Experiments in Nuclear Astrophysics I (charged-particle induced)

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With contributions from:
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Manoel Couder, University of Notre Dame
Marco Pignatari, University of Victoria, Canada
Michael Wiescher, University of Notre Dame

Scope

Other Lectures:
- …nuclei far from stability
- …under extreme conditions
- …stellar explosions

This Lecture
- …at or close to stability
- …stable beam reactions

⇩

“classical” low-energy
nuclear astrophysics

Nuclear Structure ← T ≈ 1 GK → **Nuclear Properties**

Nuclear Structure
- resonance energies
- spin&widths of levels
- e.g. CNO cycle

Nuclear Properties
- masses
- Lifetime
- e.g. r-process

Outline

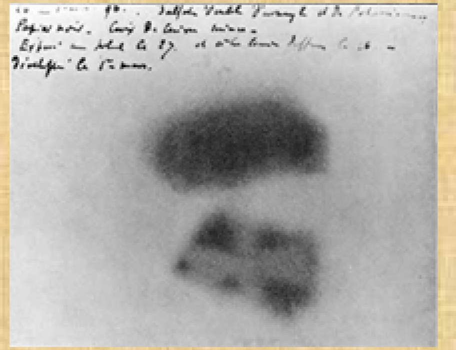
Historical Remarks
  -from Rutherford to B^2FH
  -
From Experiment to Reaction Rate
  -formalism
Experiments
  -CNO cycle
  -neutron sources
  -$^{12}C + {}^{12}C$
Future

Henri Becquerel

(15.12.1852 – 25.8.1908)

Nobel Prize in Physics (1903)

Becquerel wrapped a fluorescent substance, potassium uranyl sulfate, in photographic plates and black material in preparation for an experiment requiring bright sunlight.



Marie Skłodowska Curie

(7.11.1867 – 4.7.1934)

-first systematic studies of radioactive substances(with her husband Pierre Curie)
-first used the term “radioactive”
-discovery of Polonium & Radium
-1st victim of radiation
-founder of Nuclear Medicine

Nobel Prize in Physics (1903)
Nobel Prize in Chemistry (1911)

Ernest Rutherford,

(30.8.1871–19.10.1937)

Nobel Prize in Chemistry (1908)

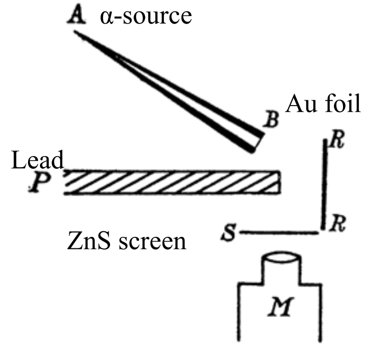
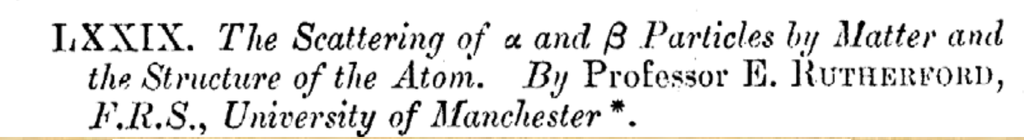


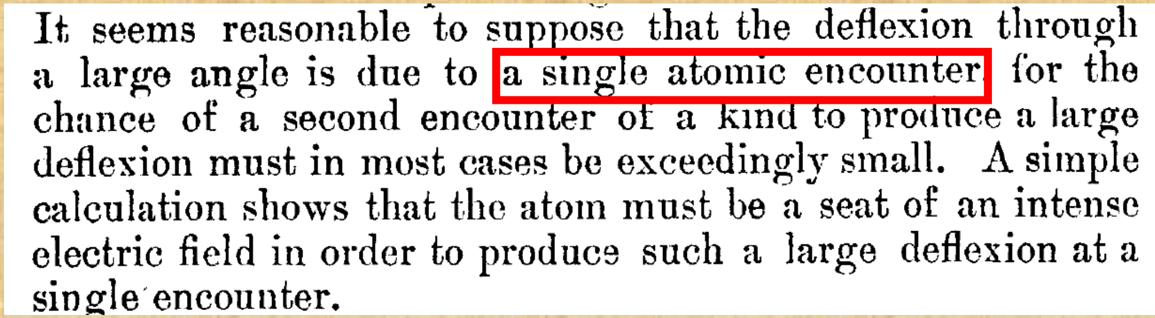
Fig. 1.

