alpha induced reactions in stellar burning

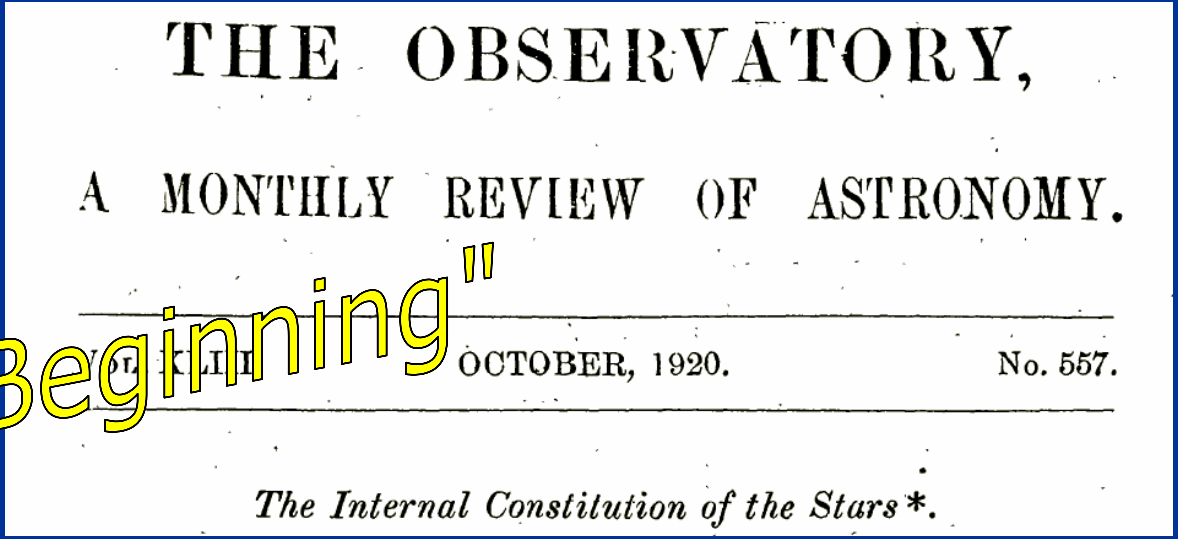
Joachim Görres, University of Notre Dame & JINA

JINA

http://www.nd.edu/~nsl

http://www.jinaweb.org

"The Beginning"

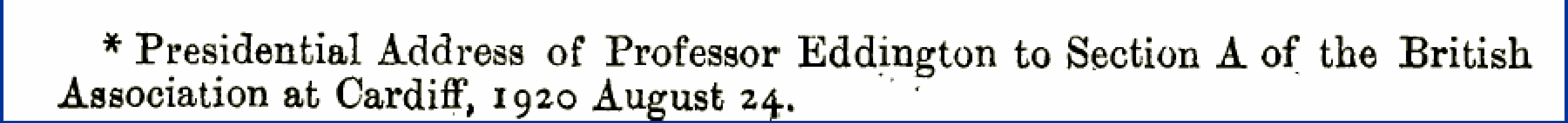


THE OBSERVATORY,

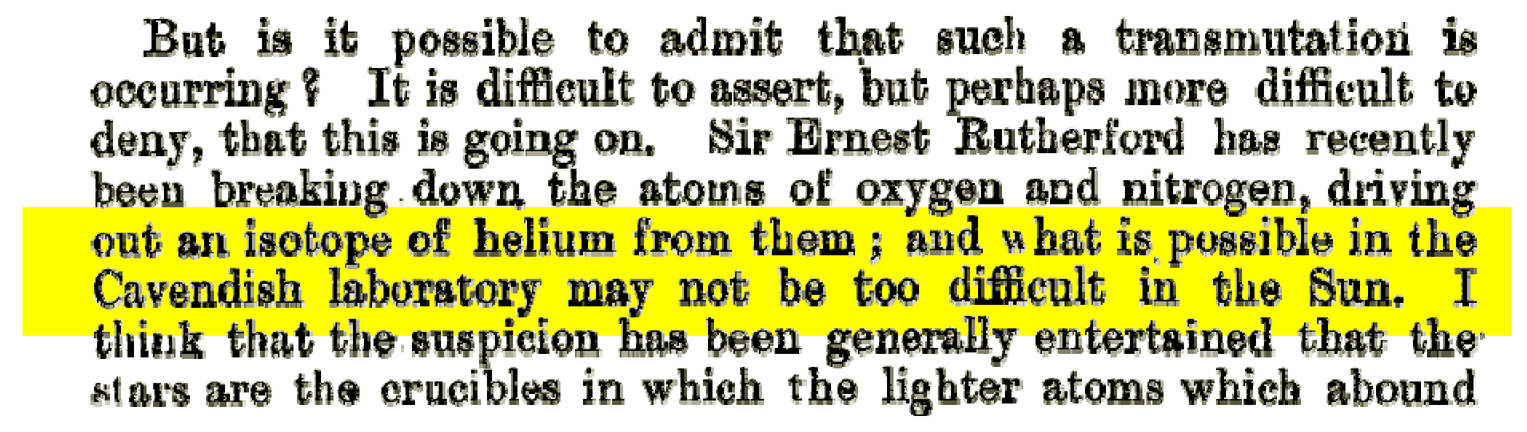
A MONTHLY REVIEW OF ASTRONOMY.

VOL. XLIII. OCTOBER, 1920. No. 557.

*The Internal Constitution of the Stars**.

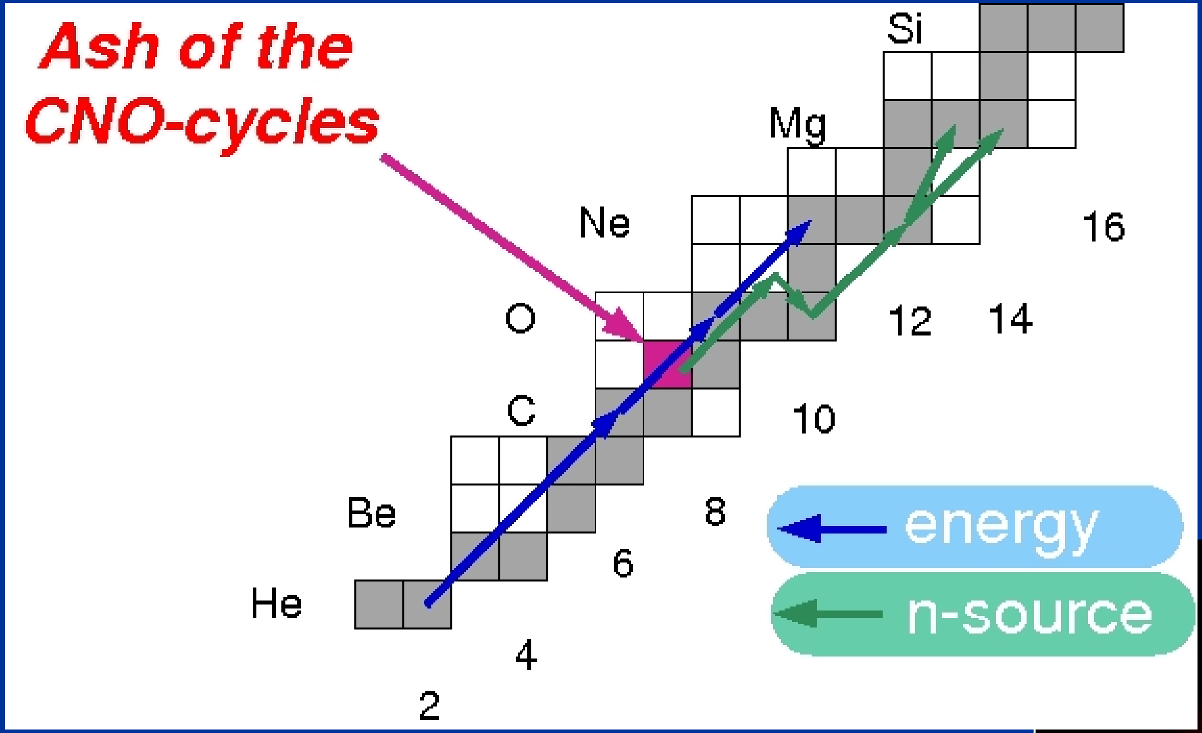


* Presidential Address of Professor Eddington to Section A of the British Association at Cardiff, 1920 August 24.



But is it possible to admit that such a transmutation is occurring? It is difficult to assert, but perhaps more difficult to deny, that this is going on. Sir Ernest Rutherford has recently been breaking down the atoms of oxygen and nitrogen, driving out an isotope of helium from them; and what is possible in the Cavendish laboratory may not be too difficult in the Sun. I think that the suspicion has been generally entertained that the stars are the crucibles in which the lighter atoms which abound

