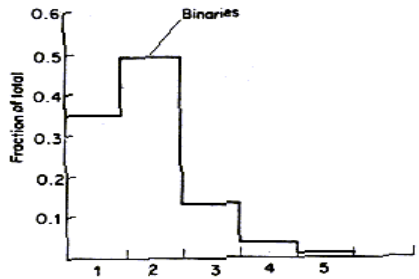
# Charge particle reactions for rapid hydrogen and helium burning

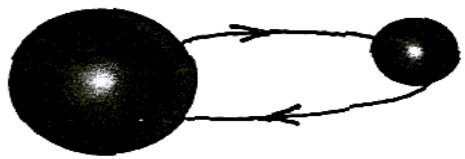
A. C. Shotter

# Charged particle reactions for Hydrogen and Helium burning

A. Shotter

Binary stellar systems

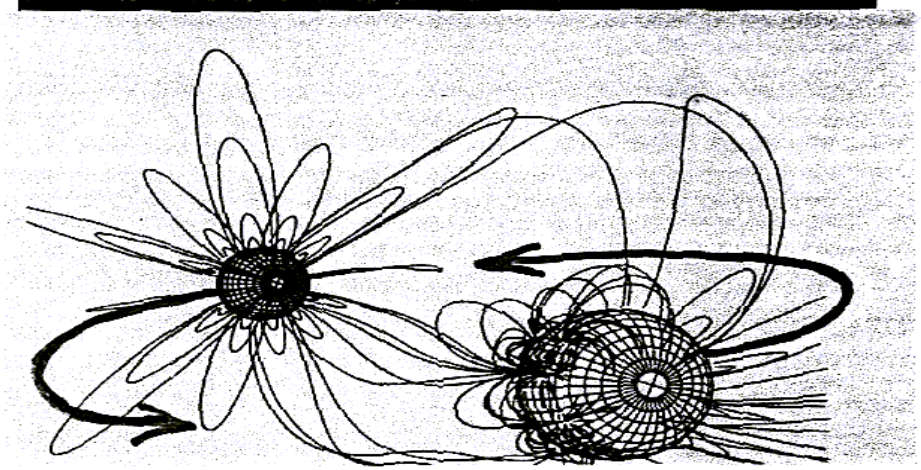


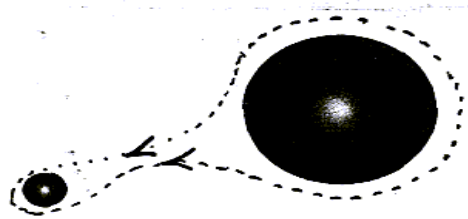



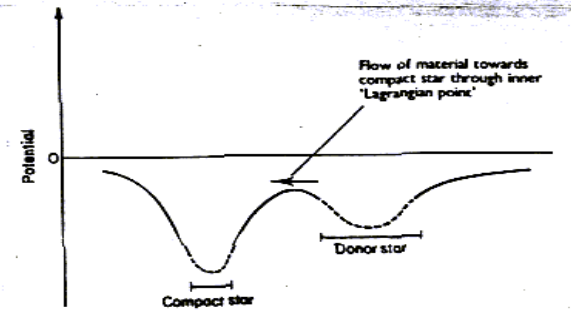
| | |
|---|---|
| Main sequence | Main sequence |
| Main sequence | White dwalf |
| Main sequence | Neutron star |
| White dwarf | White dwarf |
| White dwarf | Neutron star |
| Neutron star | Neutron star |

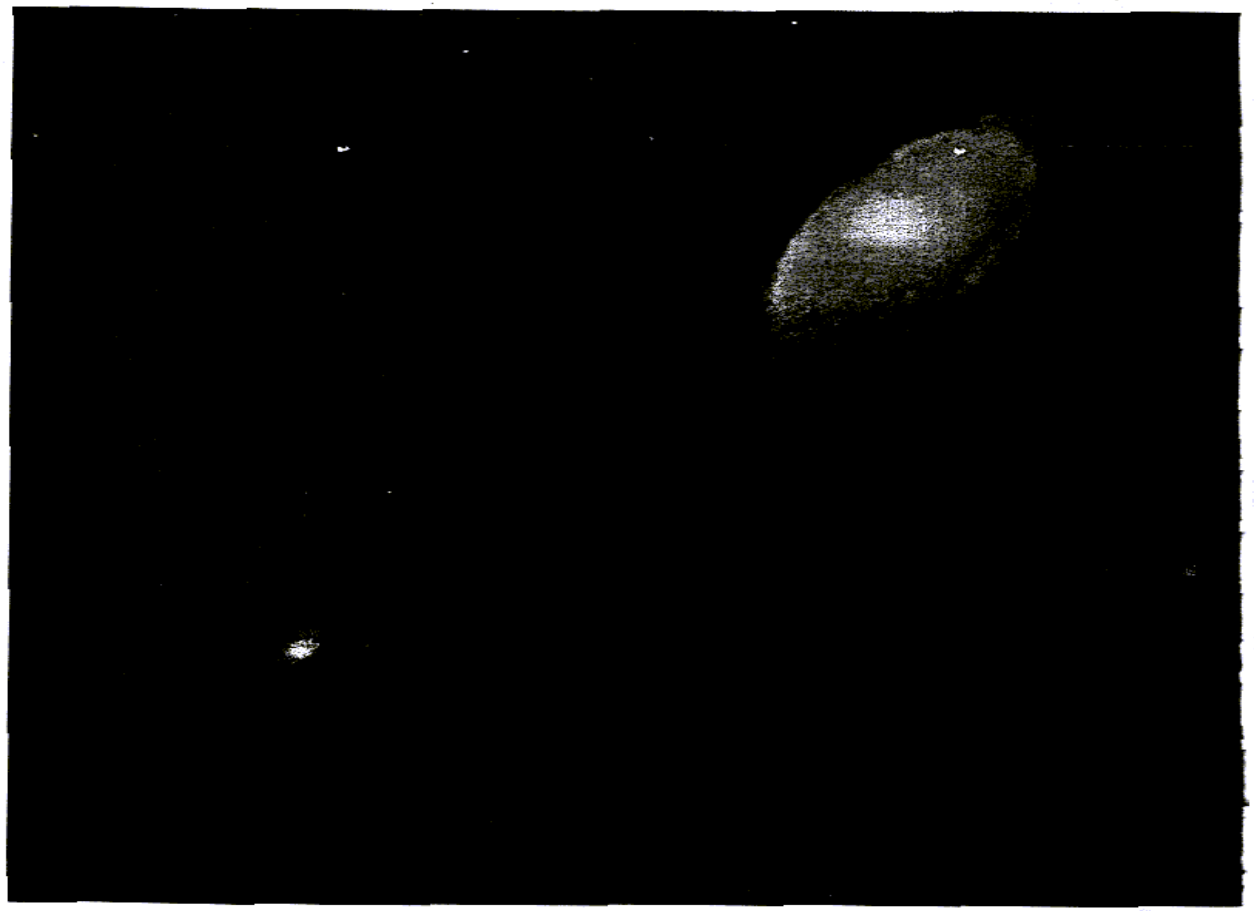
Properties depend on:
masses,
separaton,
spins,
angular momentum,
magnetic field

