a.u.)
0
500
1000
1500
2000
2500
Energy (a.u.)

Energy and efficiency calibration:

Energy of ^{16}N alphas ~ 1.75 MeV

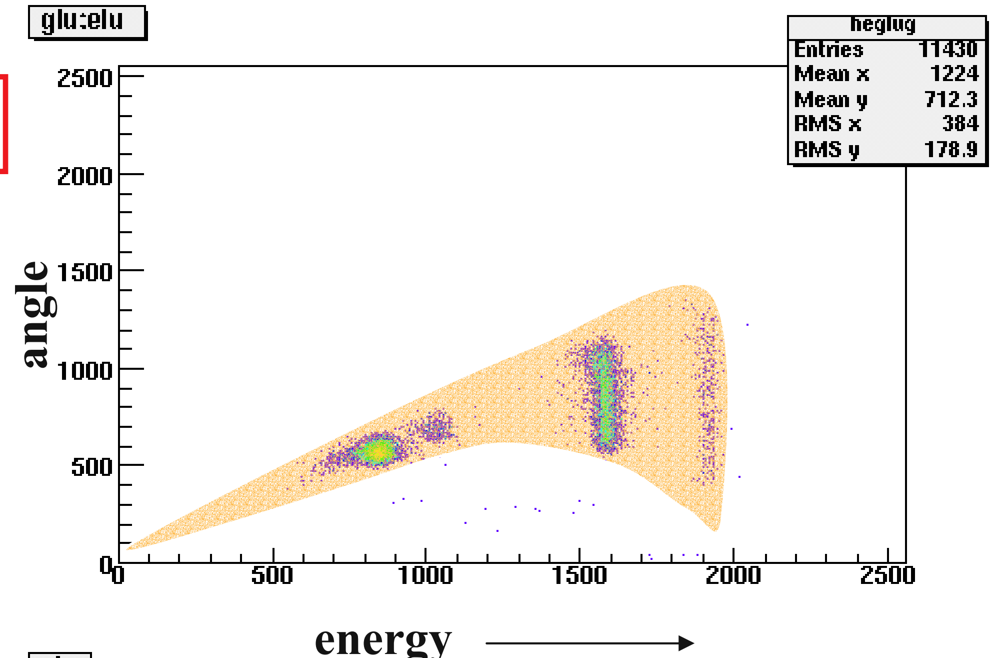
$^{10}B + n \rightarrow \alpha + {}^{7}Li$

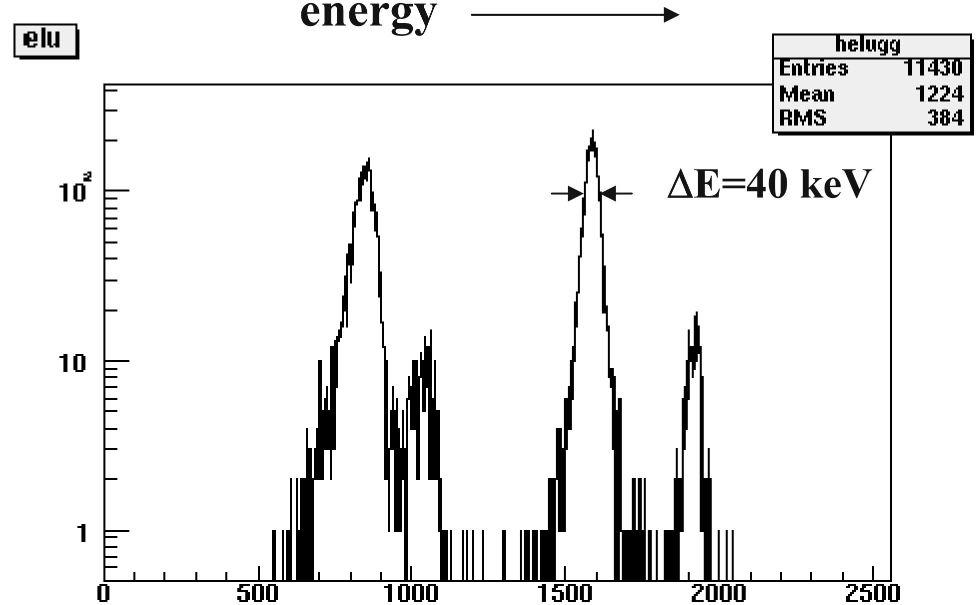
$E_\alpha =$ 1.789 MeV

1.483 MeV

$E_{Li} =$ 1.022 MeV

0.847 MeV





Slowing down the ^{16}N particles

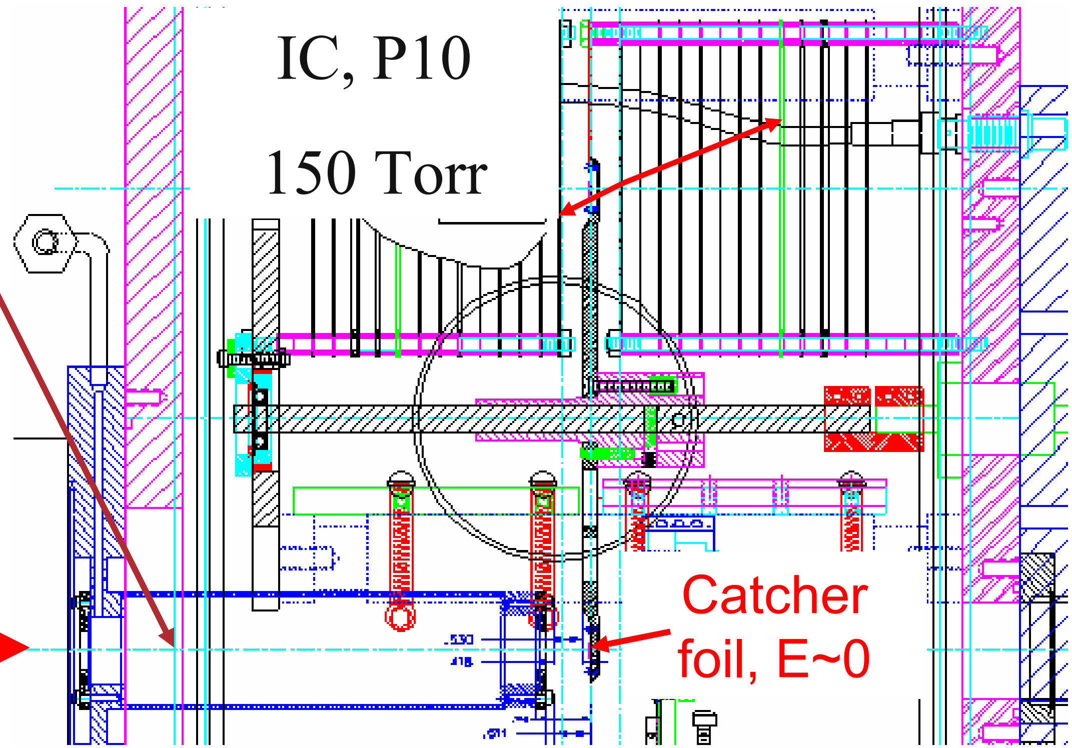
Attenuator cell,

Individual pressure control

Windows:

- **Thin**
- **low Z**
- **High Young's modulus**

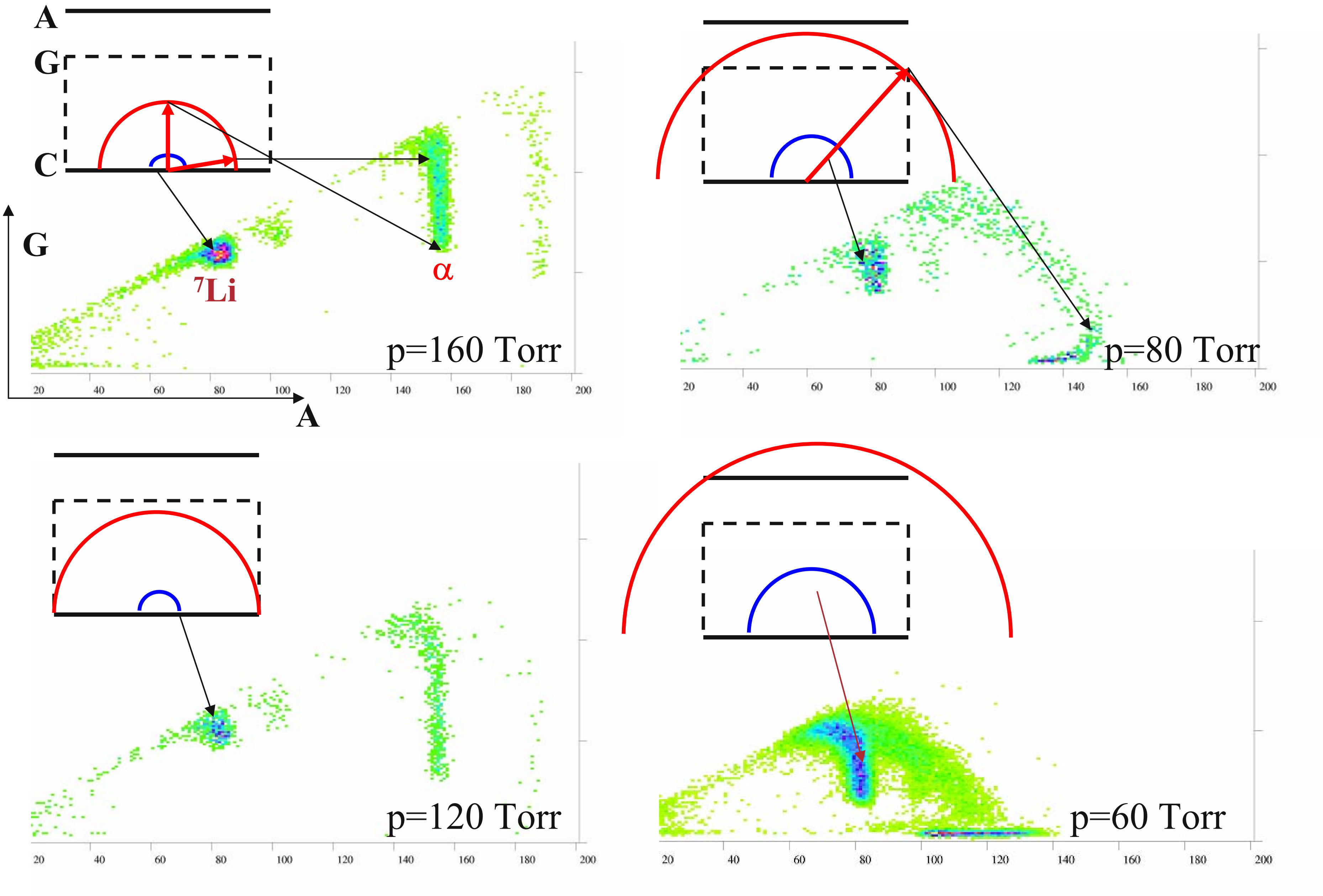
60MeV ^{16}N



In gas cells you have to use the windows you have, not the ones you would like to have.*