Core Helium Burning

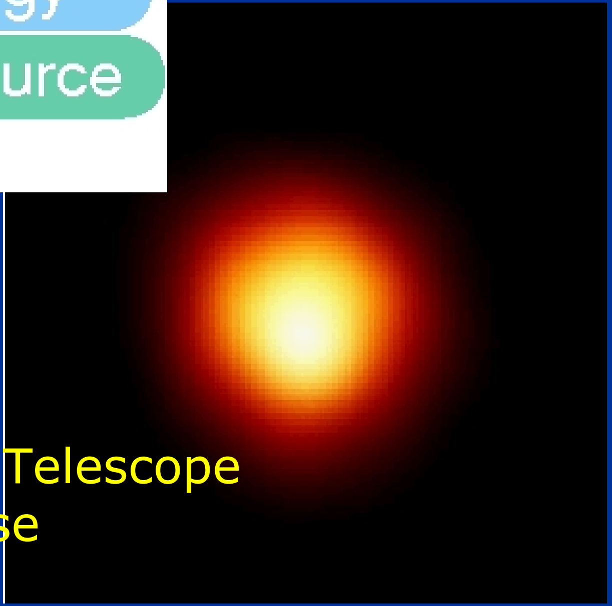


Weak Component
Of s-Process
A<100

$T \approx 0.2 - 0.4$ GK

$\Downarrow$

$E = 0.4 - 0.8$ MeV



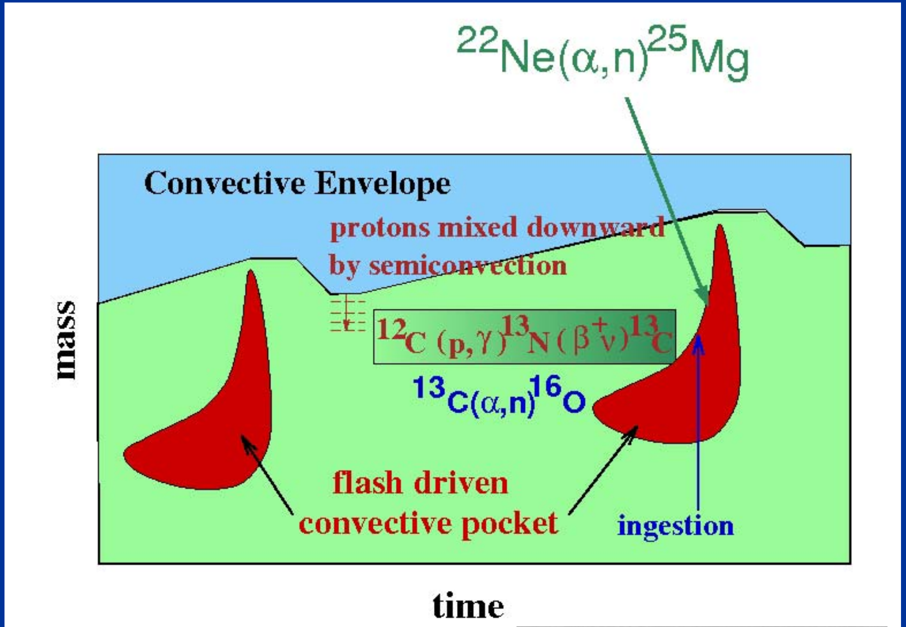
Hubble Space Telescope
Betelgeuse

See talks/posters by:
C. Digest, earlier today
C. Tur, Thursday

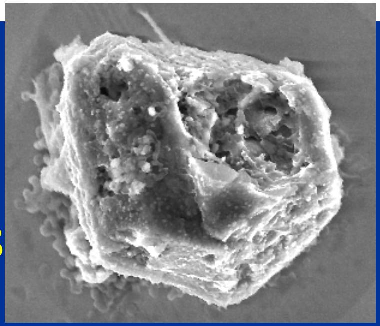
D. Schürmann, this session
C. Matei, this session
H. Makii

TP-AGB Stars

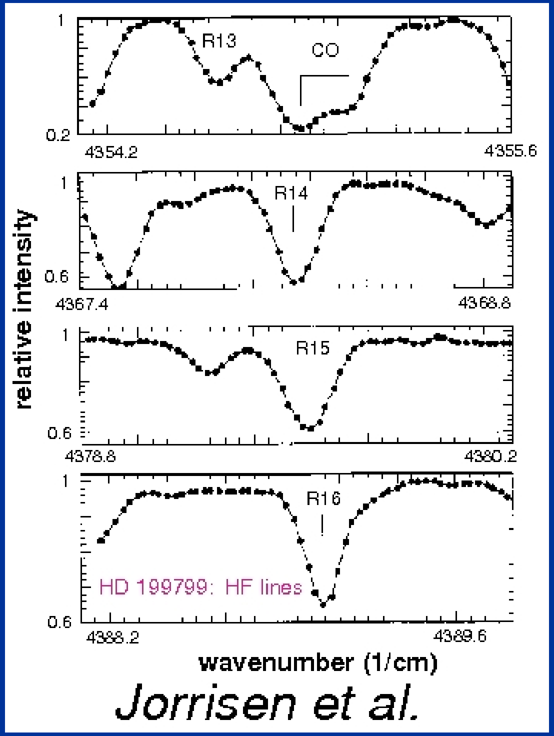
s-Process
(Main Component A>100)



Meteorite
Inclusions



Fluorine Lines Observed On Surface of AGB Star



Jorrisen et al.

$T \approx 0.1 - 0.4$ GK

$\Downarrow$

$E = 0.2 - 0.8$ MeV

See talks/posters by:
M. Busso, earlier today
F. Herwig, Friday
R. Gallino
M. Pellegriti
G. Rogachev

Later Burning Stages

Carbon/Neon Burning

protons and and alphas produced
by reactions during burning:
e.g. $^{12}C(^{12}C,p)^{23}Na(p,\alpha)$
$^{12}C(^{12}C,\alpha)^{20}Ne$

$T \approx 0.5 - 1.5$ GK
$\Downarrow$
$E = 0.85 - 1.8$ MeV

Supernova

α-rich freeze-out
during explosion

See talks/posters by:
M. Paul, this session
C. Vockenhuber, this session

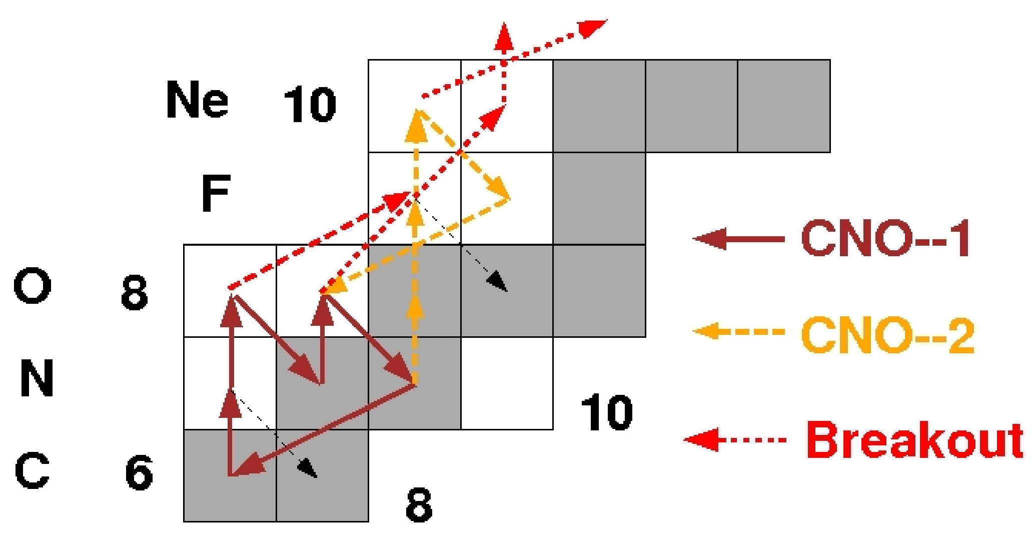
Adiabatic expansion
Starting at $T \approx 5$ GK
$\Downarrow$
$E < 5$ MeV

Shock wave passing
through outer layers

See talks/poster by:
H.Y. Lee

$T \approx 1 - 2$ GK
$\Downarrow$
$E = 1.0 - 2.0$ MeV

Breakout From The Hot CNO Cycle & αp-Process

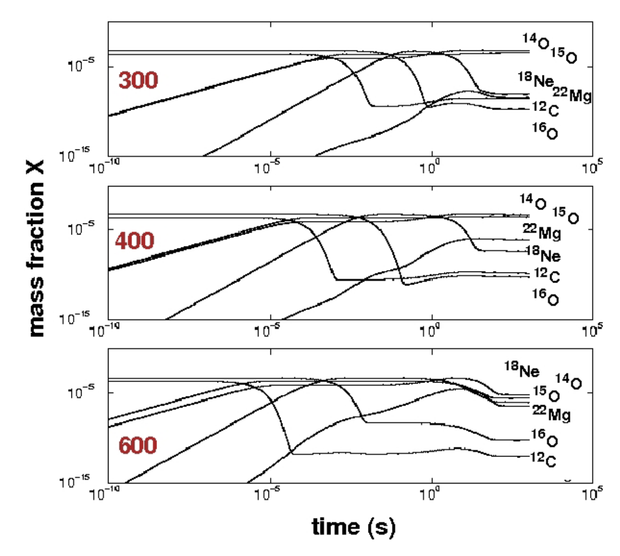


Important For The Energy Production In Explosive Hydrogen Burning,
e.g. Nova, X-Ray Burst

$T \approx 0.4 - 1.5$ GK

$\Downarrow$

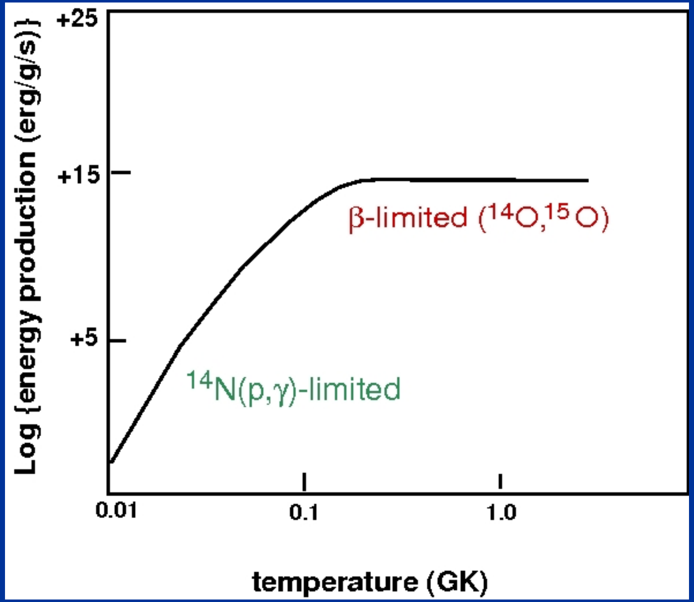
$E = 0.30 - 0.8$ MeV



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

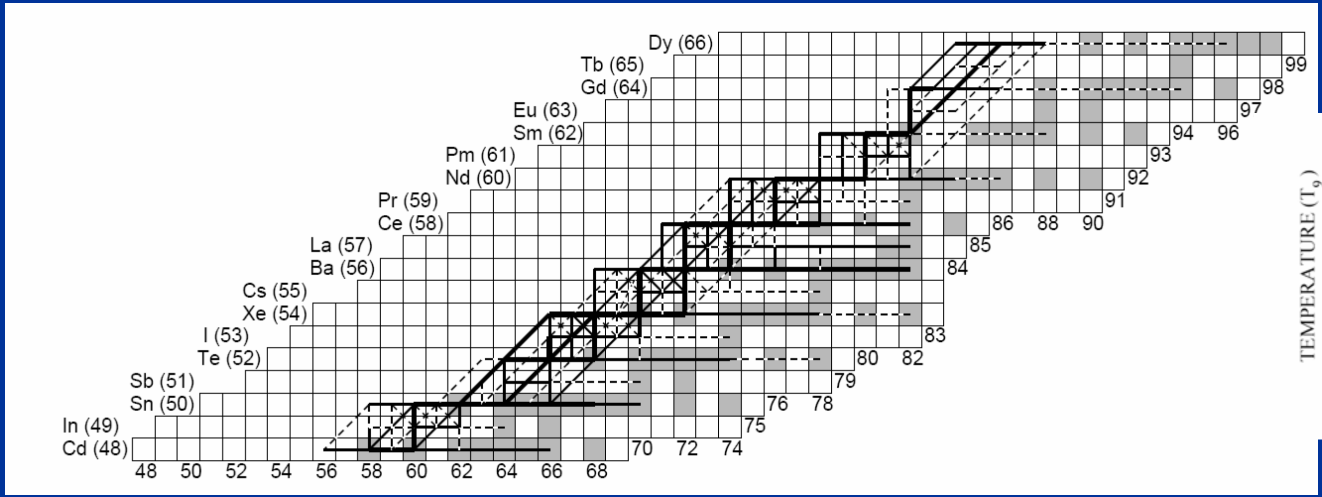
See talks/posters by:
W. Tan, earlier today
C. Angulo