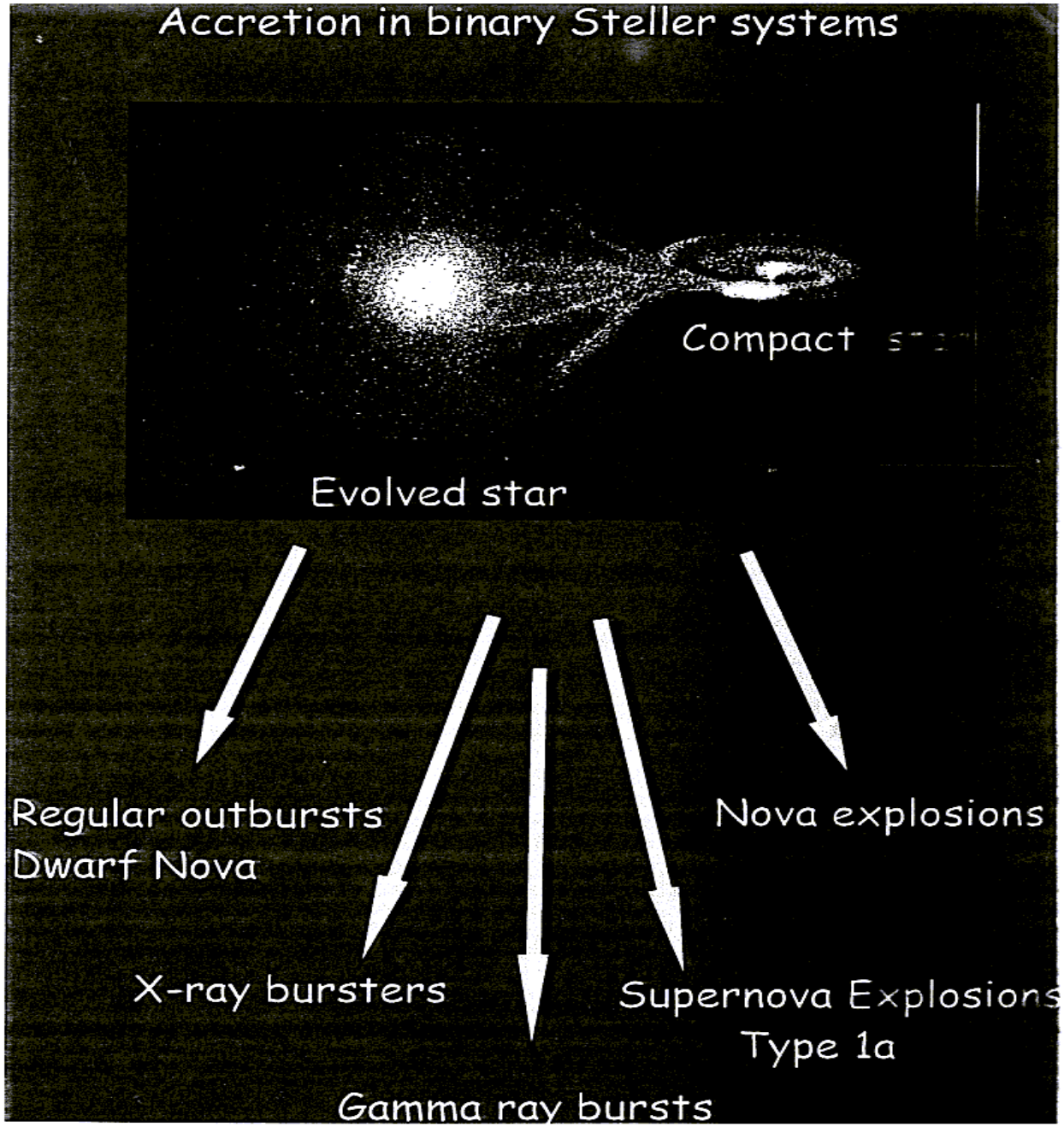
Mira • Omicron Ceti

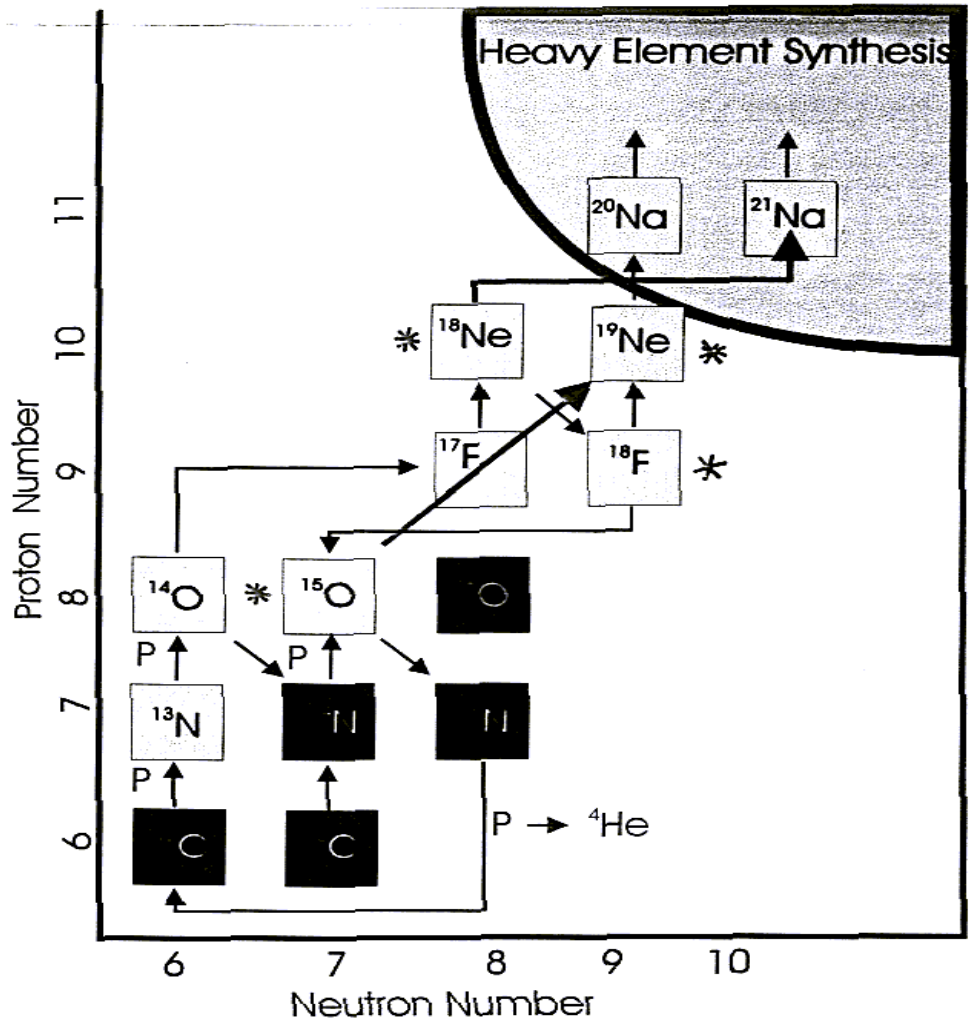


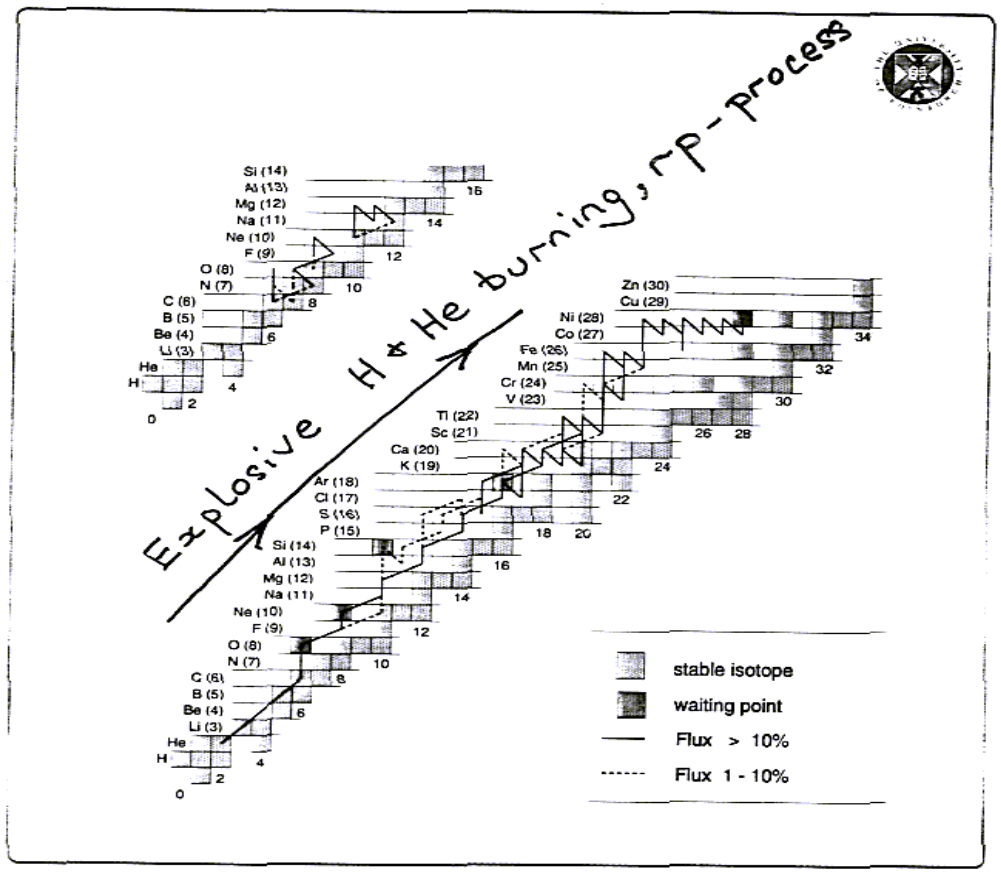



Flow of material towards compact star through inner 'Lagrangian point'
Potential
0
Donor star
Compact star




Accretion in binary Steller systems
Compact
Evolved star
Regular outbursts
Dwarf Nova
Nova explosions
X-ray bursters
Supernova Explosions
Type 1a
Gamma ray bursts


Heavy Element Synthesis
$^{20}$Na
$^{21}$Na
$^{18}$Ne
$^{19}$Ne
$^{17}$F
$^{18}$F
$^{14}$O
$^{15}$O
$^{13}$N
P
P
P
P → $^{4}$He
Proton Number
Neutron Number
6
7
8
9
10
11


Explosive H & He burning, rp-process
Si (14)
Al (13)
Mg (12)
Na (11)
Ne (10)
F (9)
O (8)
N (7)
C (6)
B (5)
Be (4)
Li (3)
He
H
0
2
4
6
8
10
12
14
16
Zn (30)
Cu (29)
Ni (28)
Co (27)
Fe (26)
Mn (25)
Cr (24)
V (23)
Ti (22)
Sc (21)
Ca (20)
K (19)
Ar (18)
Cl (17)
S (16)
P (15)
18
20
22
24
26
28
30
32
34
stable isotope
waiting point
Flux > 10%
Flux 1 - 10%

Nuclear Physics information needed for explosive burning involving radioactive beams