The Birth of Nuclear Physics



LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom. By* Professor E. Rutherford, *F.R.S., University of Manchester**.

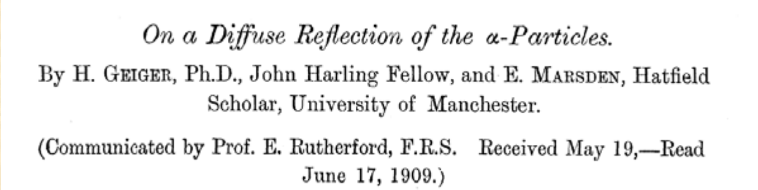
Philosophical Magazine, Series 6, vol. 21, May 1911, p. 669-688



It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

Rutherford Scattering Law is a fundamental discovery!!

Based on experiments by Geiger and Marsden



On a Diffuse Reflection of the α-Particles.

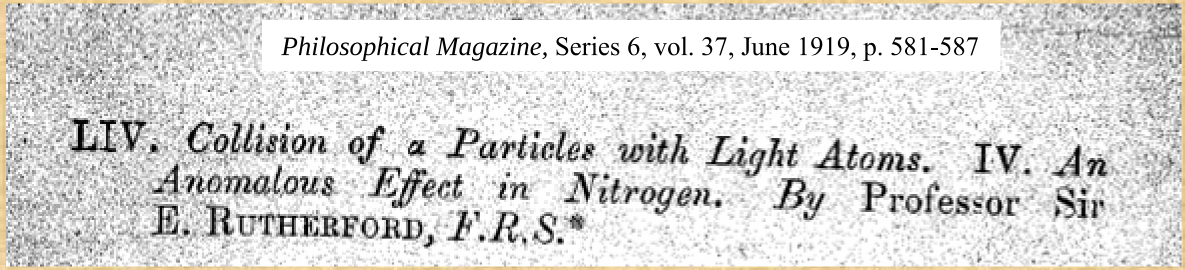
By H. Geiger, Ph.D., John Harling Fellow, and E. Marsden, Hatfield Scholar, University of Manchester.

(Communicated by Prof. E. Rutherford, F.R.S. Received May 19,—Read June 17, 1909.)

Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character, Vol. 82, No. 557 (Jul. 31, 1909), pp. 495-500

Expection: all events within <2 °

First charged particle induced reaction: $^{14}N(\alpha,p)^{17}O$



Philosophical Magazine, Series 6, vol. 37, June 1919, p. 581-587

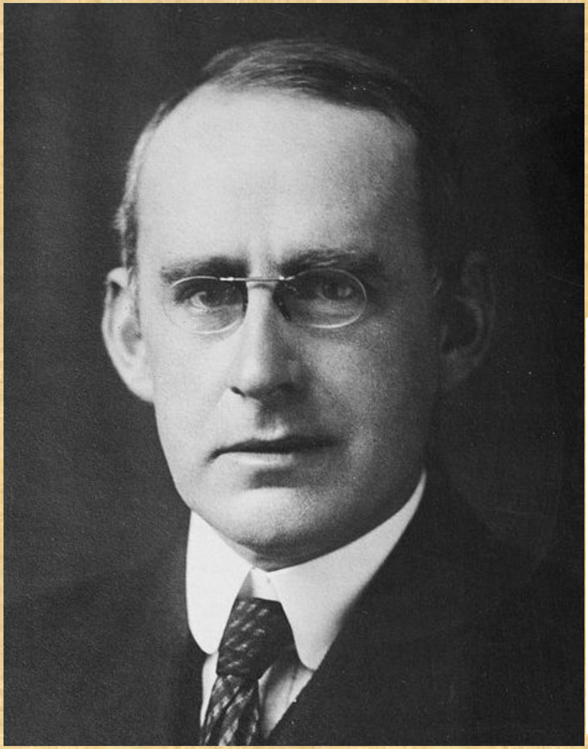
LIV. *Collision of α Particles with Light Atoms. IV. An Anomalous Effect in Nitrogen.* By Professor Sir E. RUTHERFORD, *F.R.S.**