$^{18}Ne(\alpha,p)^{21}Na$

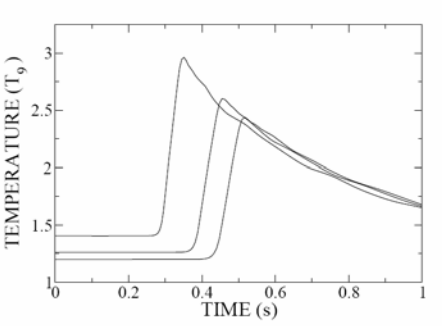


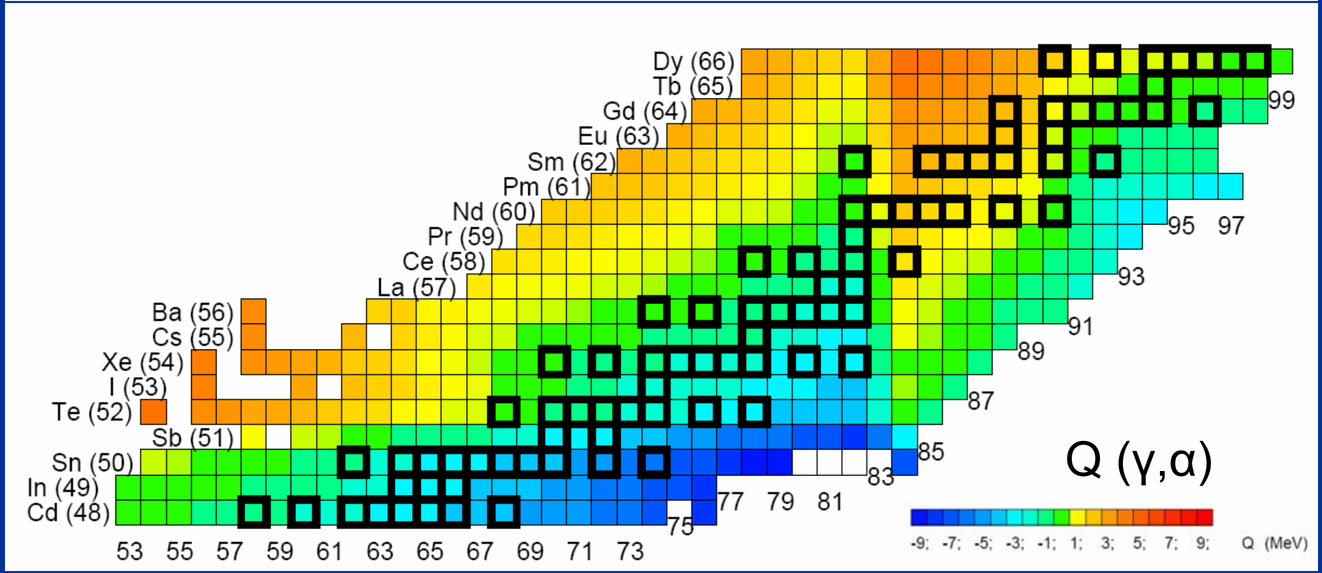
P-Process

Study of (γ,α) using the inverse (α,γ) reactions



SN II shock front passing through O/Ne layer





⇓

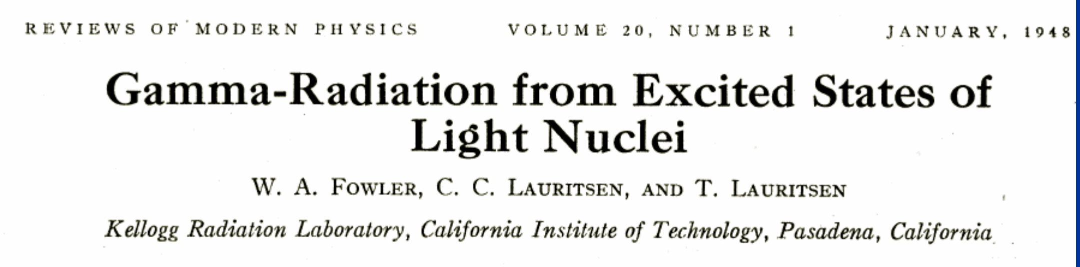
E = 5 – 15 MeV

See talks/posters by:
- S. Harrisopoulos, Thu.
- T. Hayakawa
- N. Özkan
- G. Kiss
- M. Avrigeanu

Yield Of Narrow Resonances

(Number of Reactions Per Incoming Projectile)

$$Y = \int_{E-\xi}^{E} (\sigma/\epsilon)\,dE.$$



REVIEWS OF MODERN PHYSICS VOLUME 20, NUMBER 1 JANUARY, 1948

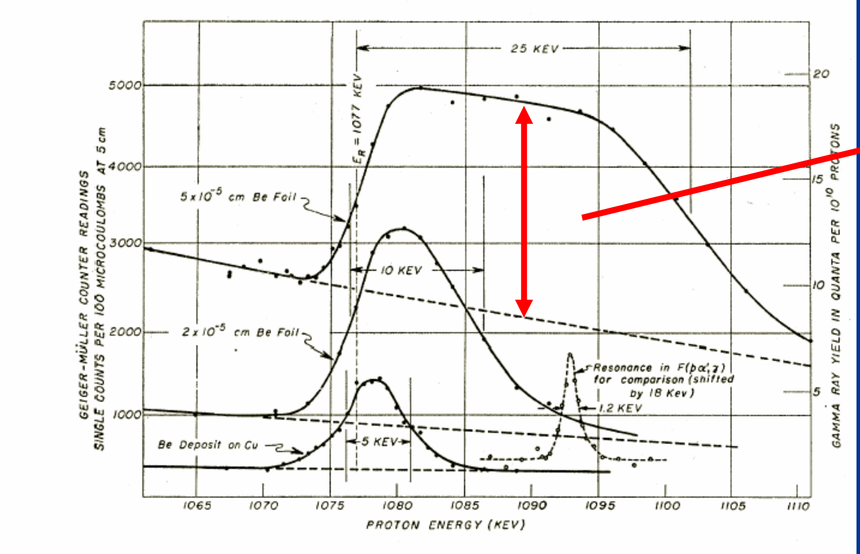
Gamma-Radiation from Excited States of Light Nuclei

W. A. Fowler, C. C. Lauritsen, and T. Lauritsen

Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

$$Y = \frac{\sigma_R\Gamma}{2\epsilon}\left[\tan^{-1}\frac{E-E_R}{\Gamma/2} - \tan^{-1}\frac{E-E_R-\xi}{\Gamma/2}\right] = \frac{\sigma_R\Gamma}{2\epsilon}\left[\frac{\pi}{2} + \tan^{-1}\frac{E-E_R}{\Gamma/2}\right].$$

$\Gamma << \xi$



$$Y_{\max}(\infty) = \frac{\pi}{2}\frac{\sigma_R\Gamma}{\epsilon} = \frac{\lambda^2}{2\varepsilon}\,\omega\gamma$$

$\lambda^2 \sim 1/\mu$

$\varepsilon(\alpha,E) \approx (2\text{-}4)\ \varepsilon(p,E/4)$

$\Big\}$ $Y(\alpha)/Y(p) \approx 1/10$ for same $\omega\gamma$ and E

Targets (α-beam)

Better Than Protons:

Larger Coulomb Barrier

Use of lower Z target material is possible: e.g TiN, Cu backing

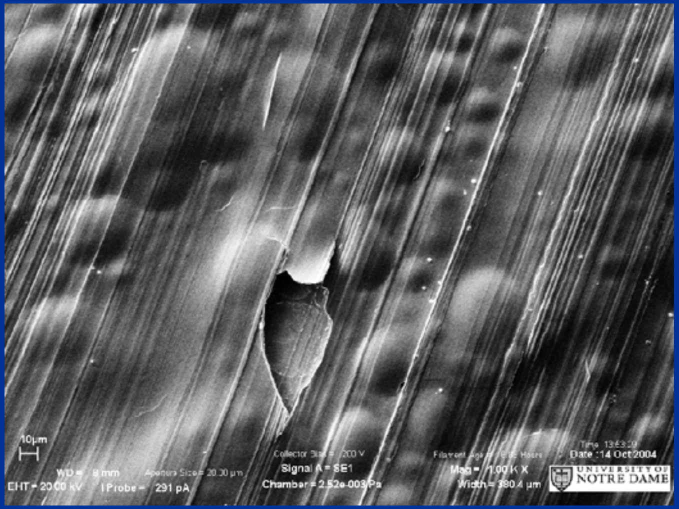
Less beam induced background than protons at same energy

Worse Than Protons

$Y \sim \lambda^2/\varepsilon$ (factor ≈ 10)

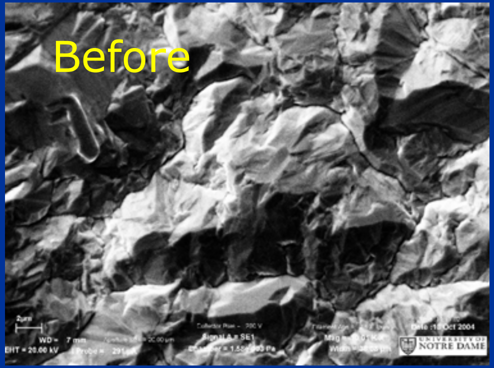
Blistering (in many metals)