A) Hot CNO cycle

$^{13}N(p,\gamma)$ $^{14}O(\alpha,p)$ $^{17}F(p,\gamma)$ $^{18}F(p,\gamma)$ $^{18}F(p,\alpha)$

B) Breakout Reactions

$^{18}Ne(\alpha,p)$ $^{15}O(\alpha,\gamma)$ $^{19}Ne(p,\gamma)$

C) Post Breakout Reactions

$^{21}Na(p,\gamma)$ $^{22}Na(p,\gamma)$ $^{23}Mg(p,\gamma)$ $^{24}Al(p,\gamma)$
$^{25}Al(p,\gamma)$ $^{26}Al(p,\gamma)$ $^{27}Si(p,\gamma)$ $^{28}P(p,\gamma)$
$^{29}P(p,\gamma)$ $^{30}P(p,\gamma)$

d)

$(p,\gamma)$
$(\alpha,\gamma)$ } Reactions involving proton rich radioactive nuclei up to A~100
$(\alpha,p)$

Collaboration: Louvain-la-Neuve
Edinburgh
Leuven

# $^{19}Ne(p,\gamma)^{20}Na$

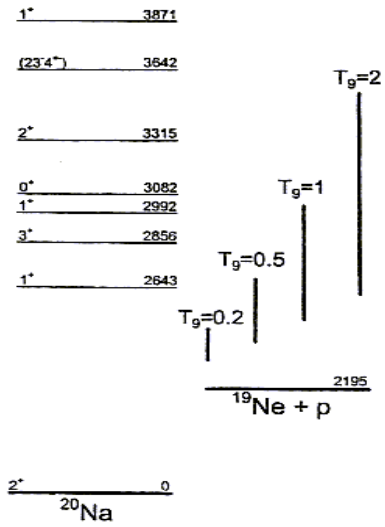
Dominant :- 2.643 MeV state

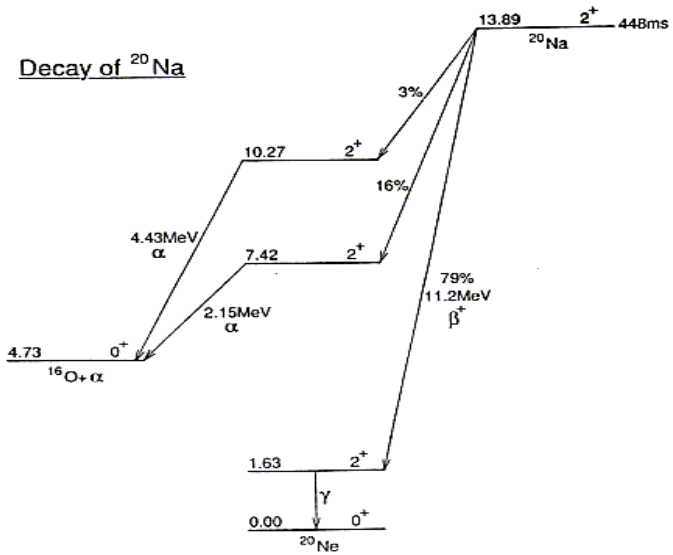
Methods of $^{20}Na$ measurement

⇩

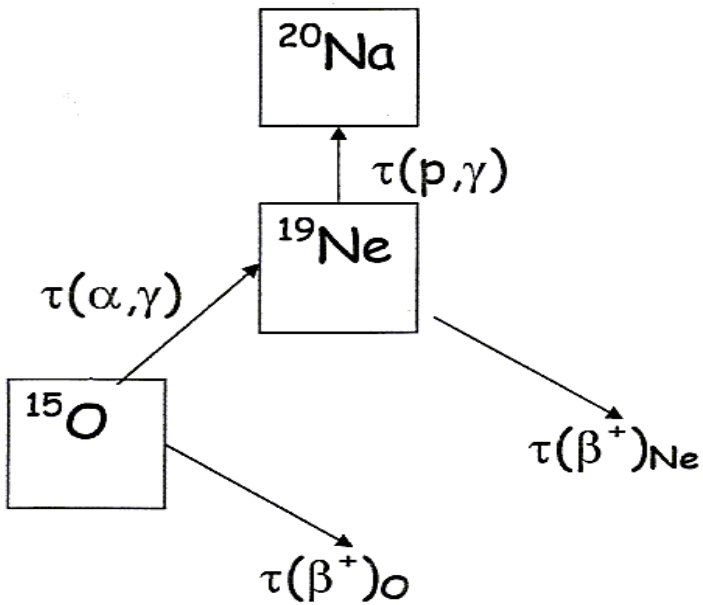
Detection of $\beta^+$

Detection of $\alpha$


1+ 3871
(23'4+) 3642
2+ 3315
0+ 3082
1+ 2992
3+ 2856
1+ 2643
Tg=2
Tg=1
Tg=0.5
Tg=0.2
2195
19Ne + p
2+ 0
20Na


Decay of 20Na
13.89 2+ 448ms
20Na
3%
10.27 2+
16%
4.43MeV
α
7.42 2+
79%
11.2MeV
β+
2.15MeV
α
4.73 0+
16O+α
1.63 2+
γ
0.00 0+
20Ne

# $^{19}Ne(p,\gamma)^{20}Na$ and CNO Breakout Conditions




$\tau = 1/(\rho\langle\sigma v\rangle)$

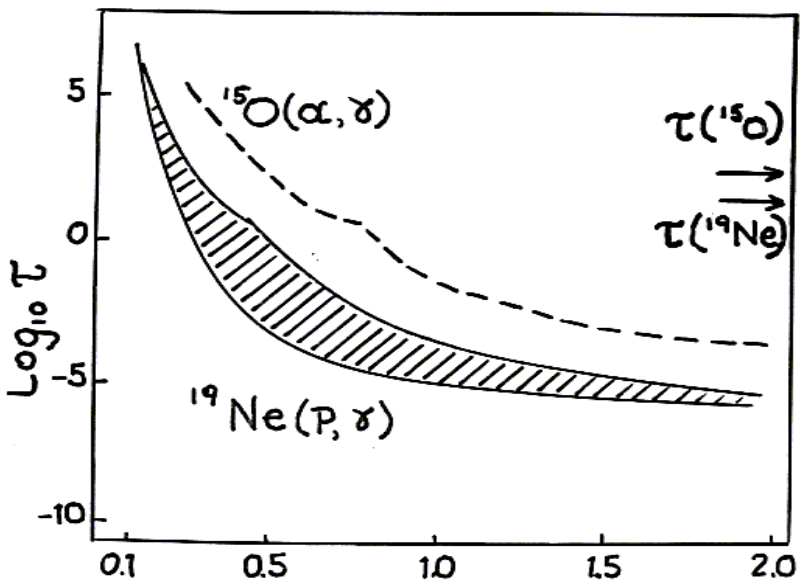
**Breakout occurs if:**

$\tau(\alpha,\gamma) < \tau(\beta^+)_O$

$\tau(p,\gamma) < \tau(\beta^+)_{Ne}$

**Breakout rate**

$^{15}O \rightarrow {}^{20}Na \propto 1/\tau(\alpha,\gamma)$



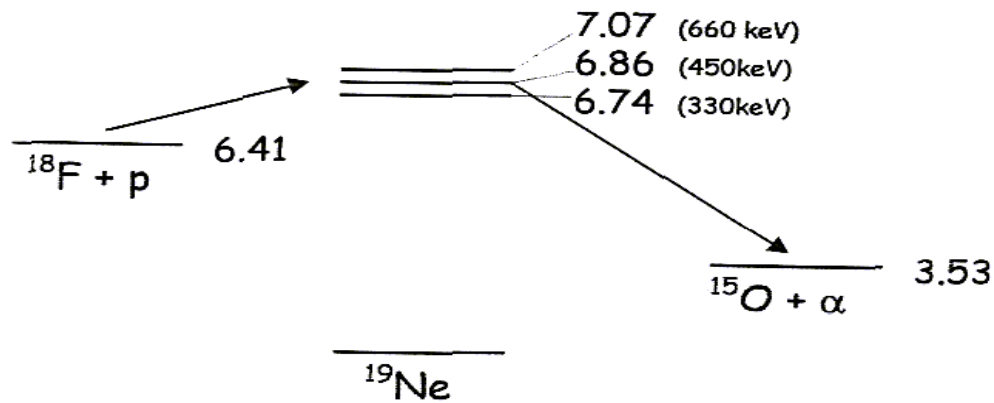

Tighter limits?