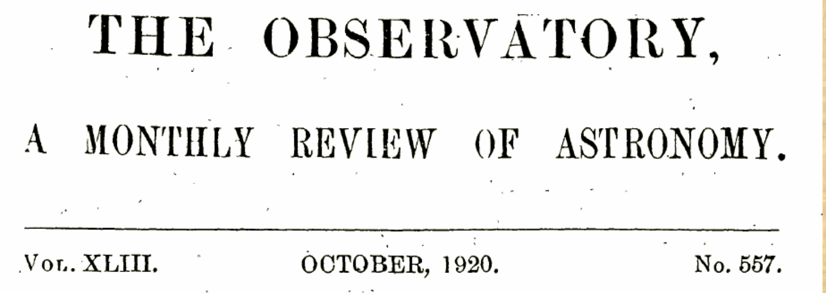
It is difficult to avoid the conclusion that these long-range atoms arising from the collision of α-particles with nitrogen are not Nitrogen atoms, but probably charged atoms of hydrogen or atoms of mass 2. If this be the case, we must conclude that the nitrogen atom is disintegrated under the intense forces developed iJ;l a close collision with swift a-particles, and that the atom liberated formed a constituent part of the nitrogen nucleus.

Times Cited: 51 !

Arthur Stanley Eddington

(28.12.1882 – 22.11.1944)

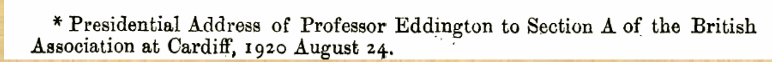




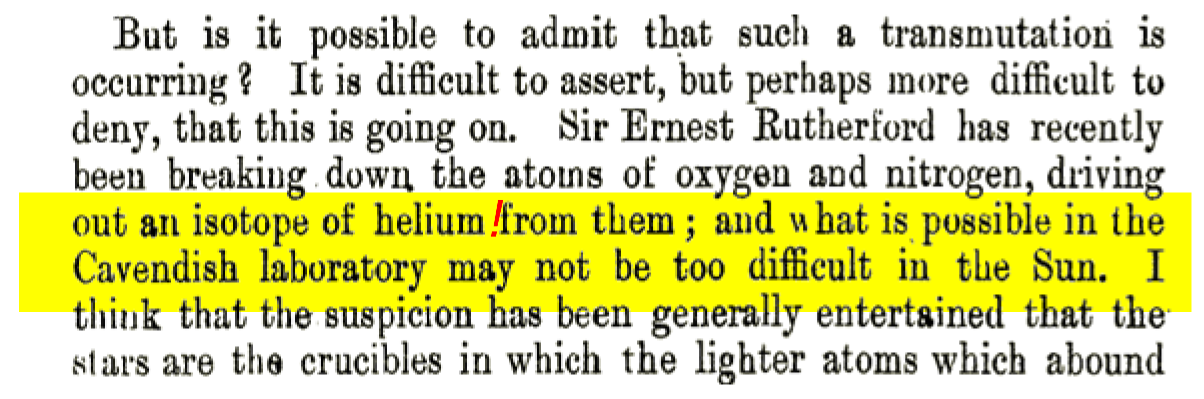
THE OBSERVATORY,

A MONTHLY REVIEW OF ASTRONOMY.

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



* 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

Proton or alpha induced reaction as energy source of stars ??