free after D. Rumsfeld

Pressure dependence

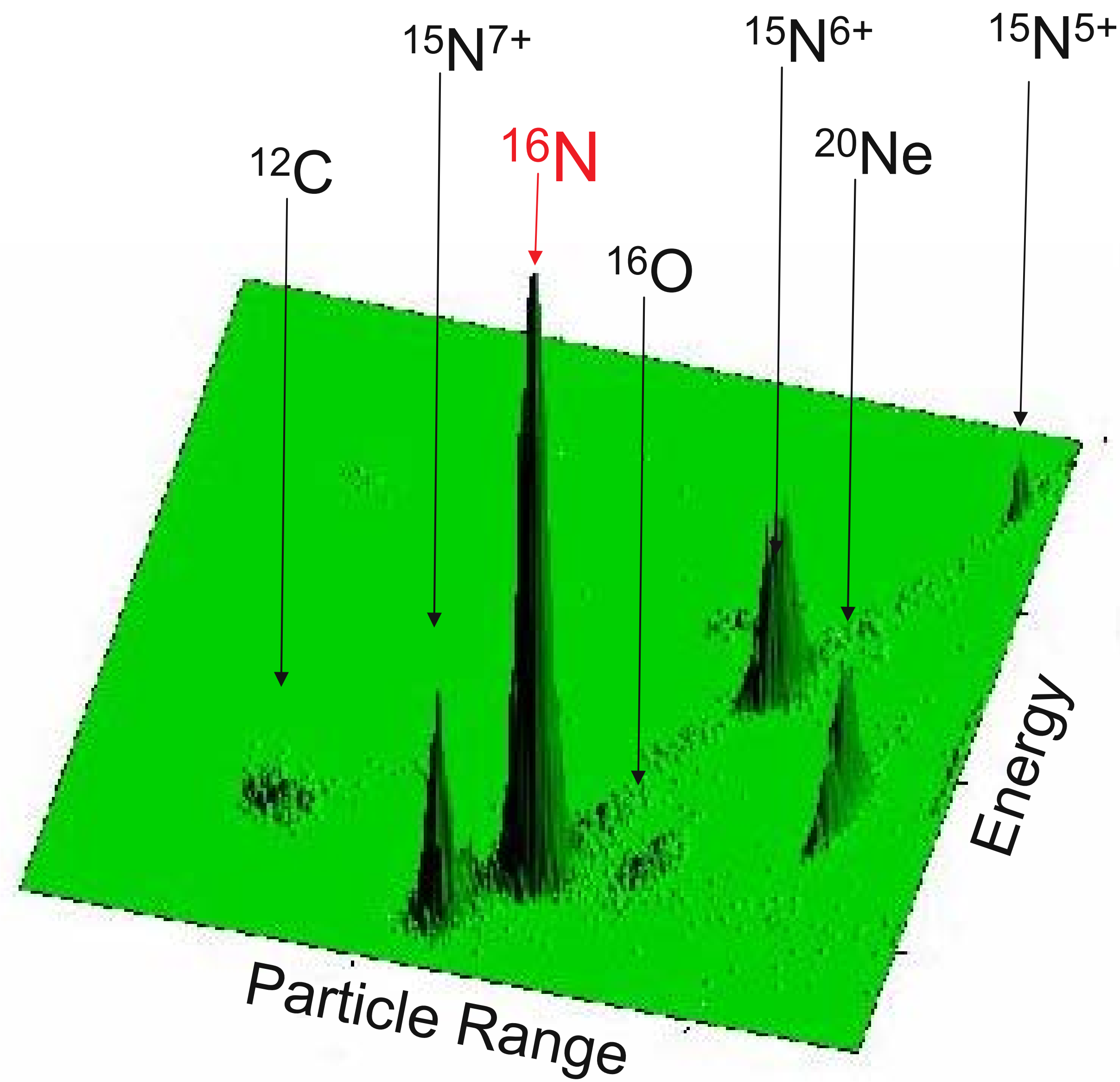


Future Plan

- Increase Gas Pressure to stop 2.5 MeV alpha's

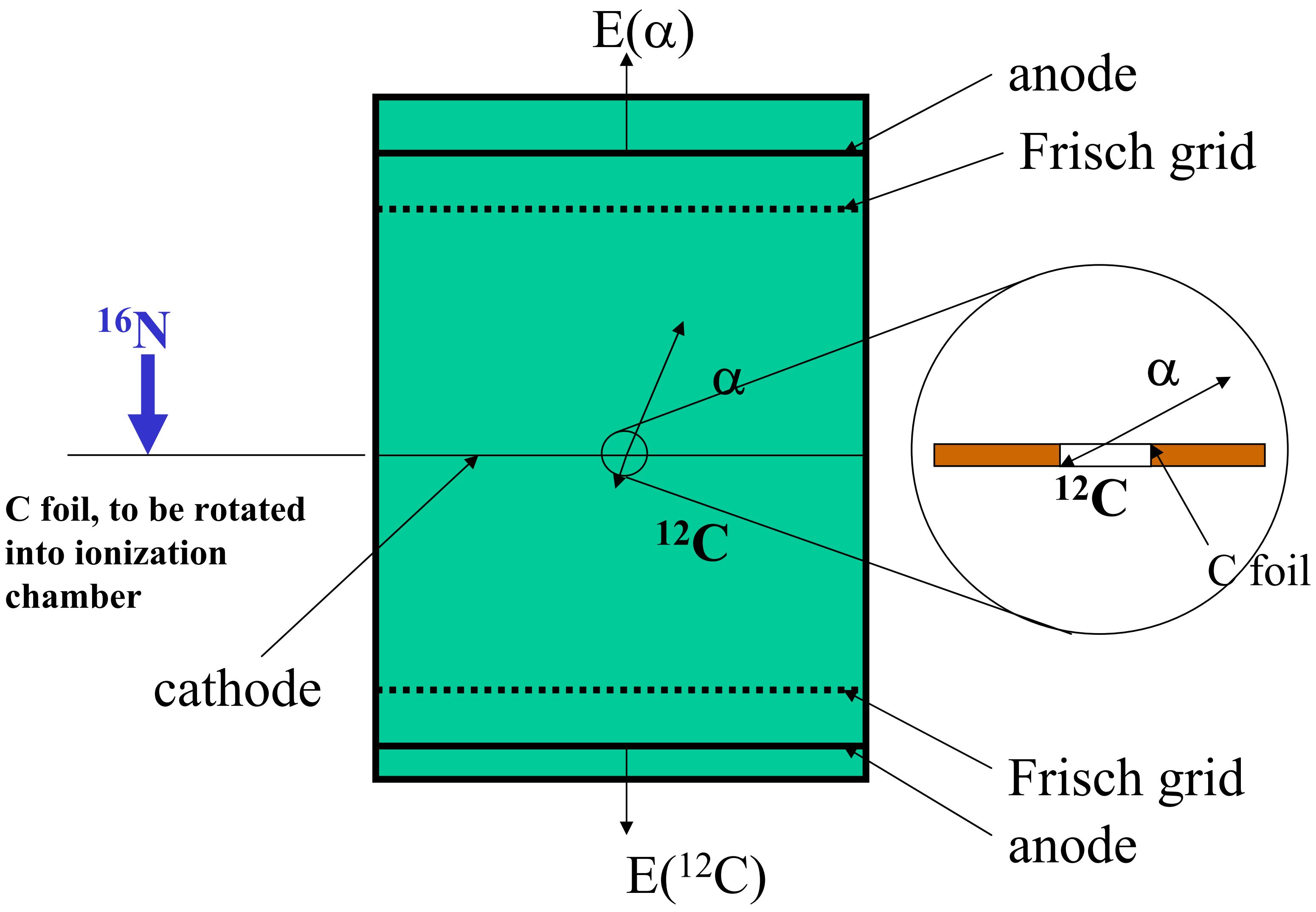
- Improve statistics
  TRIUMF: $1x10^6$
  Yale-Uconn: $6x10^4$, $0.27x10^6$
  ANL: $0.16x10^6$/4 days; 0.16*2*2.5($0.8x10^6$)/10 days