Future possibilities

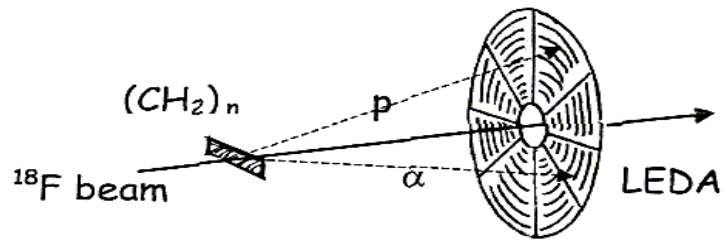
*Recoil Spectrometer detection of $^{20}Na$

*Increased $^{19}Ne$ intensity

## $^{18}F(p,\alpha)^{15}O$

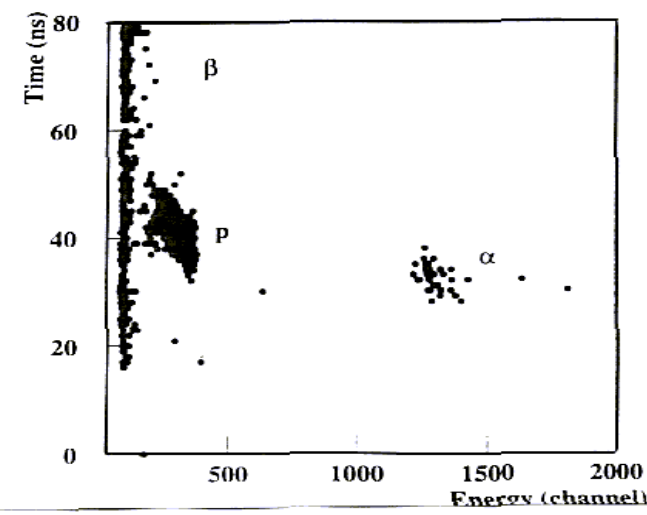



Experiment:

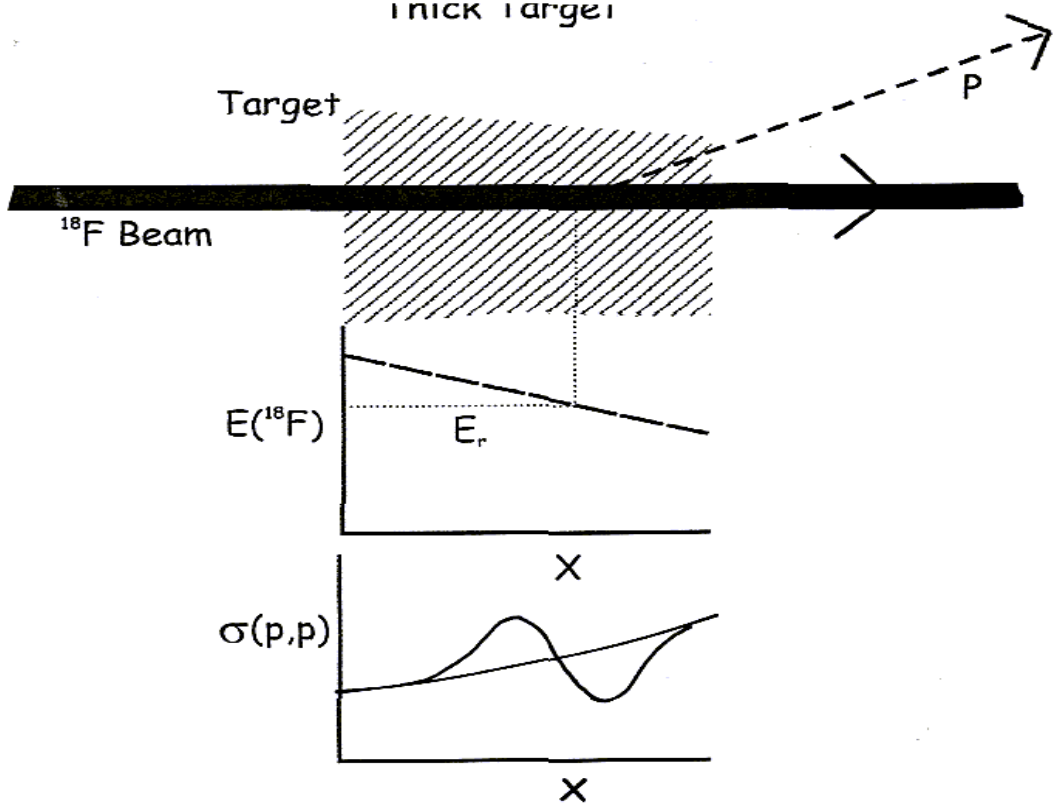



Results

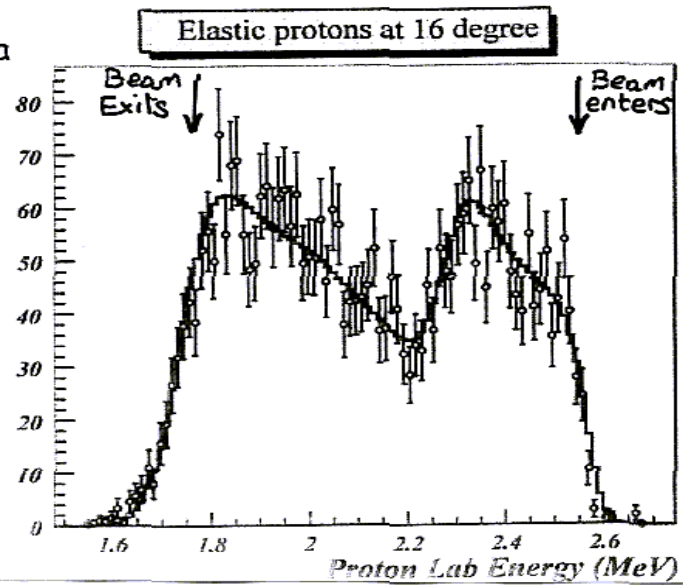
Two energy scans:
550-740 keV
265-535 keV



Thick Target




New Data




$^{18}$F 14 MeV

200μg (CH4)