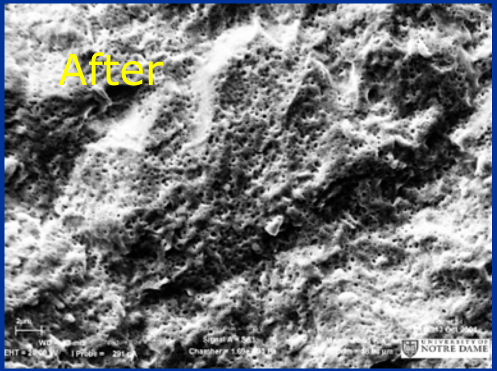
Blisters after α-bombardment



Sputtering

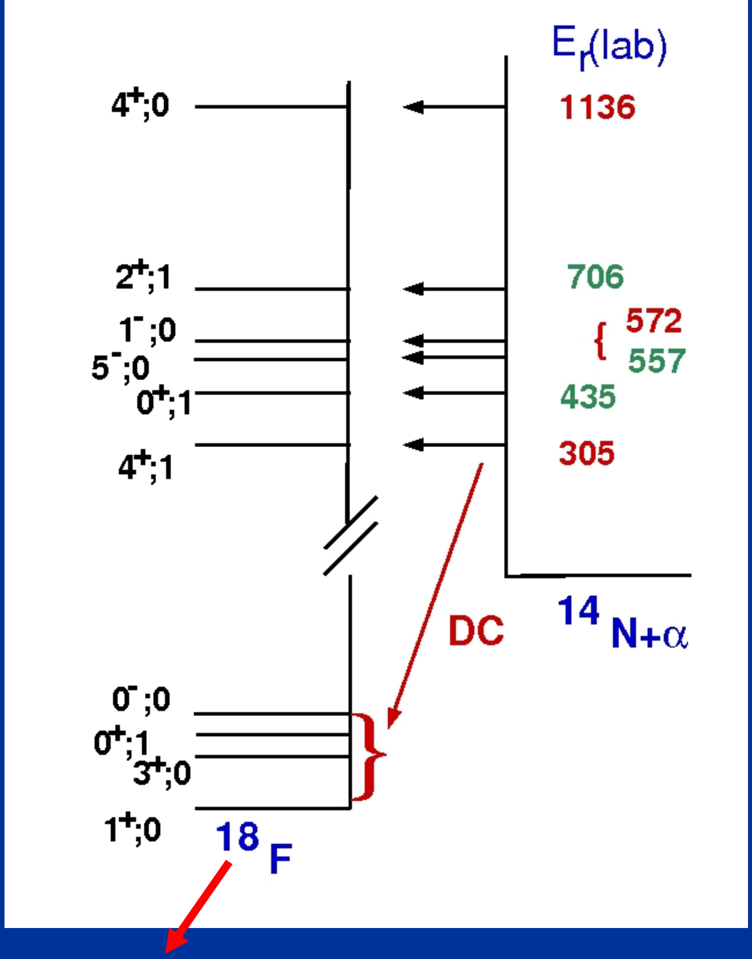
^{21}Ne implanted in Cu



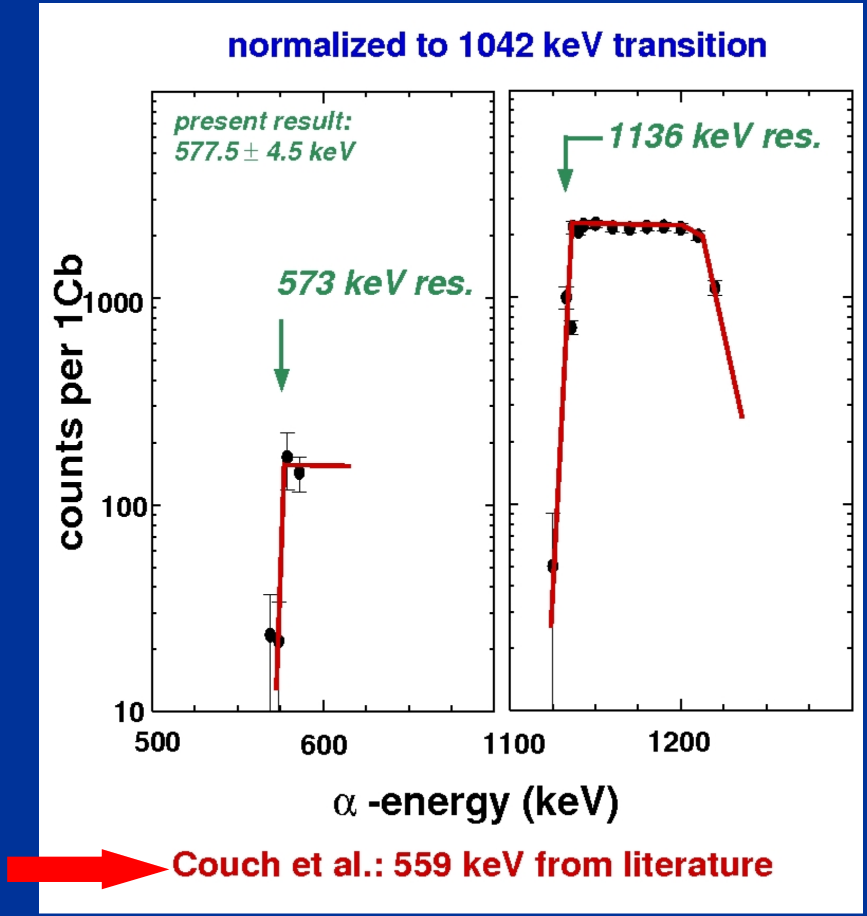


Surface Damage → Thicker Target

Activation Method: $^{14}N(\alpha,\gamma)^{18}F$



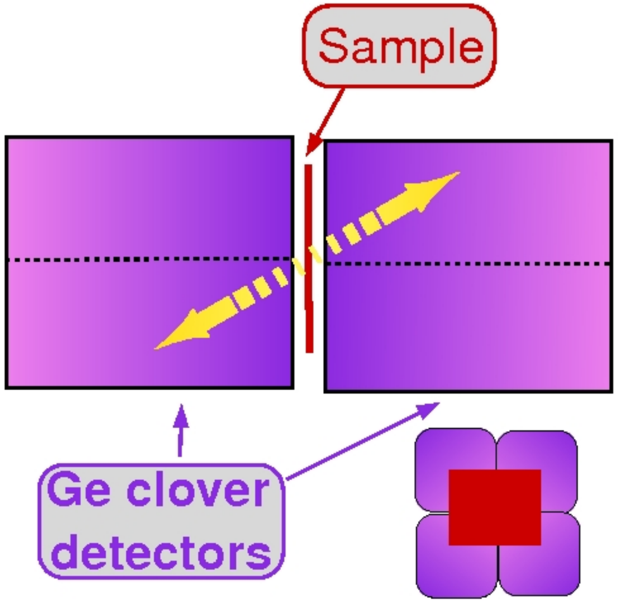
β^+ ,$t_{1/2}$= 110 min.