- R-matrix fitting

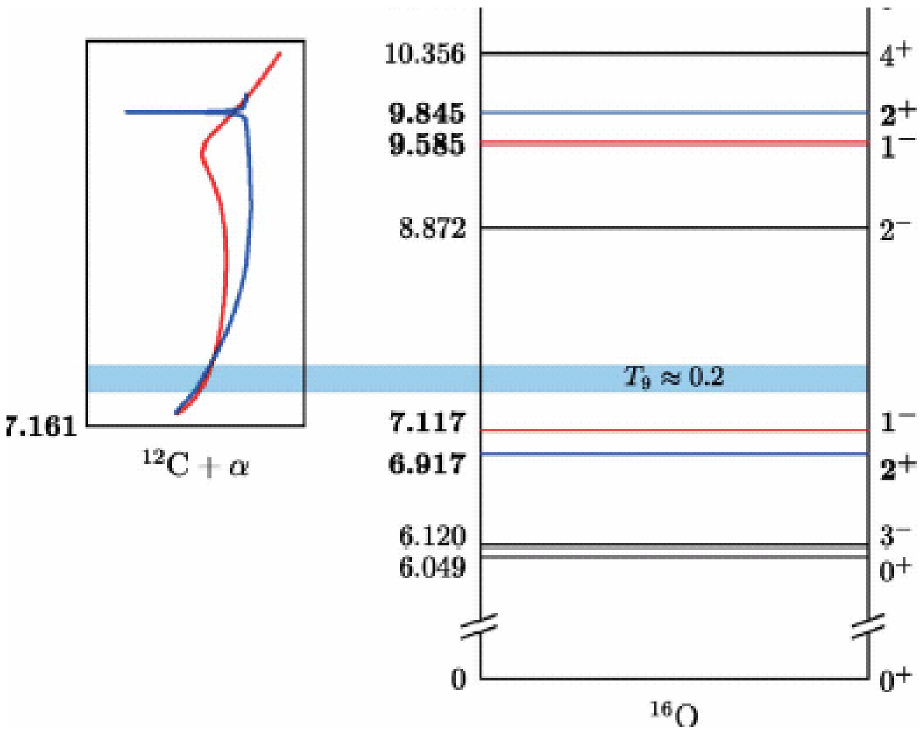


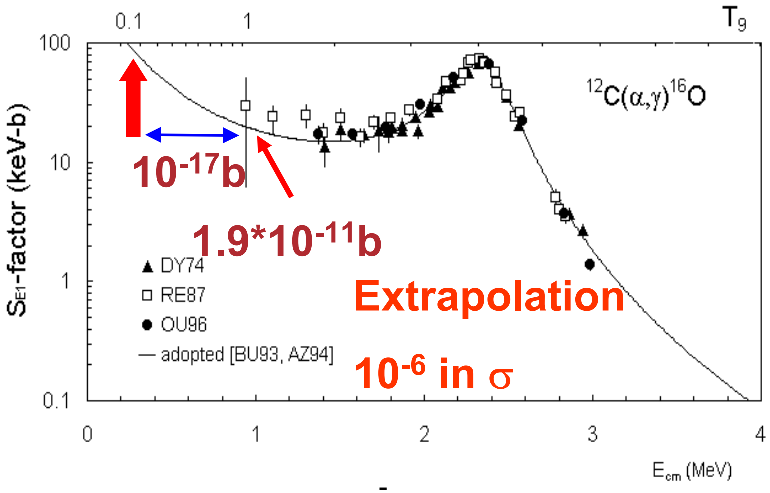
Particle Identification Spectrum

Twin-Ionization Chamber



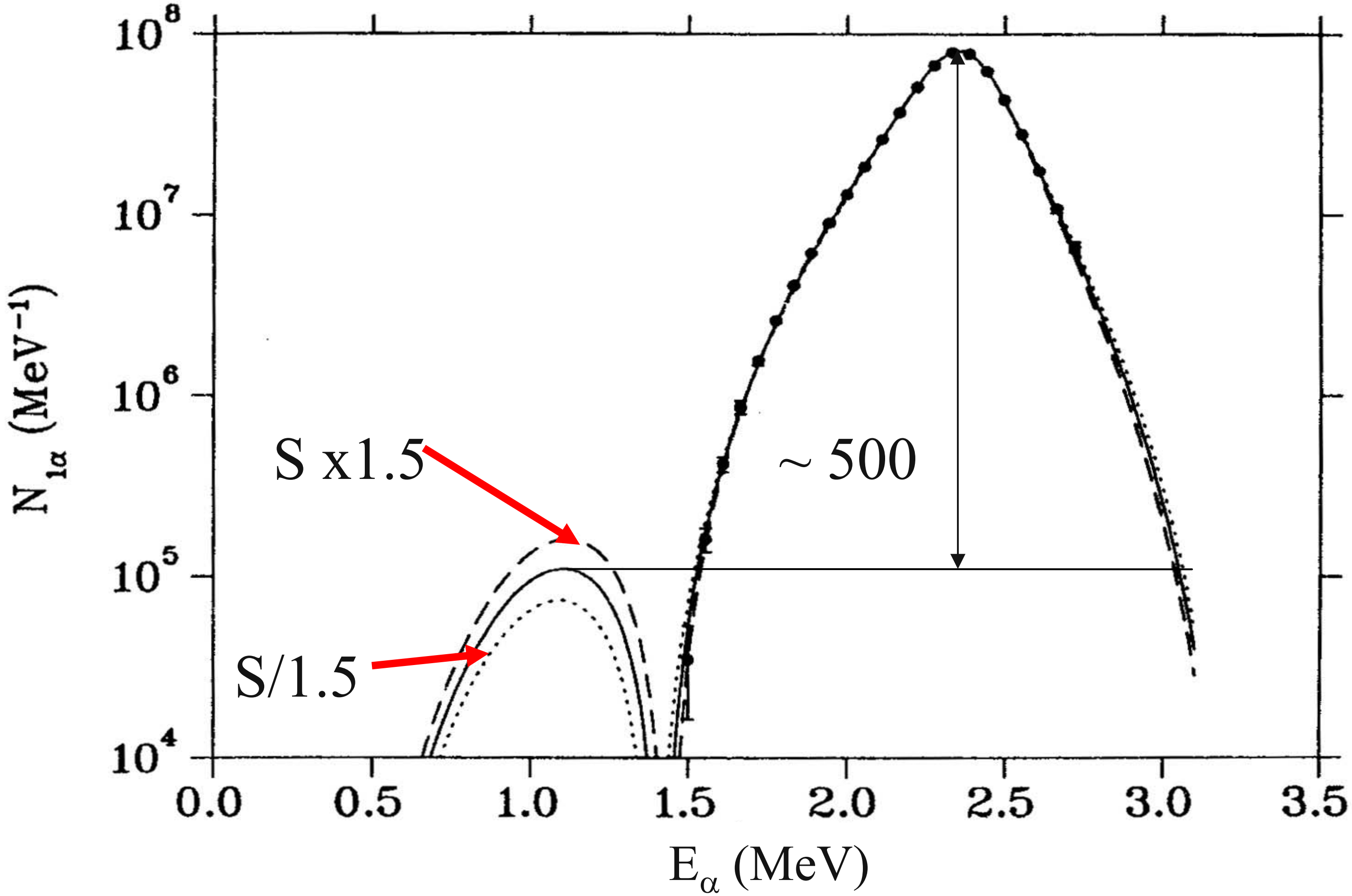
Level structure of ^{16}O





- Beam production
- (Stopping of the ^{16}N beam)
- Detector
- Energy calibration
- Backgrounds
- Preliminary results