550- 740 keV

Er=660+_2 keV

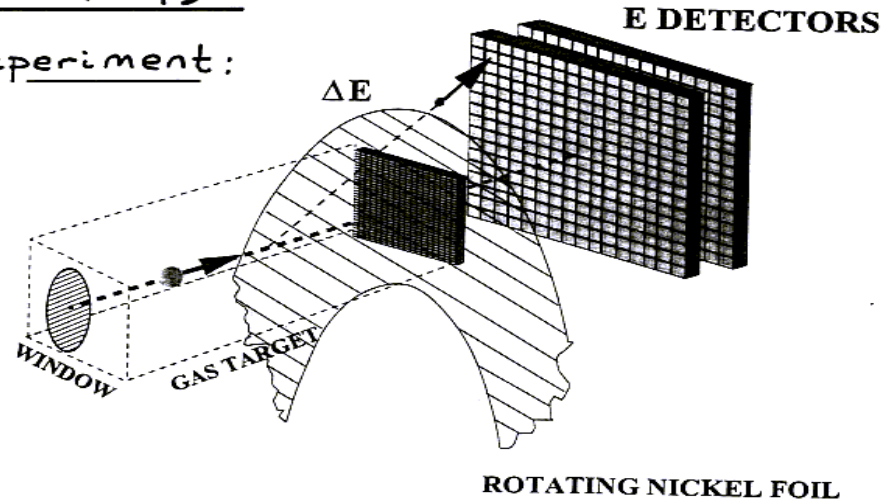
$\Gamma_p/\Gamma_T$=0.26+-0.03

Γ=30+-4 keV

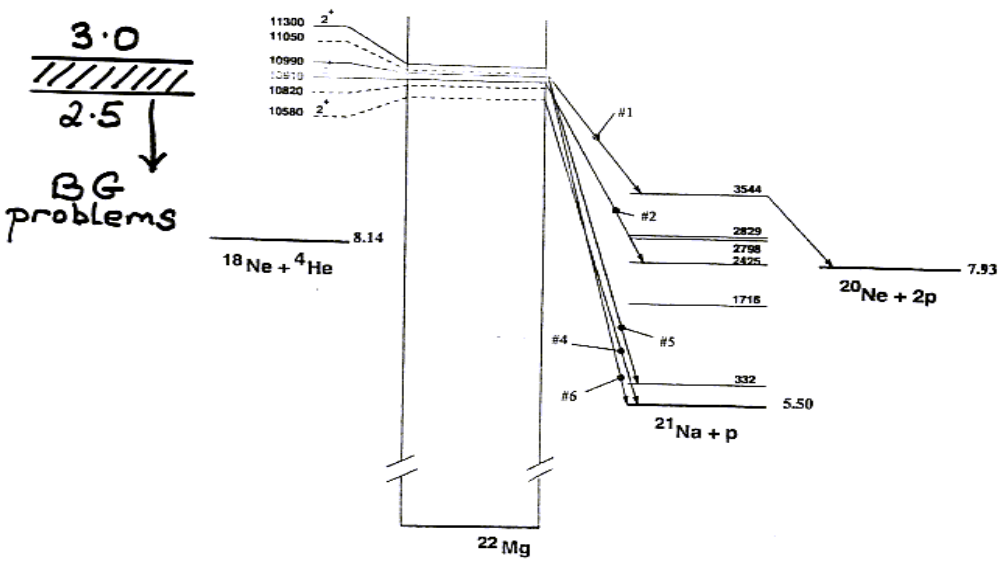
ωγ=3.9+- 0.8 keV

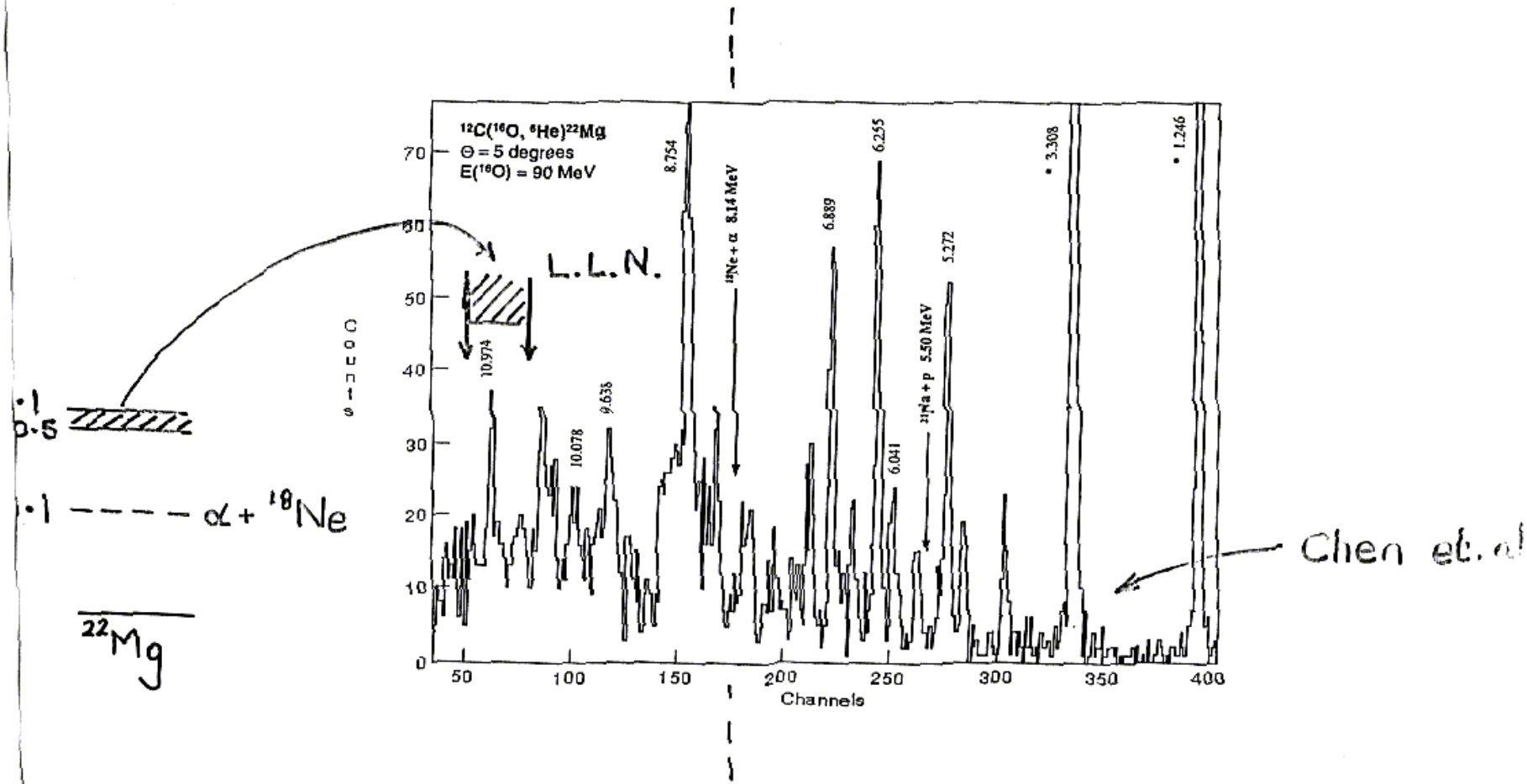
# $^{18}Ne(\alpha, p)$

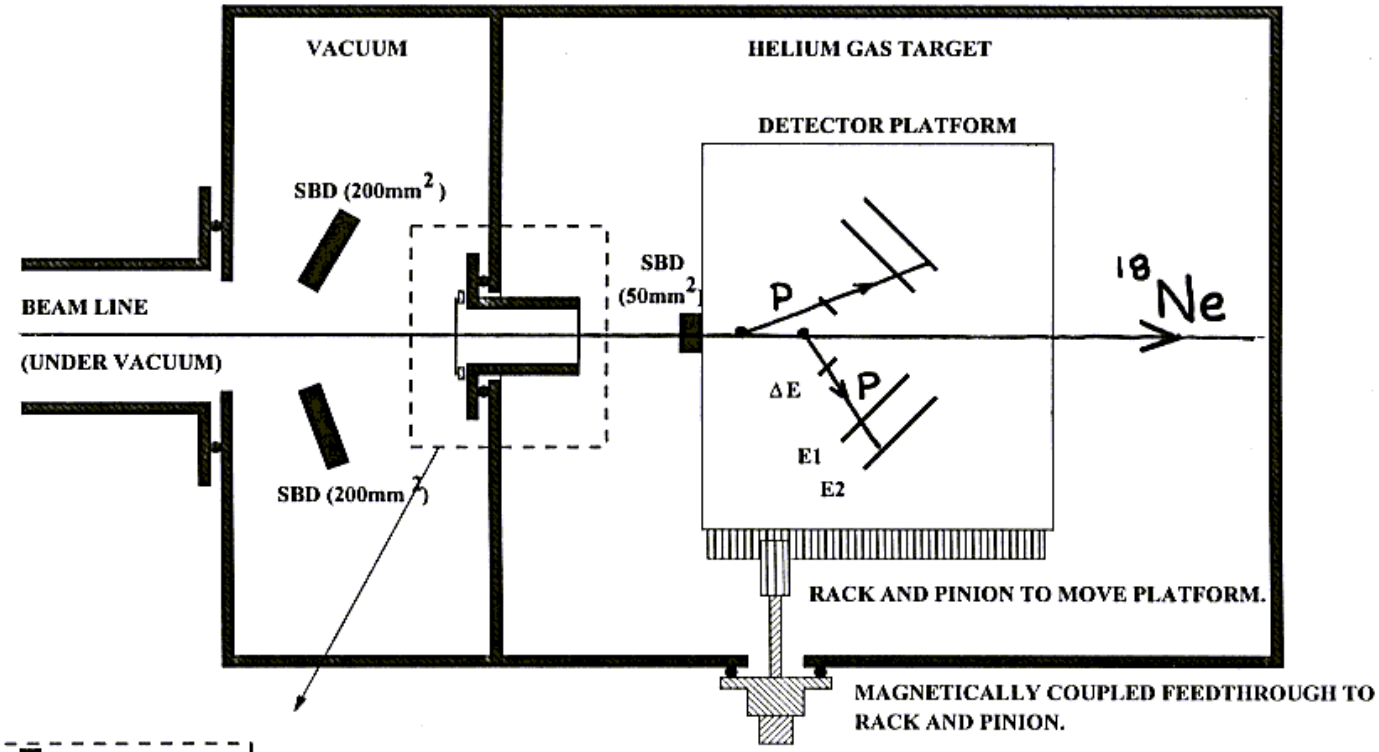
## Experiment:

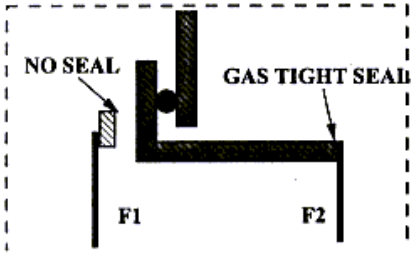



## Results:



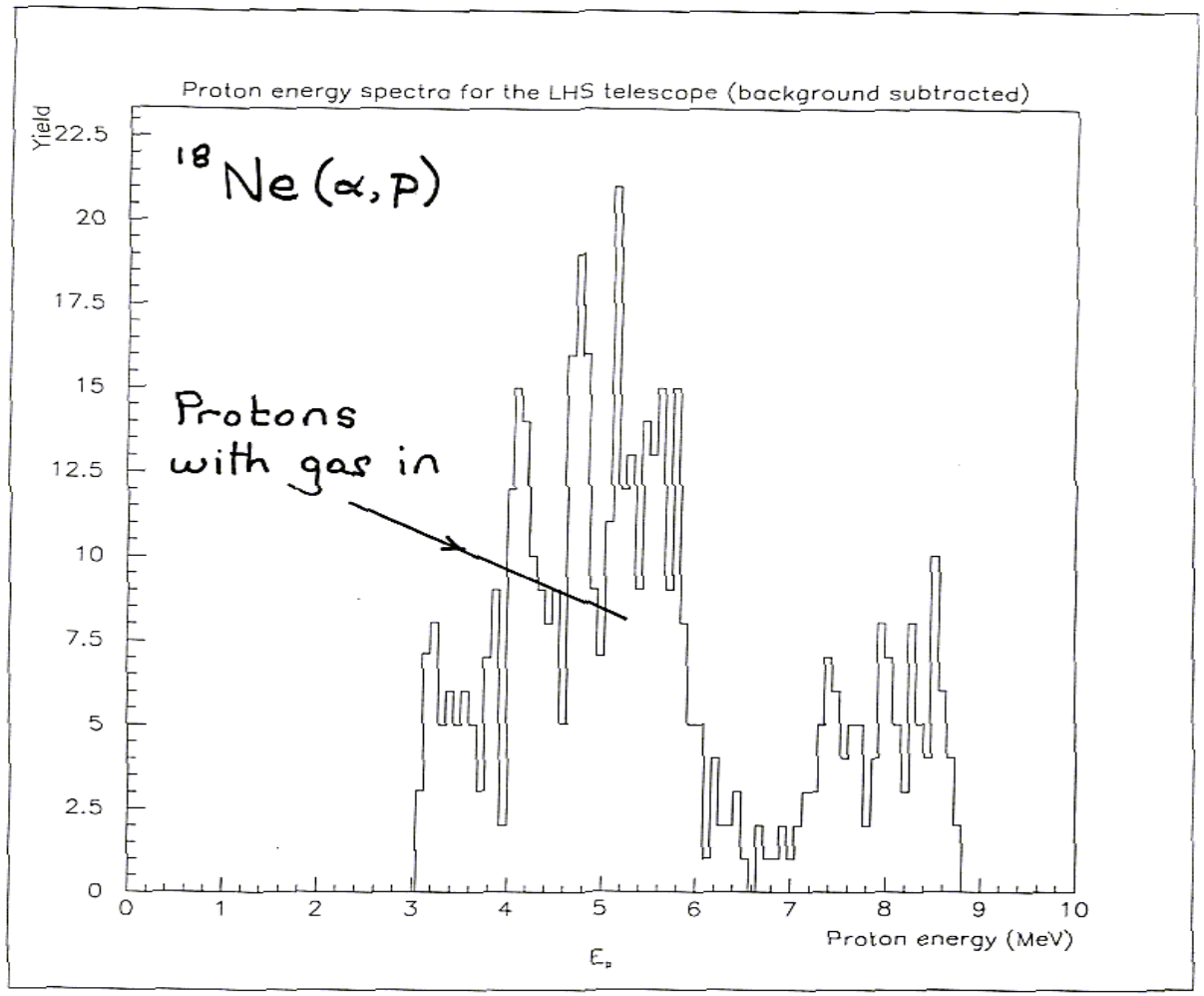

$^{12}C(^{16}O, ^{6}He)^{22}Mg$
Θ = 5 degrees
E($^{16}$O) = 90 MeV
L.L.N.
8.754
$^{18}$Ne + α 8.14 MeV
6.889
6.255
6.041
$^{21}$Na + p 5.50 MeV
5.272
3.308
1.246
10.974
10.078
9.638
Counts
Channels
0
10
20
30
40
50
60
70
50
100
150
200
250
300
350
400
α + $^{18}$Ne
$^{22}$Mg
Chen et. al



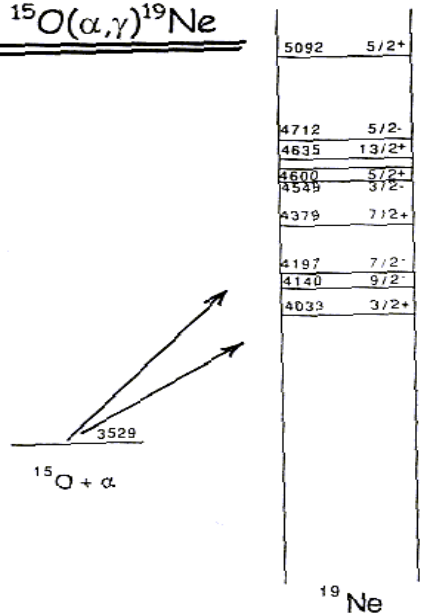

E: Delta E detector, double sided silicon strip detector of thickness 67 um, 48 by 48 strips of pitch 335 um.

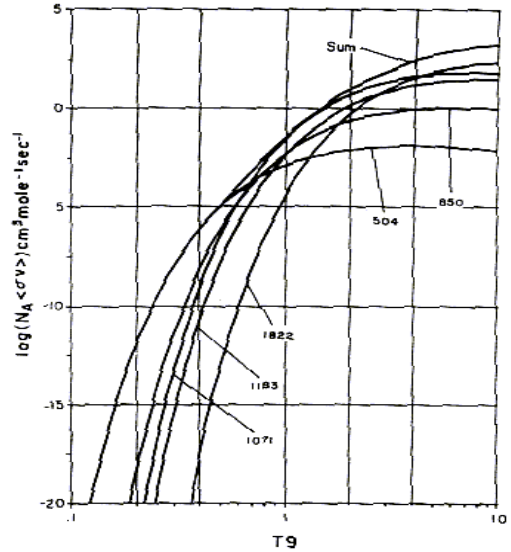
E1: E1 detector, double sided silicon strip detec-