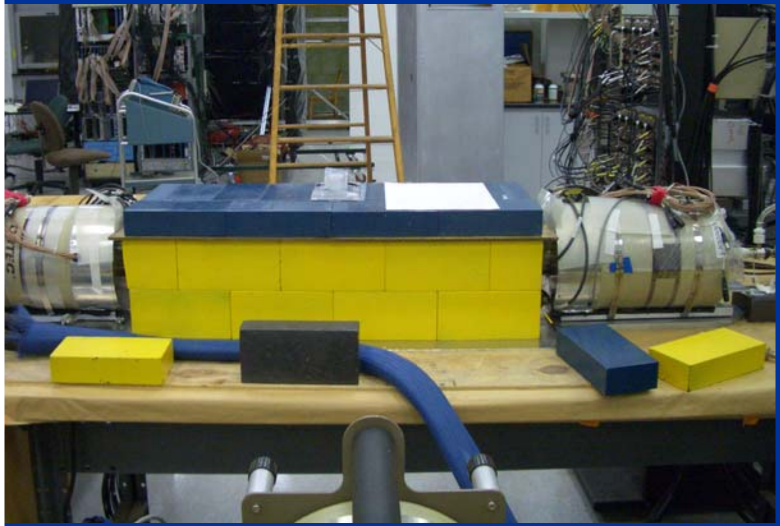
Couch et al.: 559 keV from literature

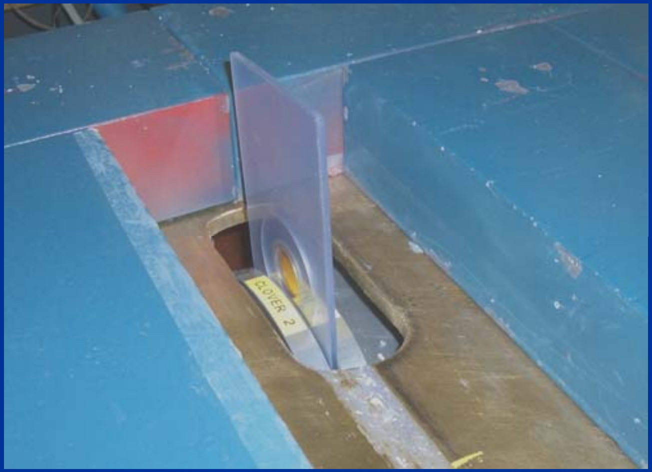
Online Spectroscopy

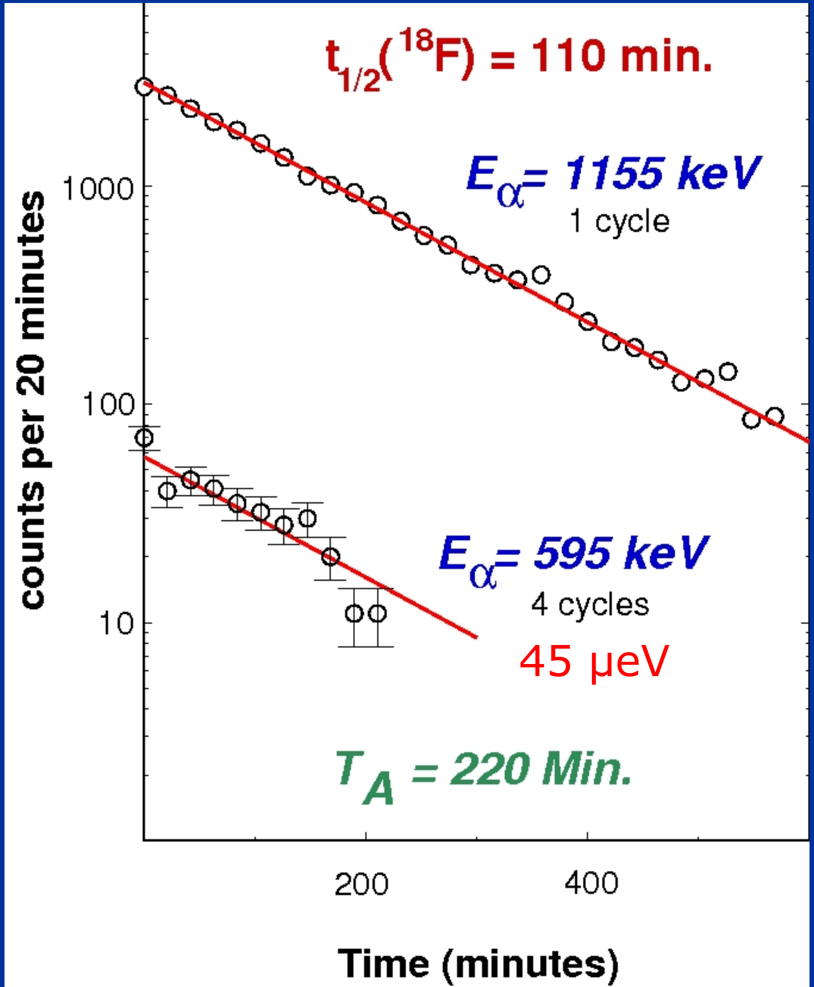
511keV coincidences

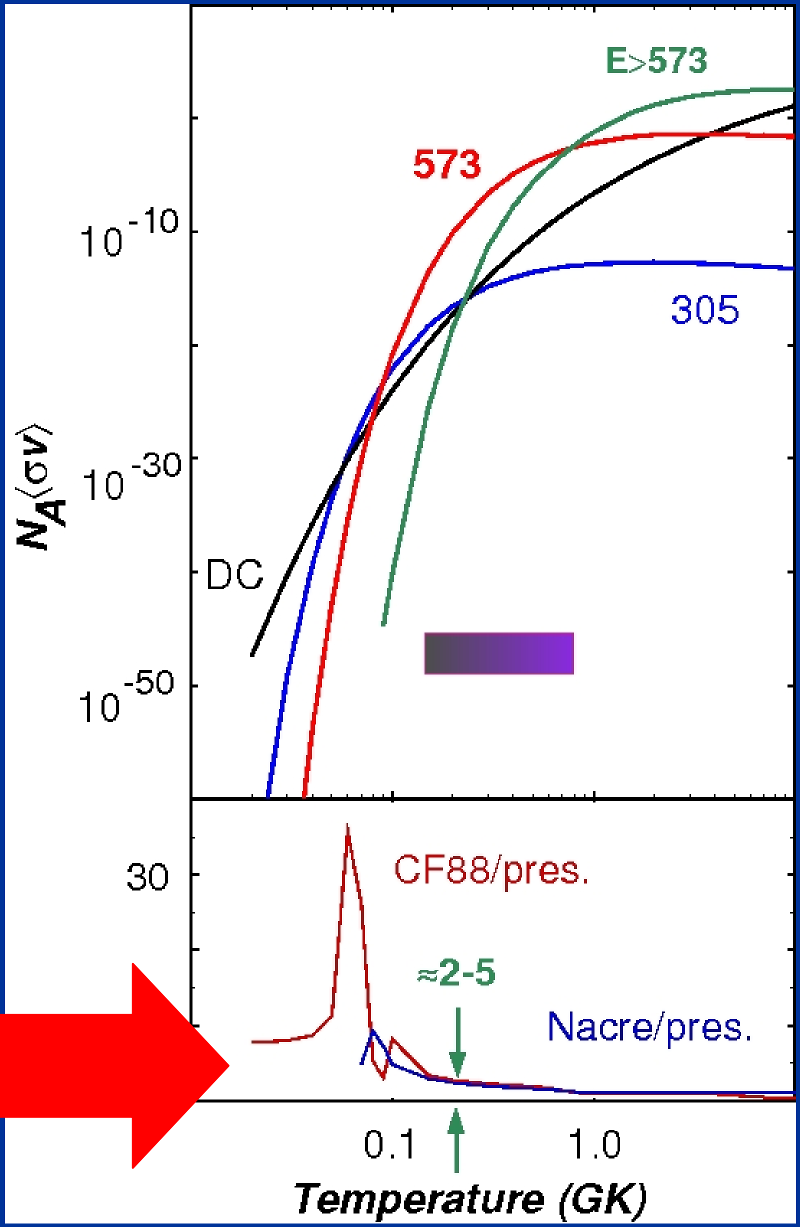


Advantage: **high efficiency** =3.46%
(large detector volume)
low background =0.6/h
(high energy resolution)
(granularity: directional correlation!)



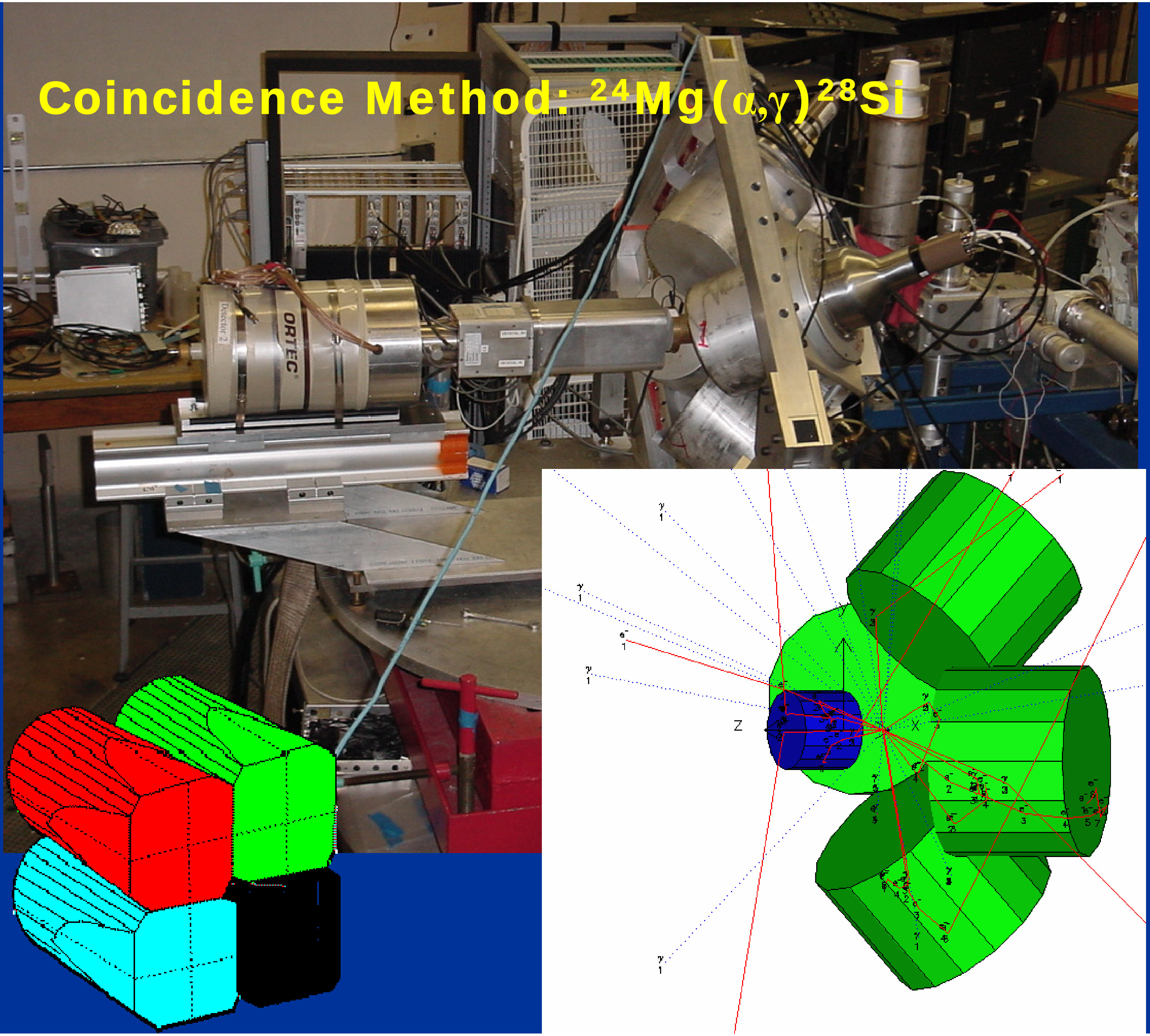






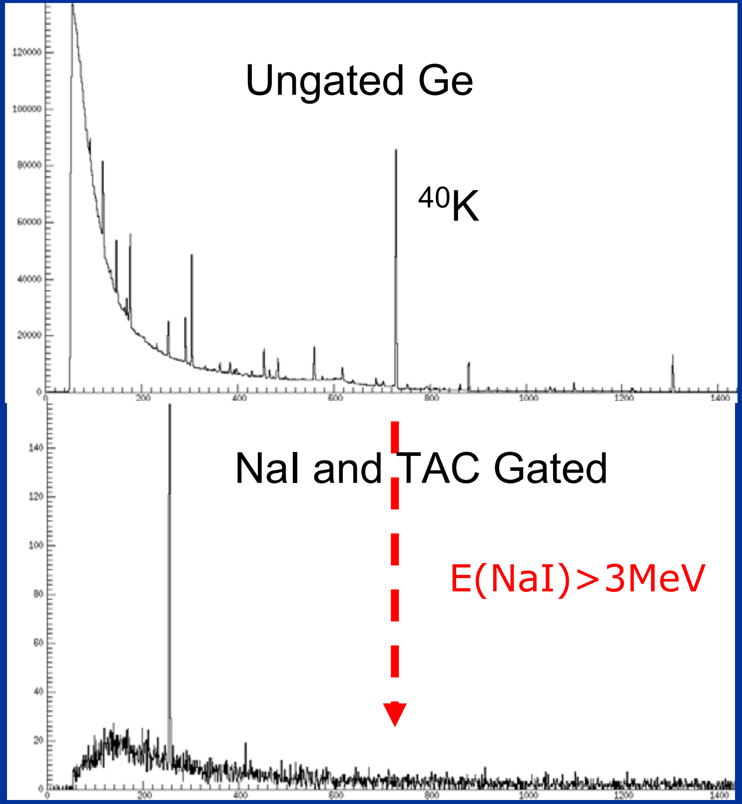
Reduction Of Reaction Rate Mainly Because Of Change In Resonance Energy Of 14 keV !!