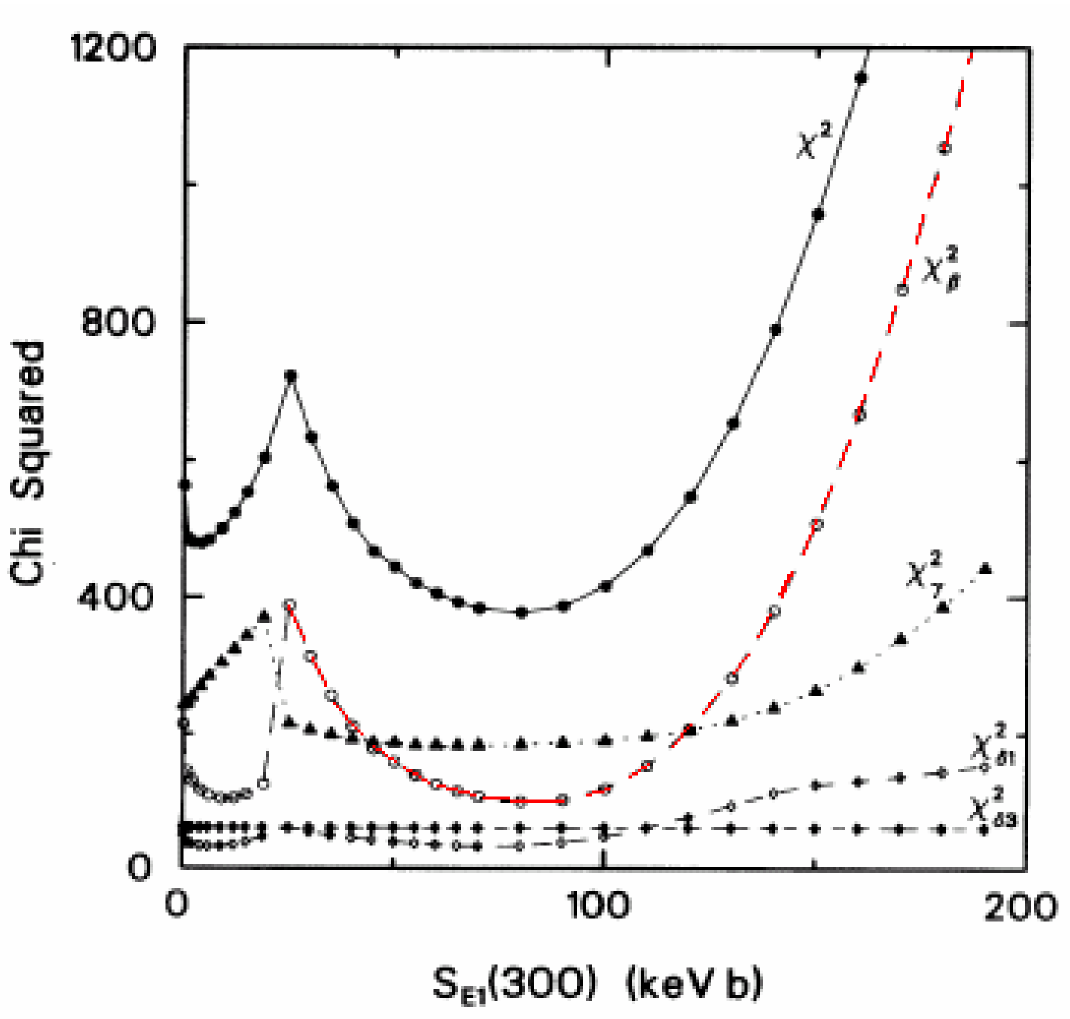
Interference between the allowed and subthreshold 1^- states in the ^{16}N β decay



J. Humblet et al., Phys. Rev. C44, 2530(1991)

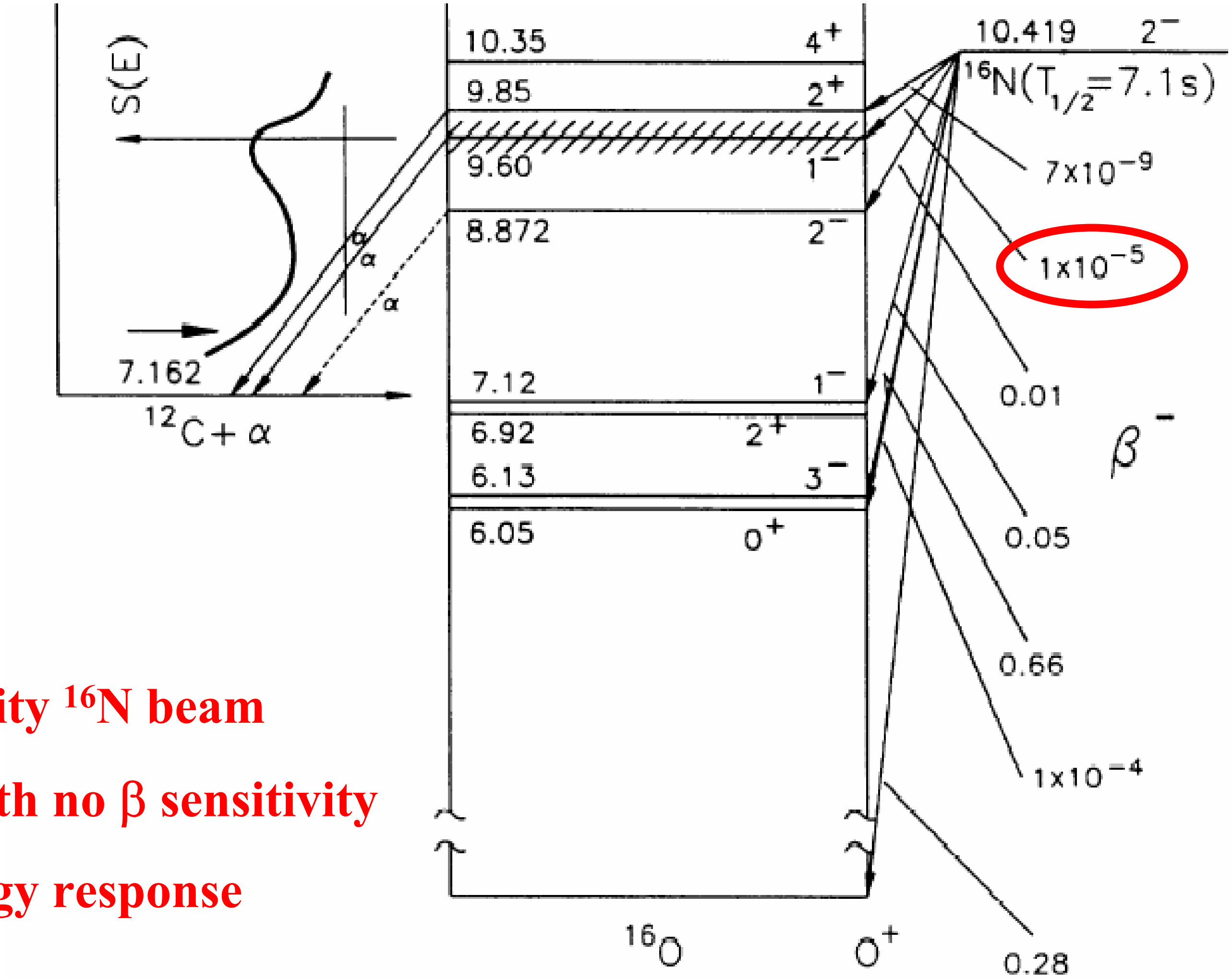
Sensitivity of S(E1) to various parameters