Proton Energy

## $^{15}O(\alpha,\gamma)^{19}Ne$




Rate $\propto \Gamma_\alpha \exp(-E_r/kT)$

→ Determine $\Gamma_\alpha$

a) Populate and tag 4.033 MeV state

b) Measure $\alpha$ yield of tagged 4.033 MeV events

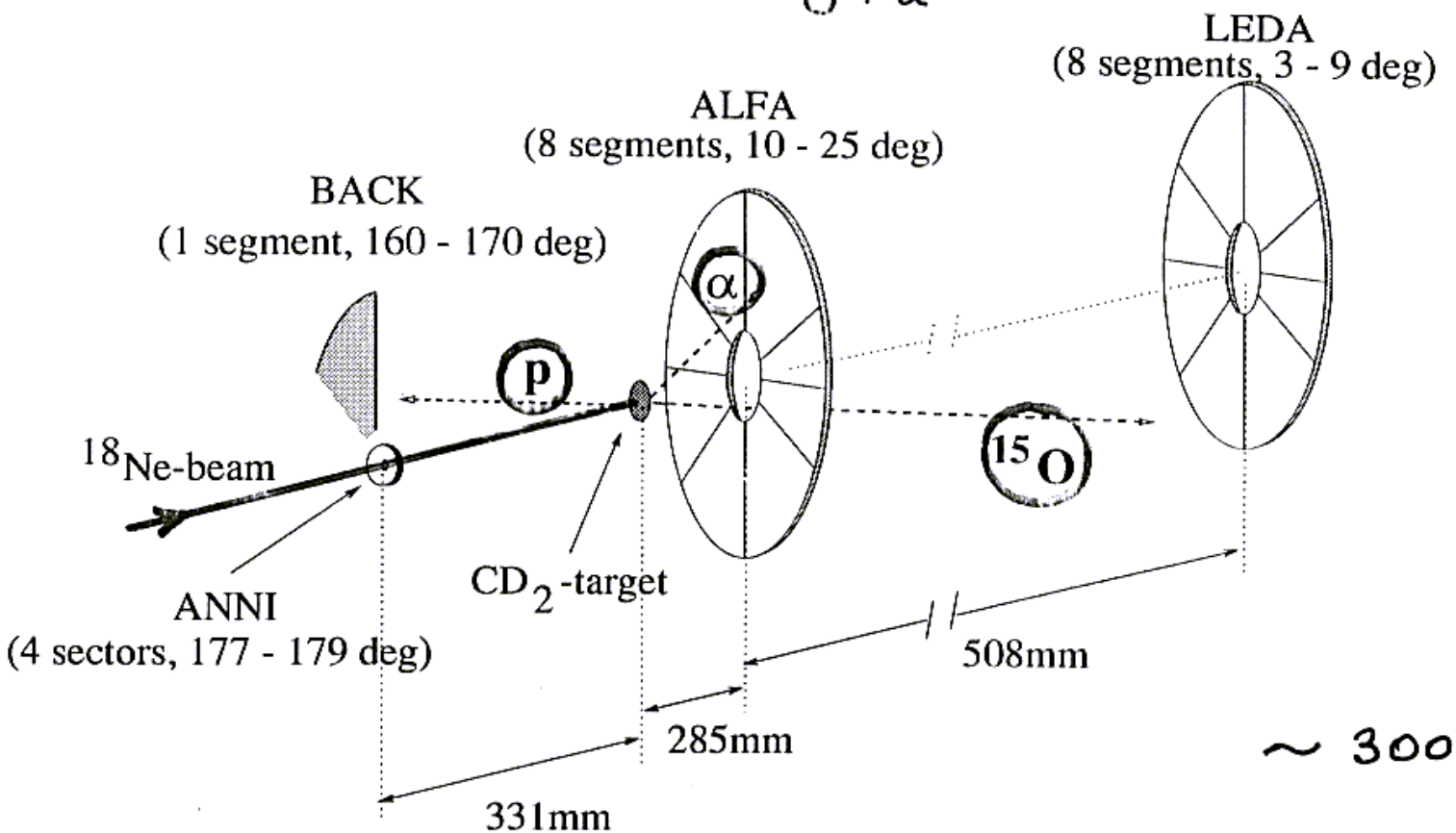
→ $\Gamma_\alpha/\Gamma$

c) Measure $\Gamma$

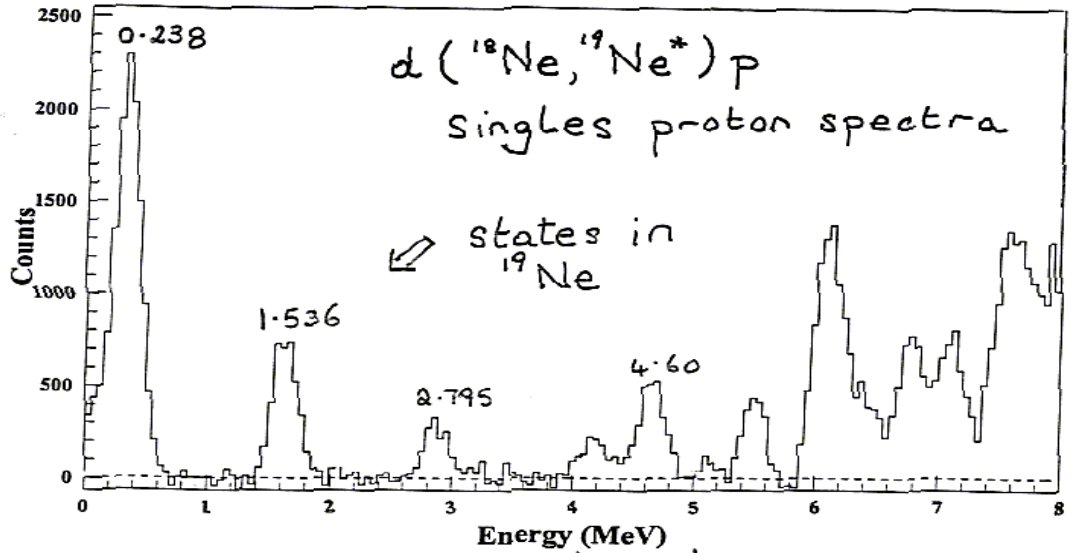
# $d(^{18}Ne, ^{19}Ne^*)p$

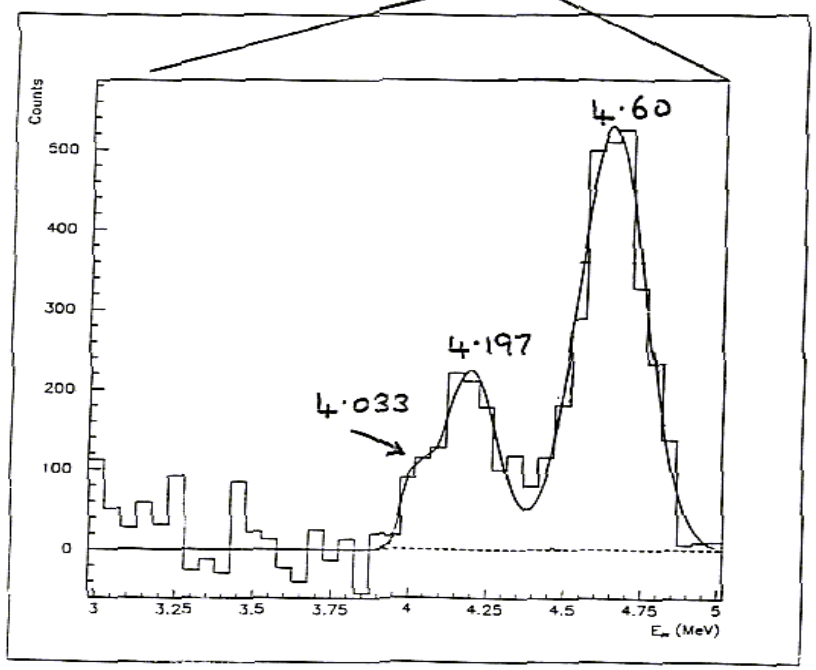
$\downarrow$

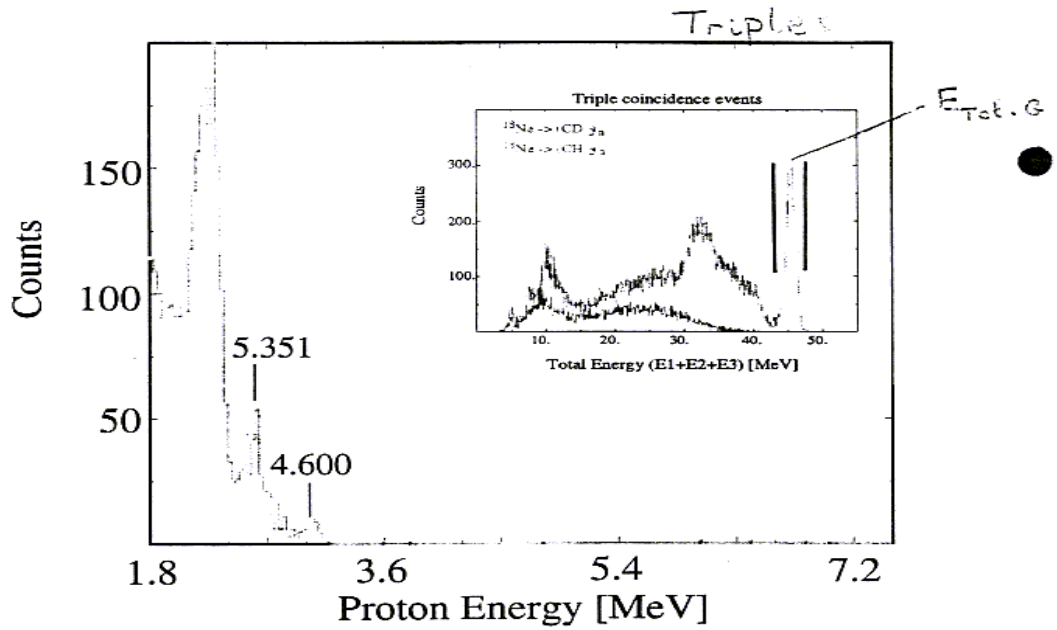
$^{15}O + \alpha$




~ 300 channels


d ( $^{18}$Ne, $^{19}$Ne* ) p
singles proton spectra
states in $^{19}$Ne
0·238
1·536
2·795
4·60
Counts
Energy (MeV)


4·60
4·197
4·033
Counts
$E_x$ (MeV)

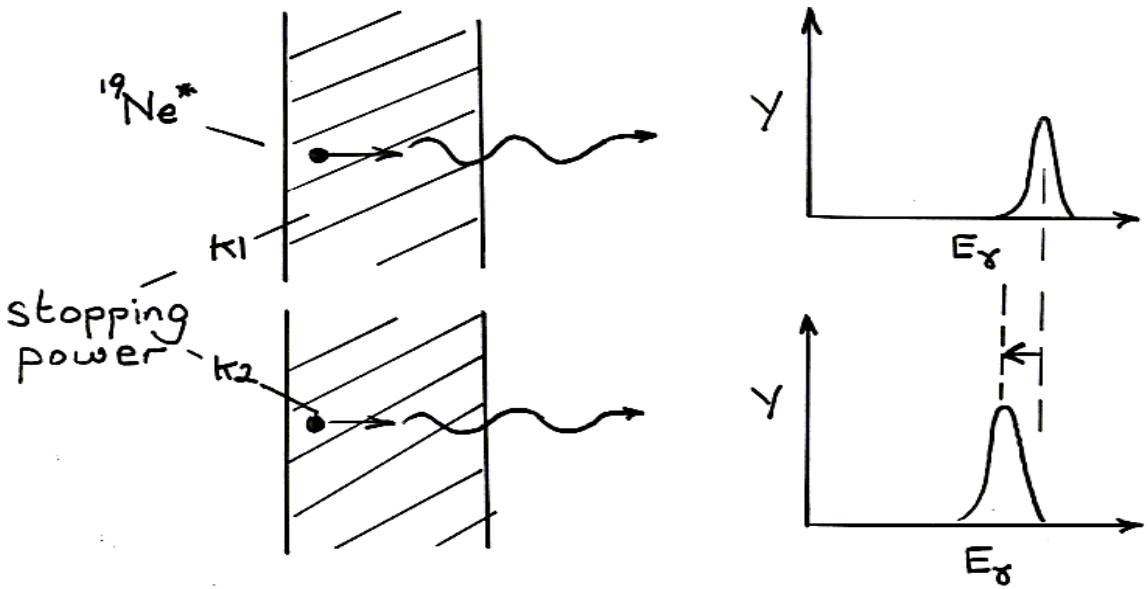

Triplet
Triple coincidence events
Counts
300
200
100
10.
20.
30.
40.
50.
Total Energy (E1+E2+E3) [MeV]
$E_{Tot.G}$
150
100
50
Counts
5.351
4.600
1.8
3.6
5.4
7.2
Proton Energy [MeV]

## Γ (4.03 MeV)

Principle:

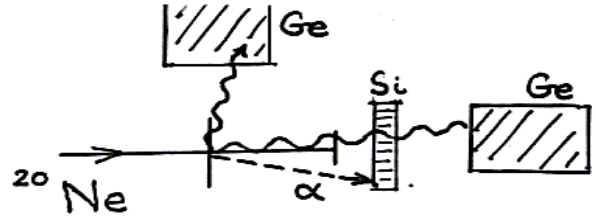
a) Populate and tag 4.033MeV state of recoiling $^{19}Ne$ nucleus

b) Measure Doppler shifts of decay γ-rays for different stopping powers



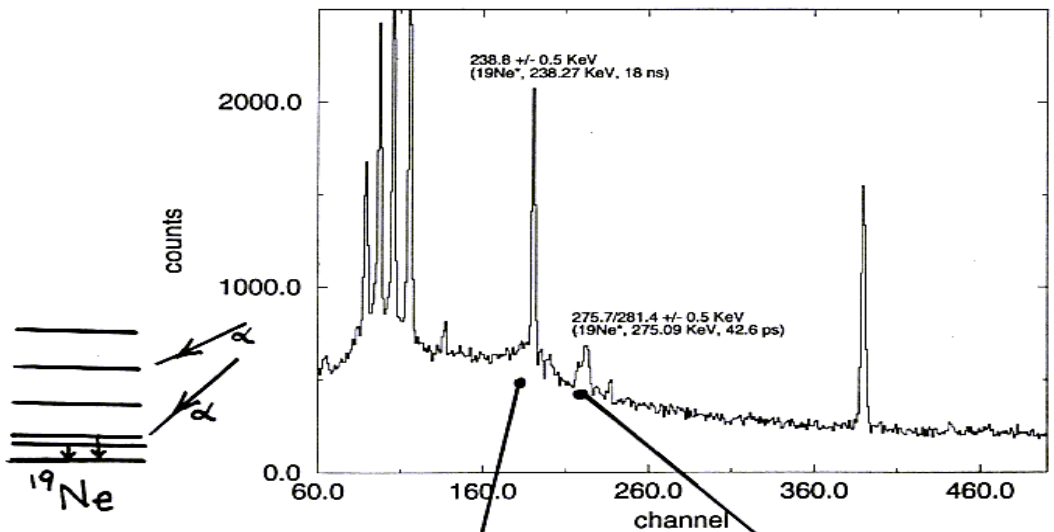

Reaction $^{20}Ne(^3He,^4He)^{19}Ne^*$ Energy = 50 MeV

Stopping material Al, W

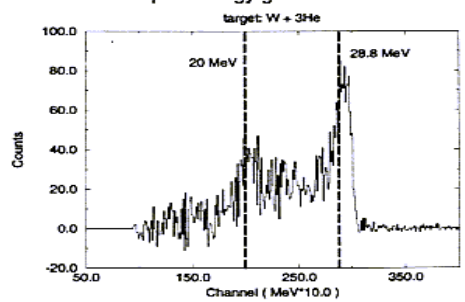



## Gamma-ray spectrum gated on alphas

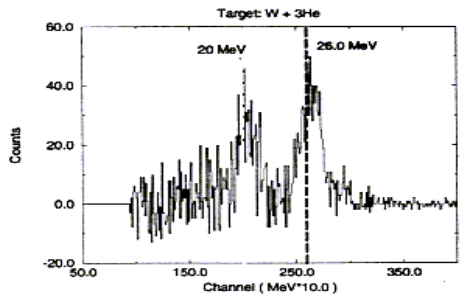
Target: W + 3He



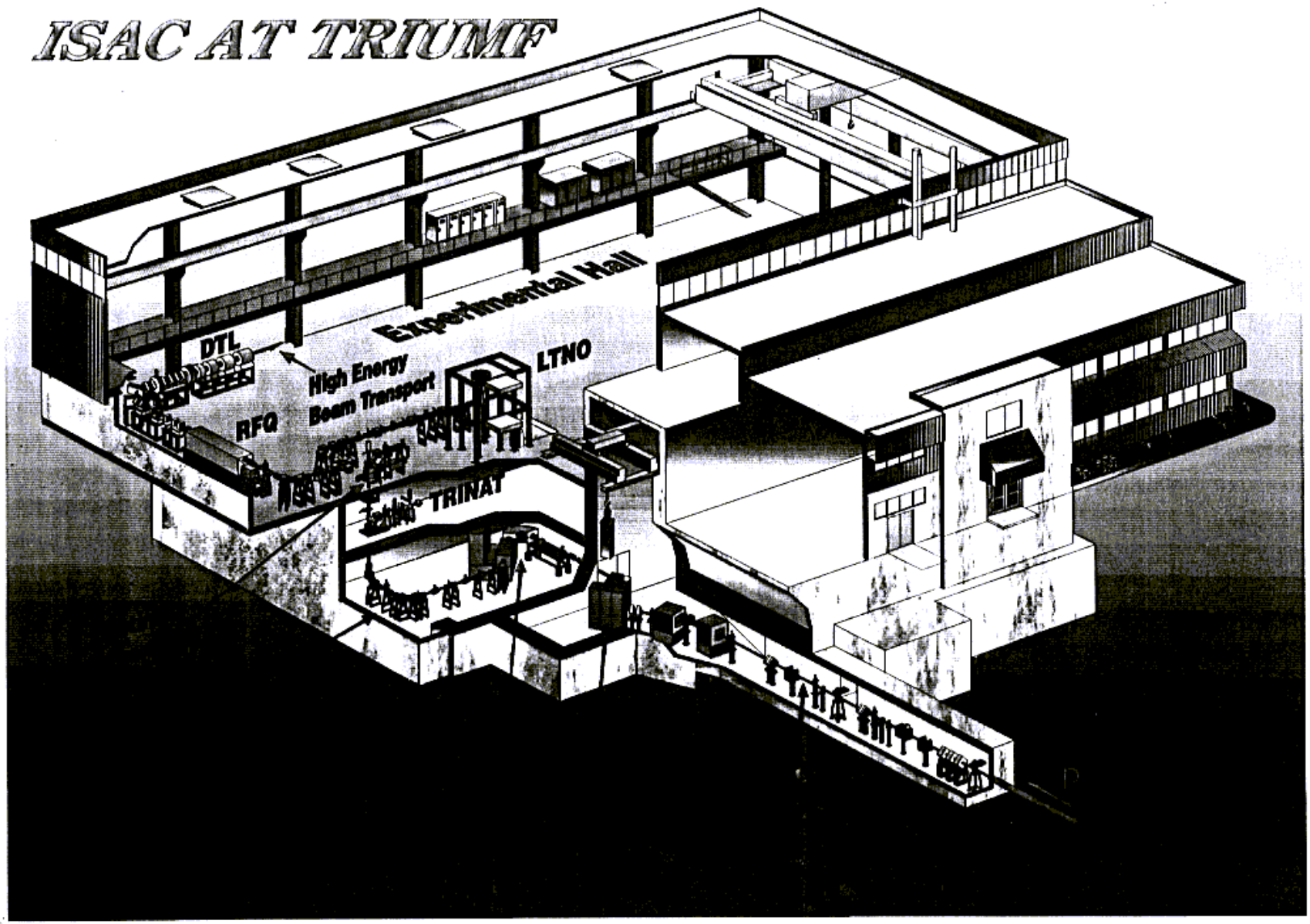

Total alpha energy gated on 1st ex. state




Total alpha energy gated on 2nd ex. state

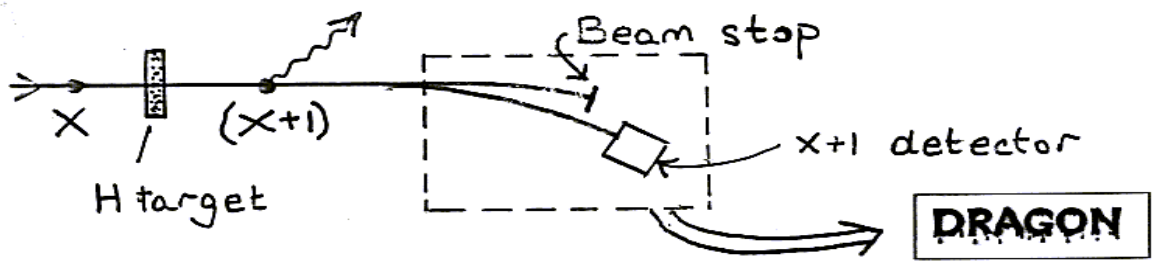


ISAC II  E = 1.5 MeV/A



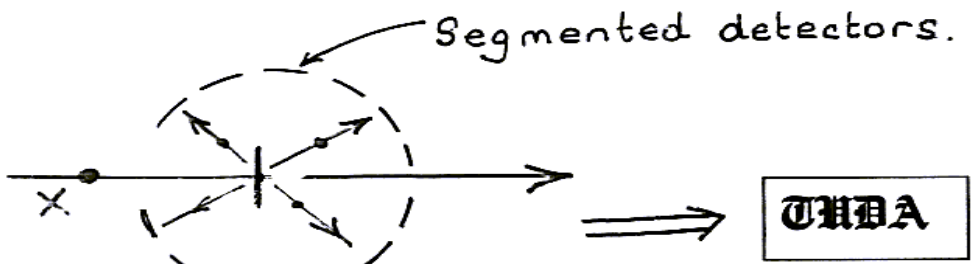
# Requirements for measurements:

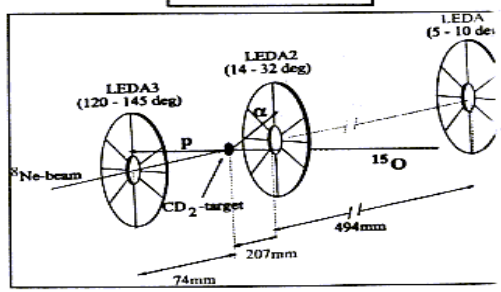
## X(p,γ), X(α,γ) reactions




- High Detection efficiency
- Good Beam/ background signal ratio
- Good energy/ mass /timing resolution

## For X(particle, particle) reactions




- High detector Solid angles,
- High detector segmentation,
- Good energy/time /mass resolution

# Summary

Explosive H, He } burning reactions

↓

Very limited data

1st generation RIB facilites ( e.g. LLN)

* Provided useful first data

* Experiments difficult → a) beam
b) Detection

2nd generation facilities ( e.g. TRIUMF)

*Wider range of reactions

* 1st generation reactions to lower energy

**Interesting times ahead!**