Coincidence Method: $^{24}Mg(\alpha,\gamma)^{28}Si$

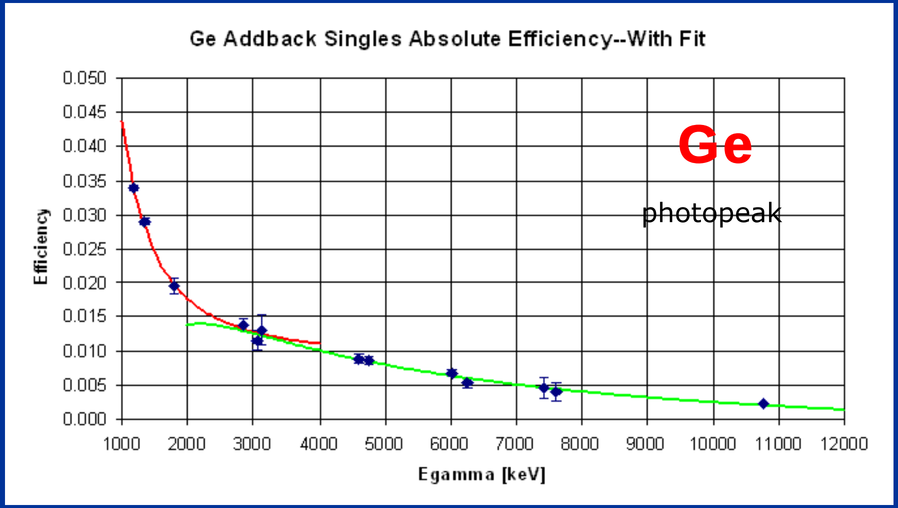


Ω(Ge) ≈ 30%   Ω(NaI) ≈ 40%

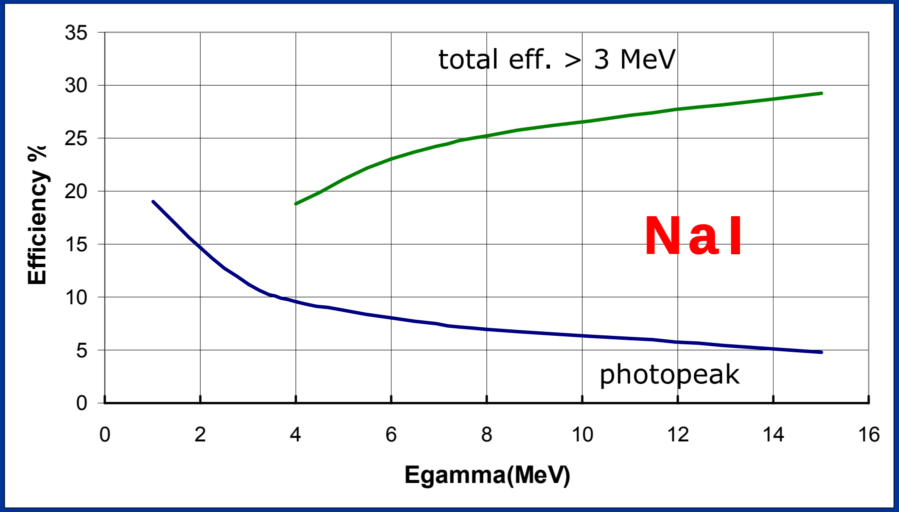
Background Run:



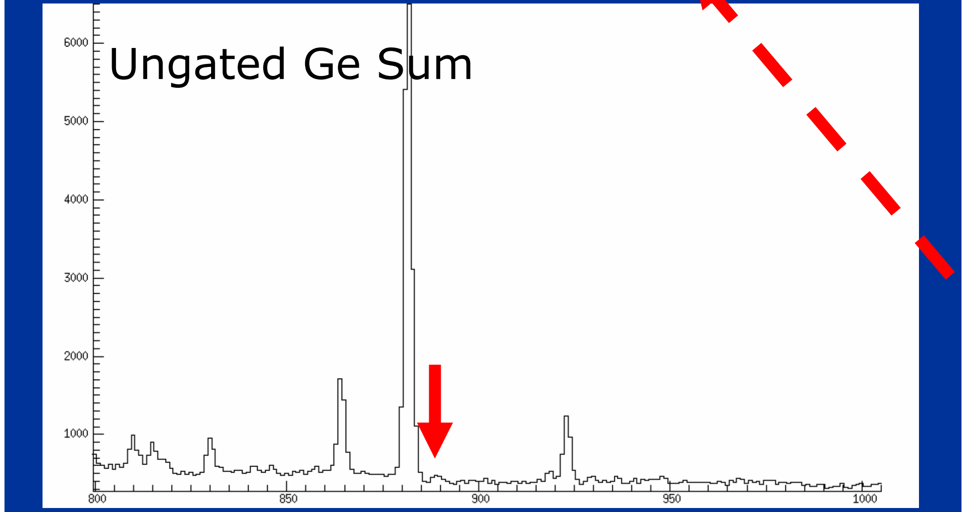
Suppression Factor > 30000

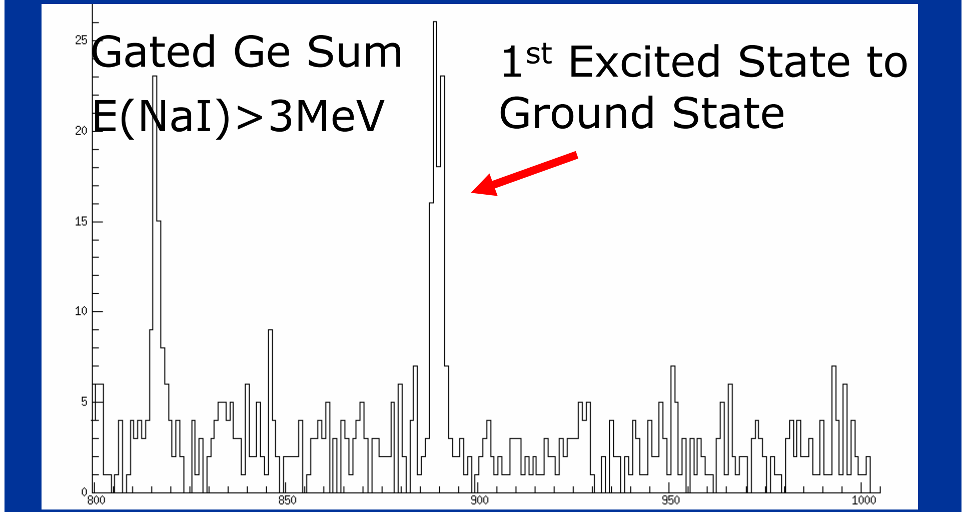


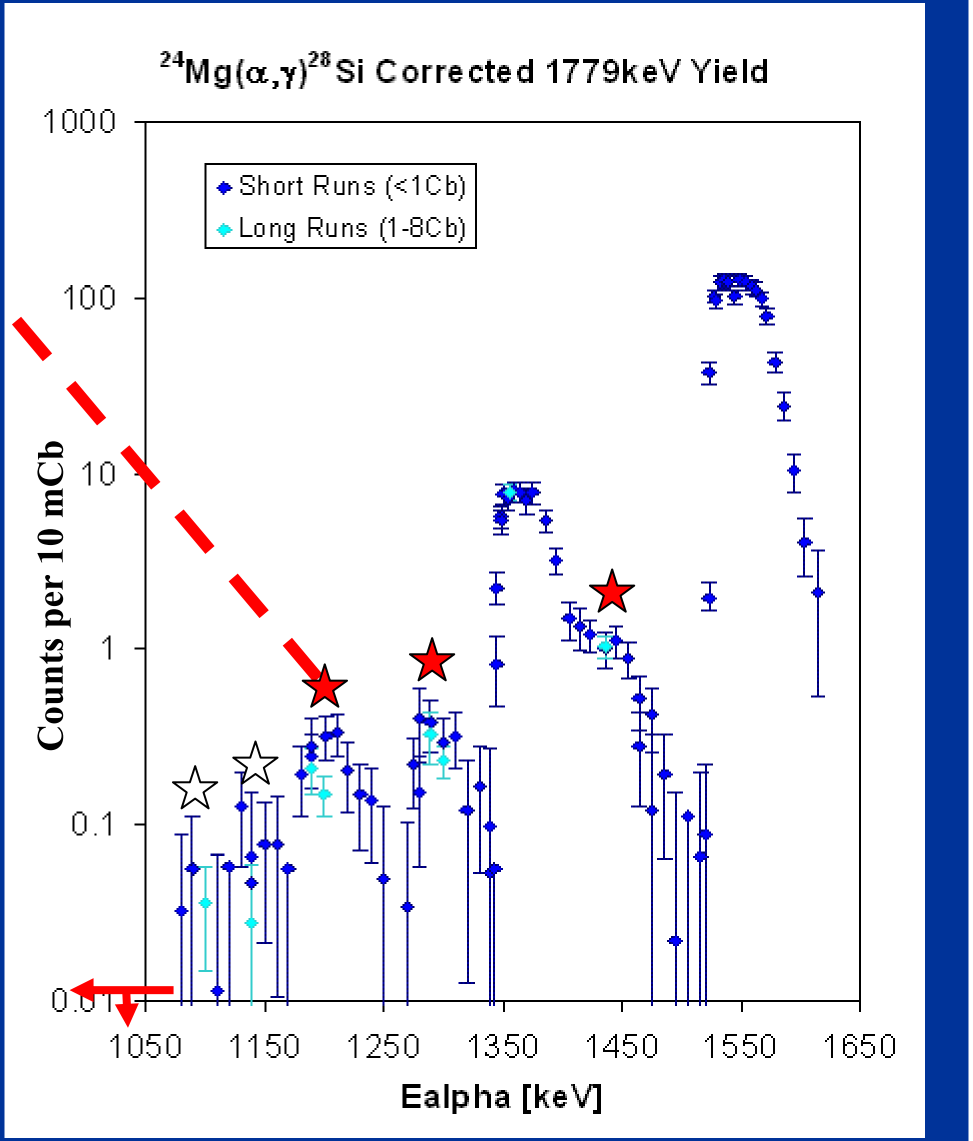
Gammasphere: 10% at 1.33 MeV



1180keV Resonance:



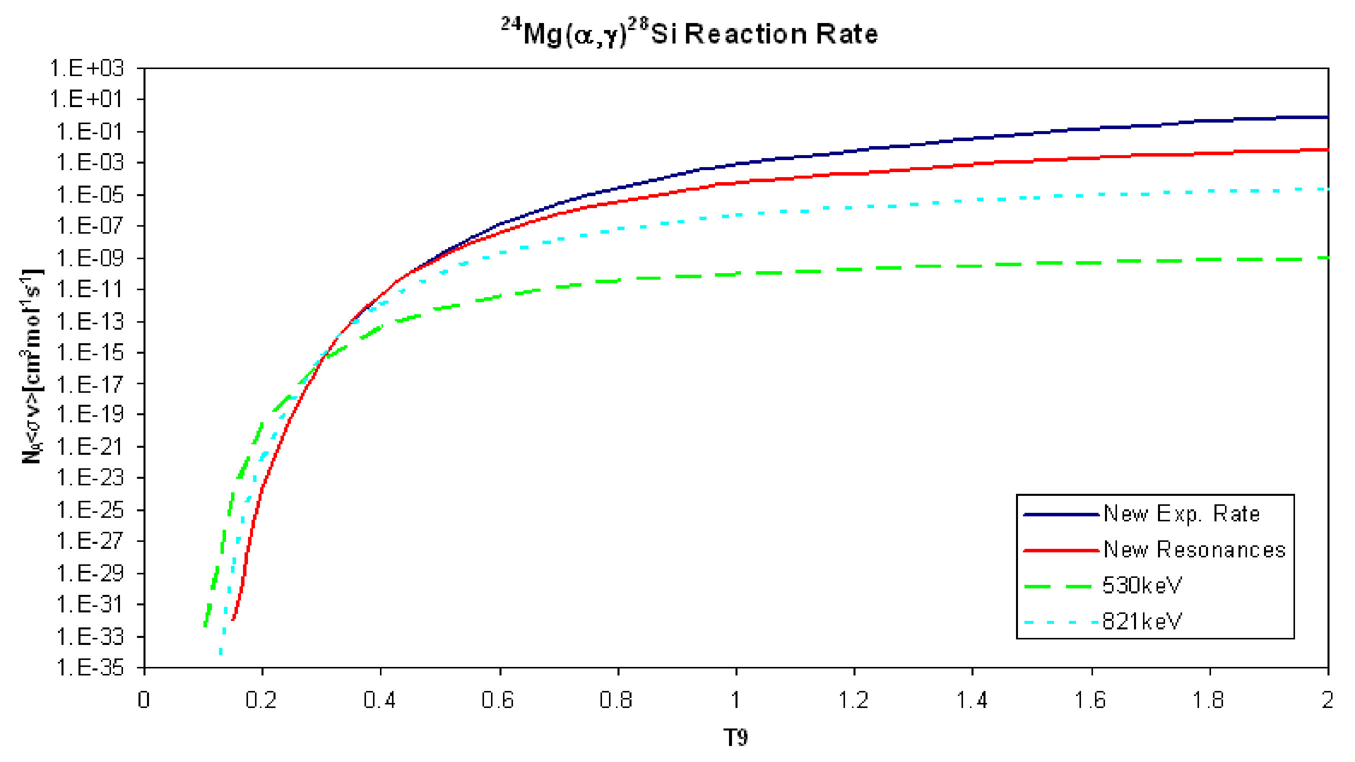




$\omega\gamma_{part} \approx 35\ \mu eV$

Compilation: 1^+, 100%-> gs

Reaction Rate



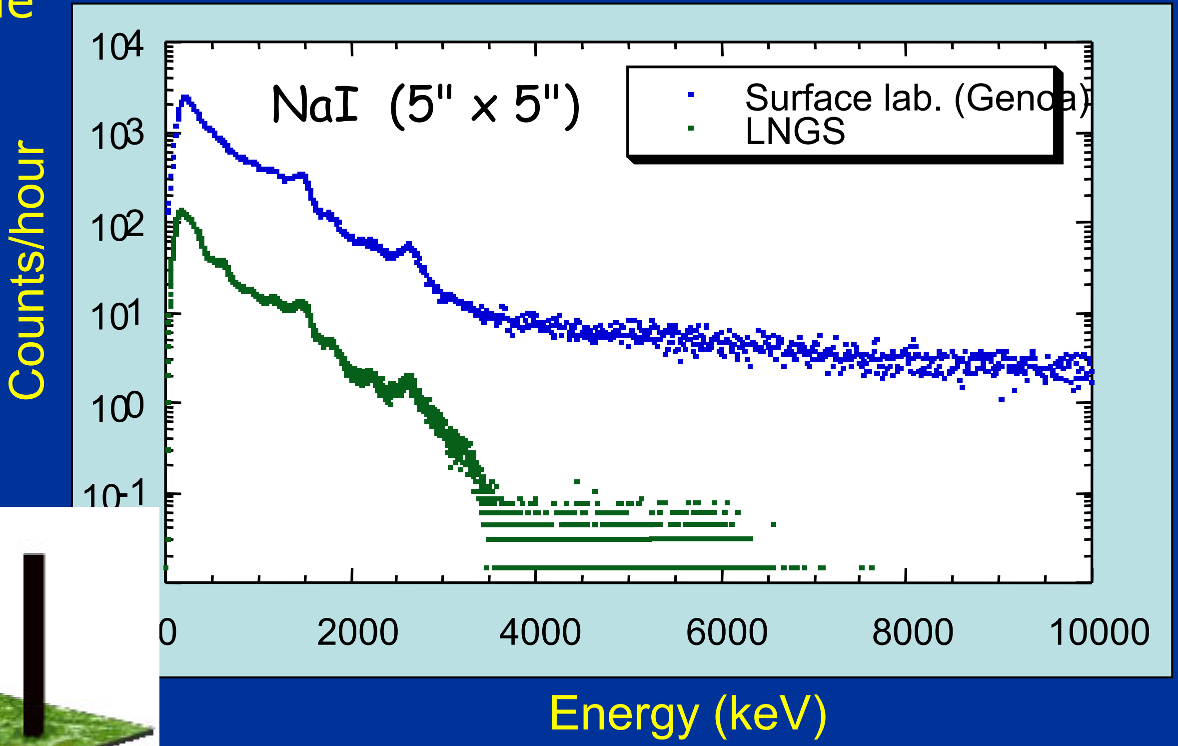
low energy contributions from:
T. Rauscher et al., Nuclear Physics A 675 (2000) 695–721

Underground Laboratory

(see H. Costantini talk)

Laboratory
Underground
Nuclear
Astrophysics

background reduction
by 3 orders of magnitude

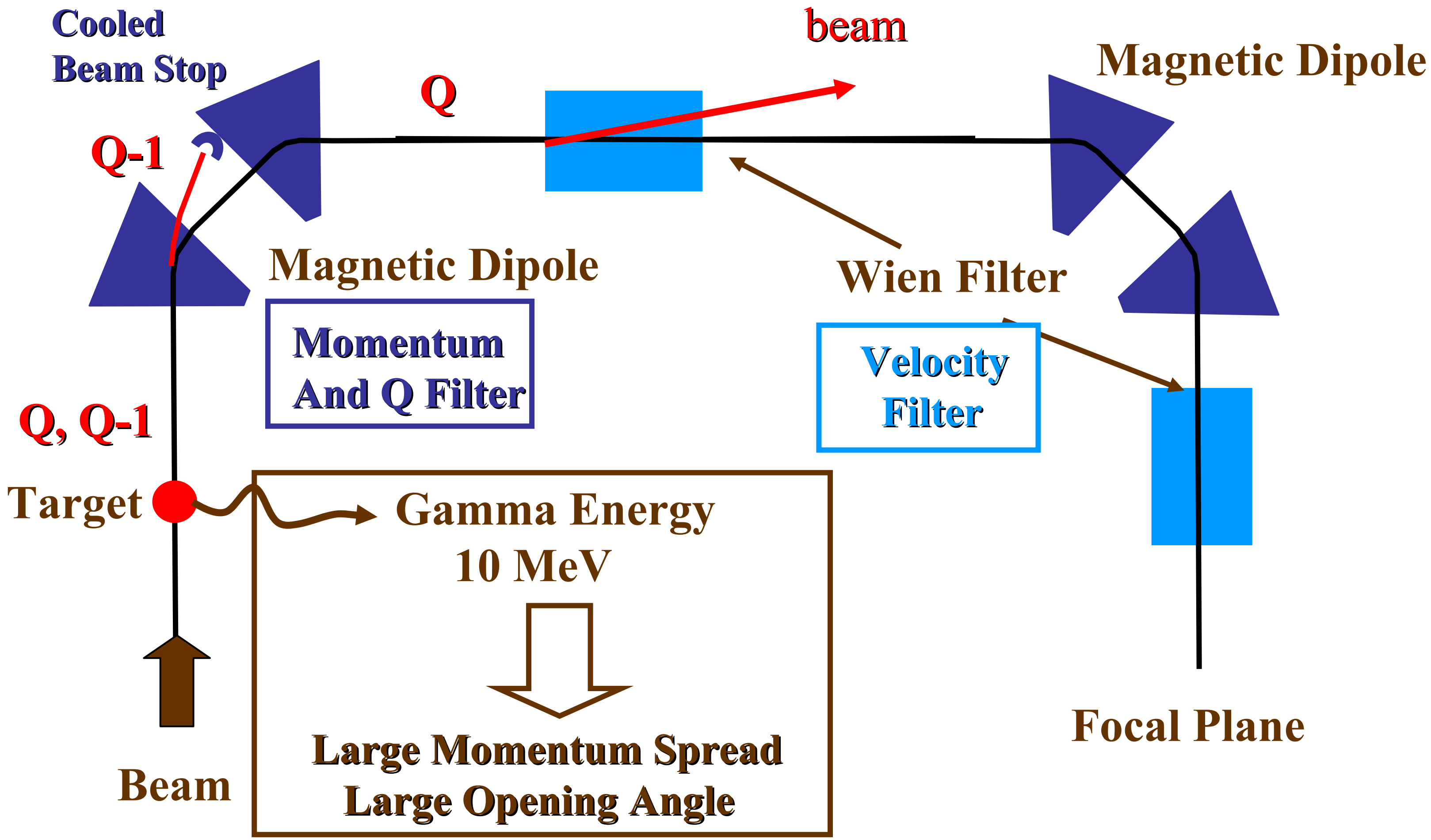


DUSEL

Recoil Separator

(general concept)