(from PRC50, 1194(1994))



- β-delayed α decay of ^{16}N
- direct (α,γ) measurements
- phase shift parameters

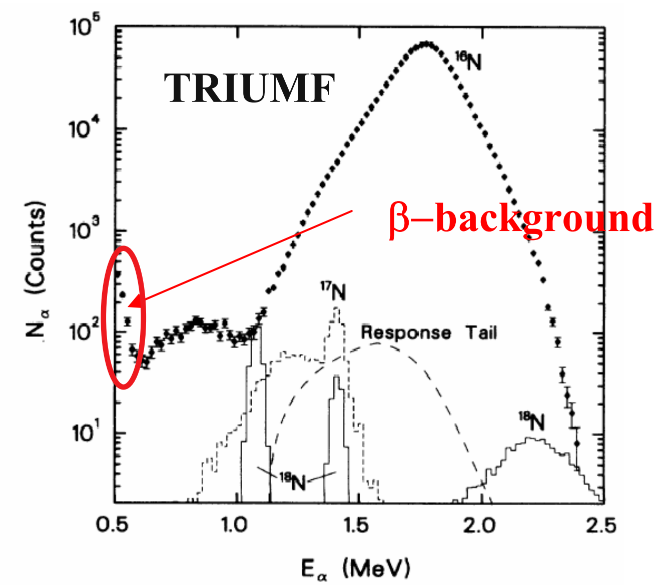
Experimental difficulties in measurements of the β-delayed α decay of ^{16}N

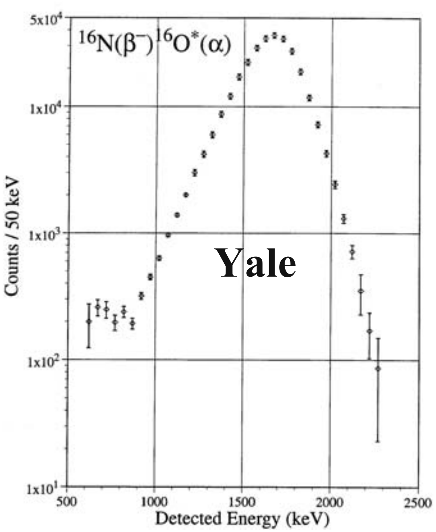


- **High intensity ^{16}N beam**
- **Detector with no β sensitivity**
- **Stable energy response**

Previous Measurements of the β-delayed α decay of ^{16}N

Mainz (1969-1974)	Si	35 μ
Yale (1993-1997)	Si	50 μ
Seattle (1994-1995)	Si	? μ
TRIUMF (1993-1997)	Si	11-16 μ





- Goal of future experiments: reduce low-energy background
- No contamination from ^{17,18}N beams

Dyer NP.233, 495(74)

Kettner et al., ZPA308,73(82)

Redder et al. NP A462,385(87)

Kremer et al., PRL 60,1475(88)

Ouelett et al. PRC54, 1982(96)

Roters et al.,EPJ6,451(99)

Kunz et al., PRL86,3244(01)

Gialanella et al. EPJ11,357(01)

Assunção et al., PRC73,055801(06)

IFK

NaI

Ge

BGO

Plaga et al., NP A465,291(87)

Tischhauser et al., PRL

Brune et al.

(6Li,d)

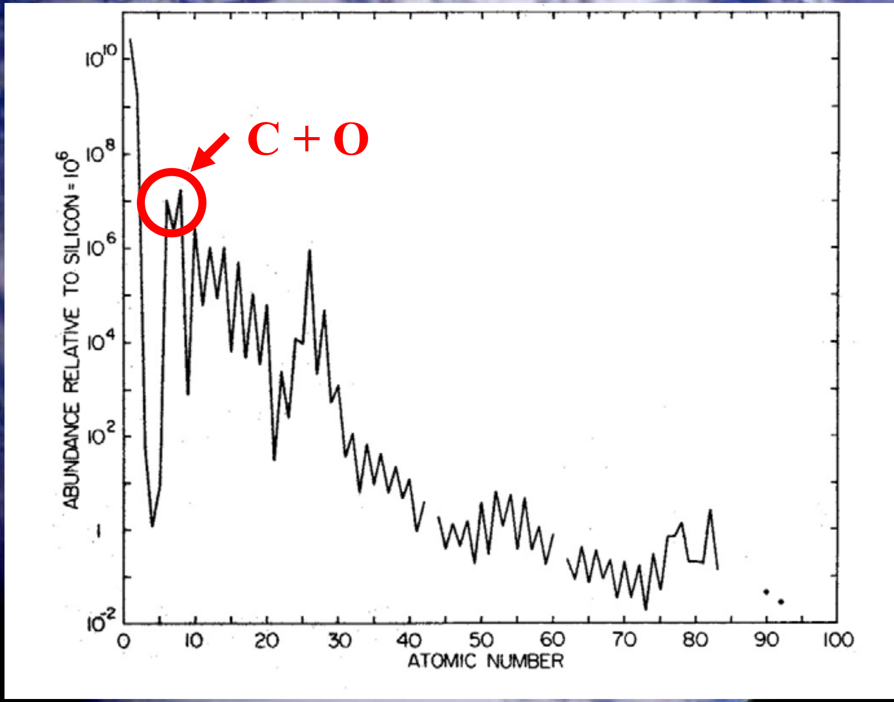
Schürmann et al.

Buchmann et al., PRL70, 726(93)

Zao et al., PRL70

Azuma et al. PRC50,1194(94)

The Origin of Carbon and Oxygen in the Universe

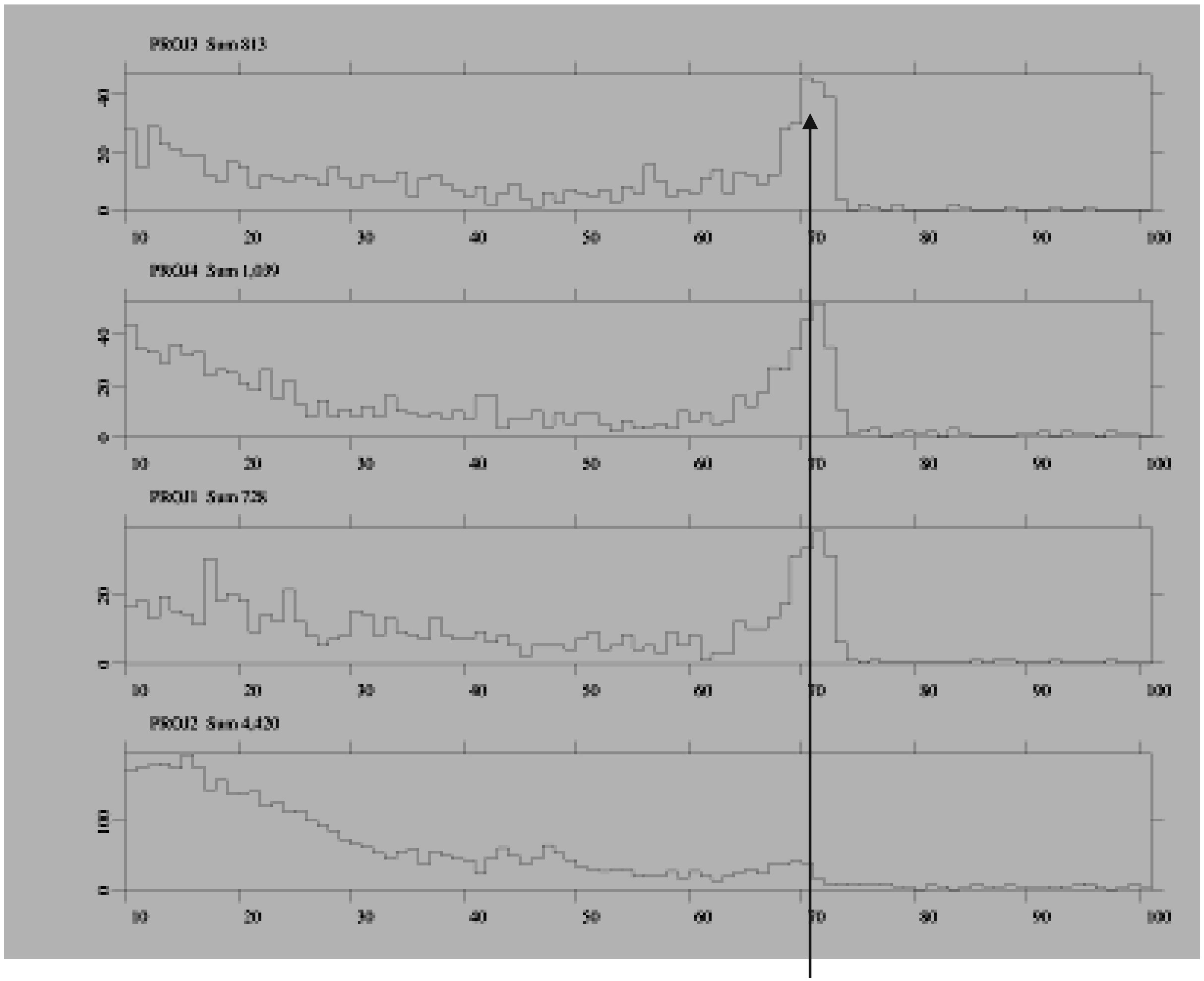


….a problem of paramount importance in nuclear astrophysics.

W. Fowler

Alpha background ($2.5x10^4$ s)

P=760 Torr



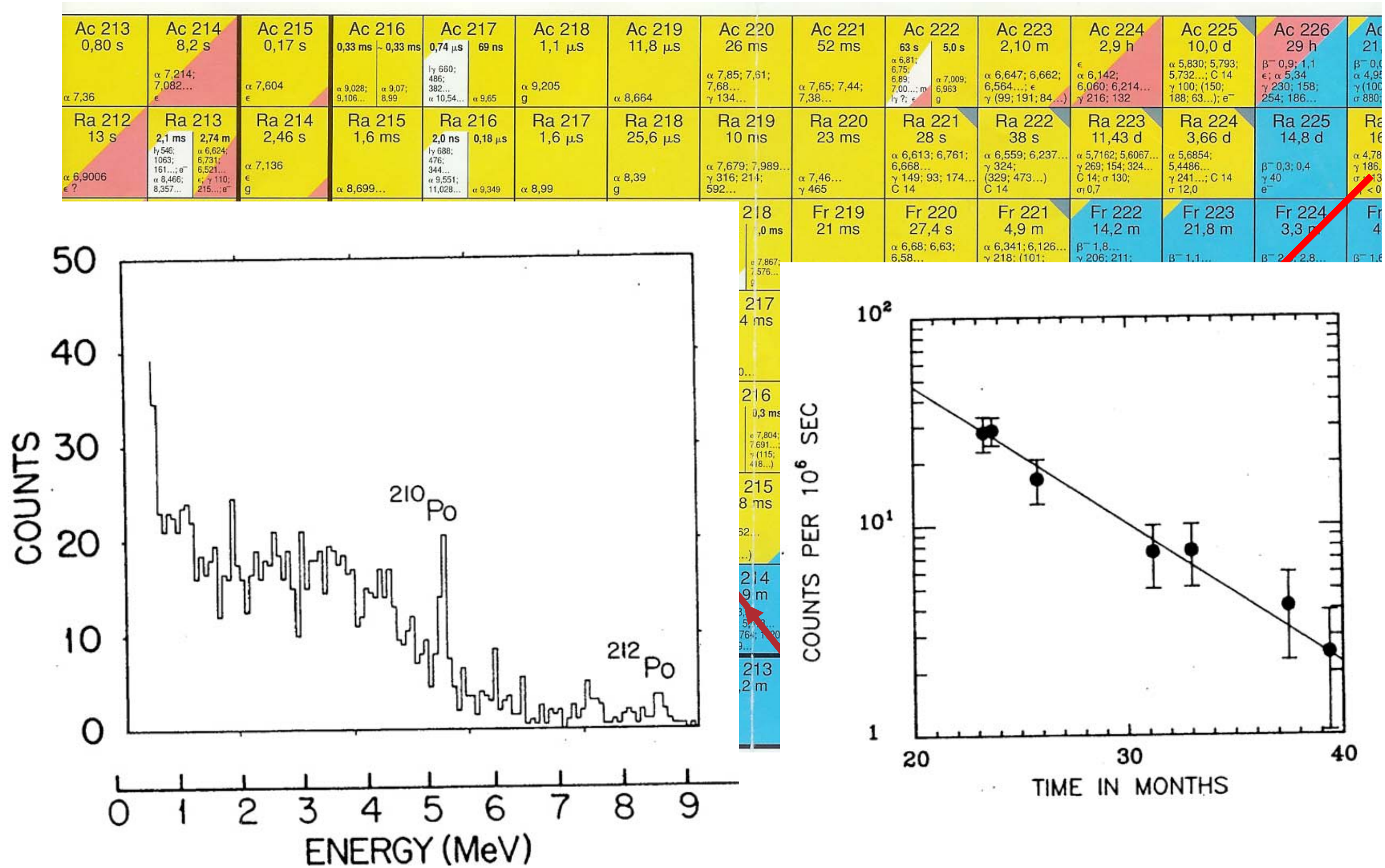
ELU	130/hr
ELD	170/hr
ERU	110/hr
ERD	700/hr