Inverse Kinematics



Cooled
Beam Stop

Q-1

Q

beam

Magnetic Dipole

Magnetic Dipole

Momentum
And Q Filter

Wien Filter

Velocity
Filter

Q, Q-1

Target

Gamma Energy
10 MeV

Large Momentum Spread
Large Opening Angle

Focal Plane

Beam

The Design Goal

Alpha and Proton Capture Reactions on sd-Shell Nuclei

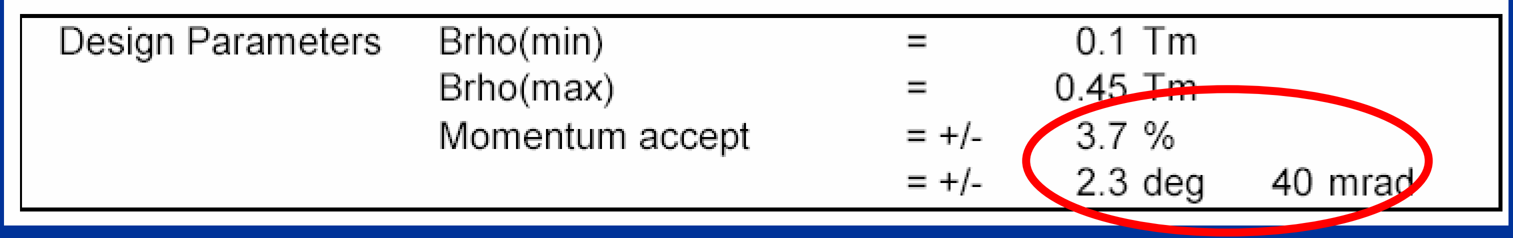
Realistic Evaluation
of Eight Reactions

Existing
Recoil Separators

Stable Beam

Assumptions:
100 microA Beam Intensity
1/h Minimum Count Rate
33 % Efficiency

Erna
Dragon
Ares
DRS



Design Parameters	Brho(min)	=	0.1 Tm	
	Brho(max)	=	0.45 Tm	
	Momentum accept	= +/-	3.7 %	
		= +/-	2.3 deg	40 mrad

Yield Estimate *(for (α,γ) reactions)*

Not including background count rates

Assume:
count rate of 1 /hour
efficiency 33%

→ Number of reactions 3/h

For 100 μA
$\Downarrow$
$Y = 1.3\ 10^{-18}$

nonresonant reactions

$N_T = 3\ 10^{17}/\mathrm{cm}^2$

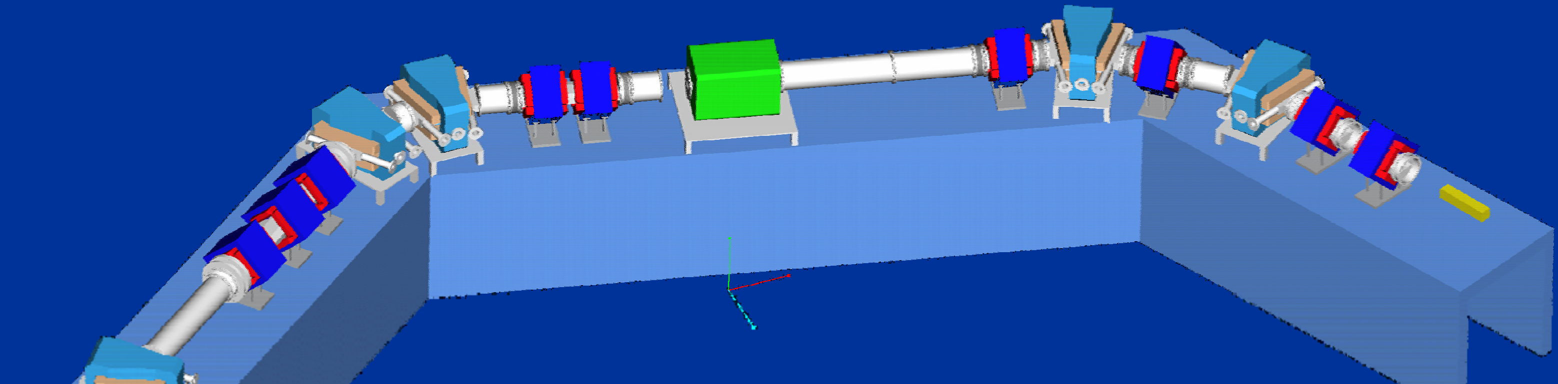
$\sigma \geq 10$ pb

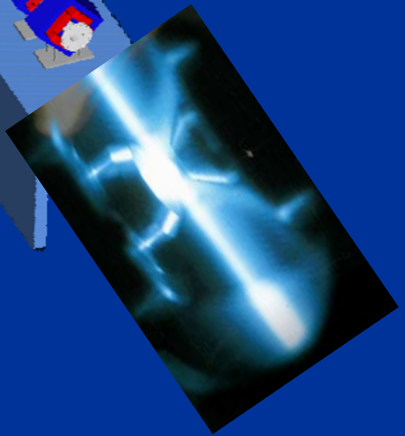
resonant reactions

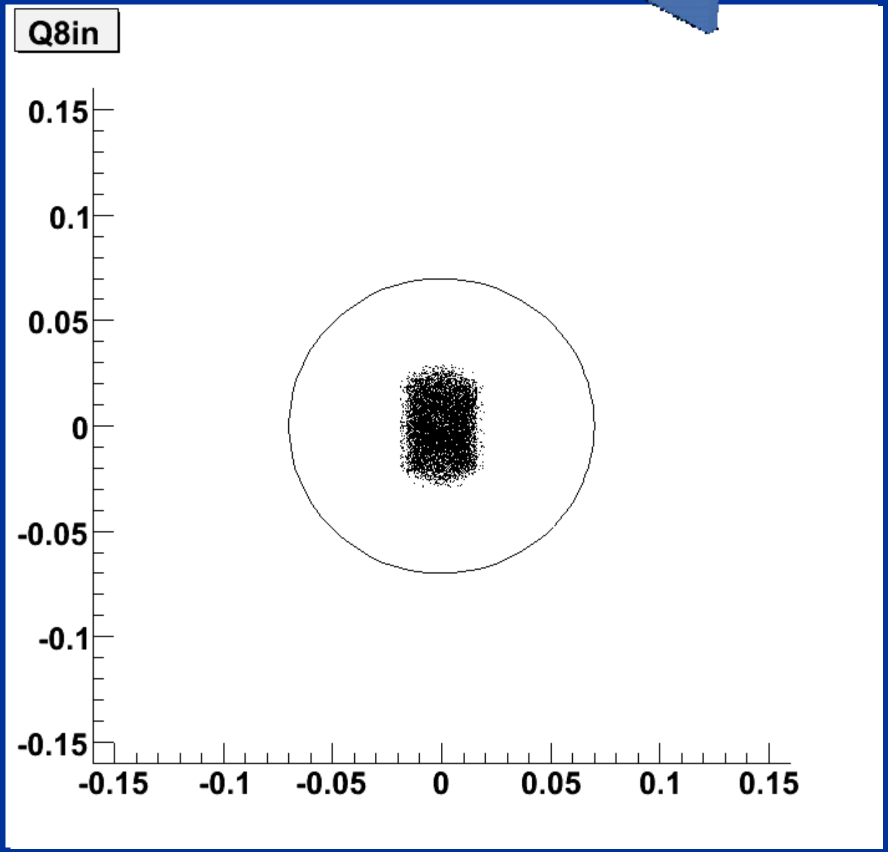
$\omega\gamma \geq 5$ neV

need γ-recoil coinc.
to clean up

→ place device underground
to reduce count rate in
γ-detector







Preliminary Layout
Of Recoil Separator
At Notre Dame

Acknowledgement

University of Notre Dame

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Joachim Görres
Larry Lamm

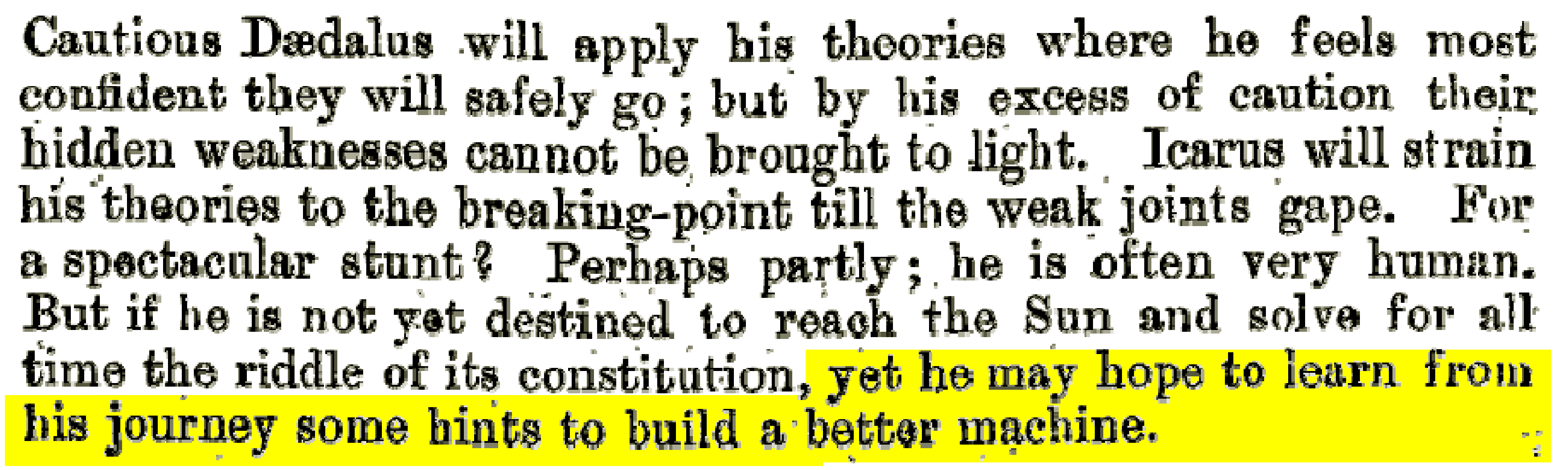
Hye-Young Lee
Ed Stech
Elizabeth Strandberg
Wanpeng Tan
Claudio Ugalde*
Michael Wiescher

Forschungszentrum Karlsruhe

Saed Dababneh*
Michael Heil*

Franz Käppeler
Rene Reifarth*

Epilogue



Cautious Dædalus will apply his theories where he feels most confident they will safely go; but by his excess of caution their hidden weaknesses cannot be brought to light. Icarus will strain his theories to the breaking-point till the weak joints gape. For a spectacular stunt? Perhaps partly; he is often very human. But if he is not yet destined to reach the Sun and solve for all time the riddle of its constitution, yet he may hope to learn from his journey some hints to build a better machine.

Sir Arthur Eddington

http://www.nd.edu/~nsl

J I N A

http://www.jinaweb.org