~5.2 MeV

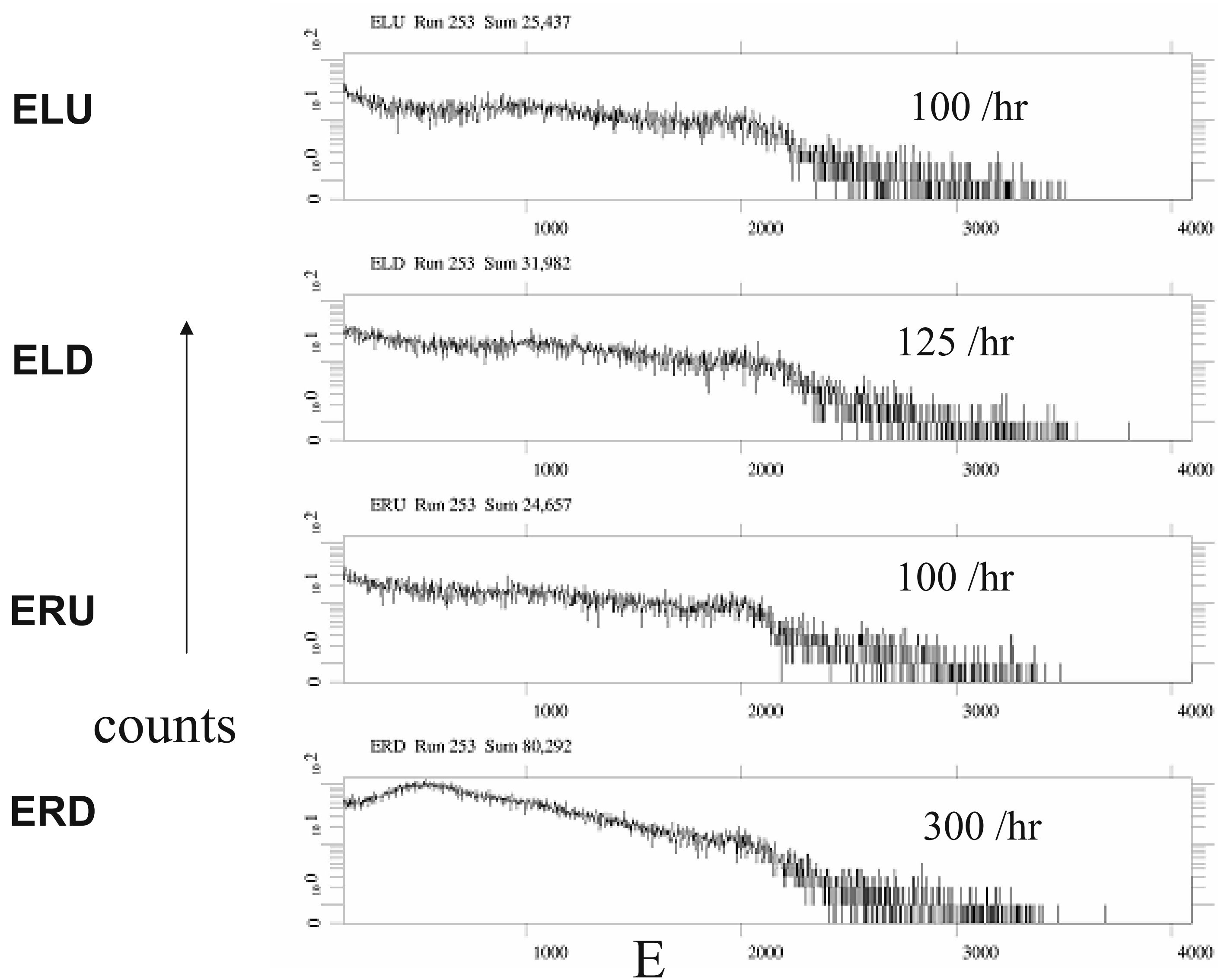
Goals:

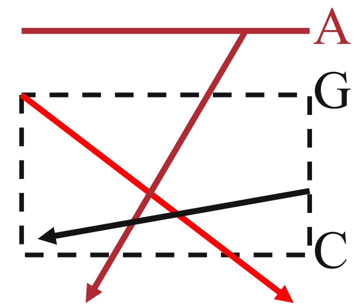
- No contamination from $^{17,18}N$
- Setup with detectors which are insensitive to β's
- Improve energy calibration
- Improve 1^- β branching ratio

^{210}Po background



Background run – 0.925×10^6 s (257 hr) (^{210}Po)





Al: 16/hr

SS: 12/hr

Solder: 240/hr

Improvement in Systematic Uncertainties:

		improvement
Energy calibration	$\pm$ 10 keVb	~1/4
β-branching ratio	$\pm$ 6 keVb	~1/4
^{17}N subtraction	$\pm$ 5 keVb	-
Systematic differences	$\pm$ 4 keVb	
Coincidence efficiency	$\pm$ 3 keVb	
Uncertainty in Γ_γ (7.12 MeV)	$\pm$ 3 keVb	
Uncertainty in energy resolution	$\pm$ 2 keVb	
Normalization of $^{12}C(\alpha,\gamma)^{16}O$	$\pm$ 2 keVb	
^{18}N subtraction	$\pm$ 1 keVb	
Noise events	$\pm$ 1 keVb	

Background in double β decay

We have discovered a broad peak at 5.2 MeV with its leading edge at 5.3 MeV followed by a significant continuum. A similar peak has been observed in the UCSB-LBL detector[31] at 5.1 MeV and has been attributed to a Doppler broadened line produced by the reaction $^{28}Si(n,n\gamma)^{28}Si$. We have been successful in reproducing our line at 5.2 MeV in a simple laboratory experiment. When soft solder is melted, the ^{210}Po, from the sequential decays of ^{210}Pb and ^{210}Bi, concentrates on the surface of the bead. After melting and solidifying several beads of solder, α spectra from their surfaces observed with a surface barrier detector were also found to contain this peak. The same phenomenon was observed in the UCI (University of California, Irvine) time projection chamber, and

T. Avignone et al. PRC 34,666(1986)