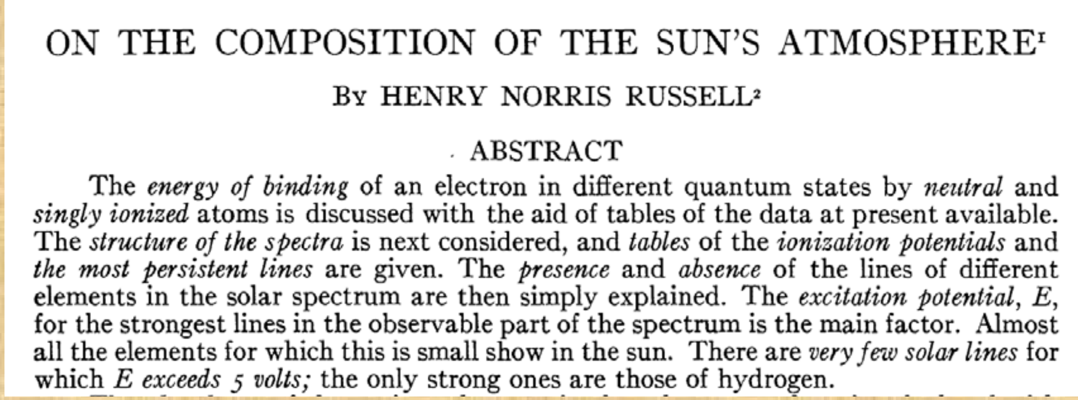
(a matter of discussion in the 1920’s)

Protons:

- 4p->4He has highest energy gain
  (from mass spectroscopy, Ashton)

Alphas:

- mainly He in sun’s surface
-forming He from 4 protons
-need high proton energies
  to overcome Couloumb barrier



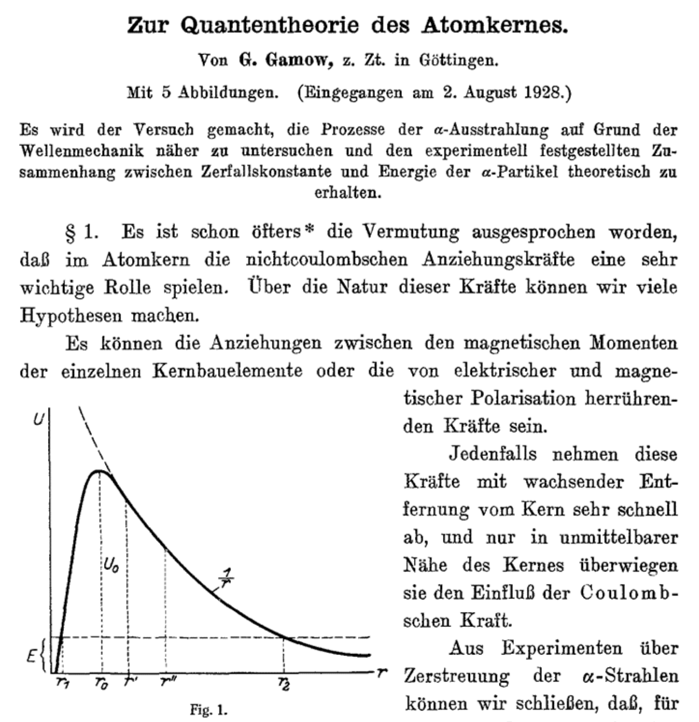
ON THE COMPOSITION OF THE SUN’S ATMOSPHERE[1]

By HENRY NORRIS RUSSELL[2]

ABSTRACT

The *energy of binding* of an electron in different quantum states by *neutral* and *singly ionized* atoms is discussed with the aid of tables of the data at present available. The *structure of the spectra* is next considered, and *tables* of the *ionization potentials* and *the most persistent lines* are given. The *presence* and *absence* of the lines of different elements in the solar spectrum are then simply explained. The *excitation potential, E,* for the strongest lines in the observable part of the spectrum is the main factor. Almost all the elements for which this is small show in the sun. There are *very few solar lines* for which *E exceeds 5 volts;* the only strong ones are those of hydrogen.

Astrophys. Journal, 70, 11R, 1929



Zur Quantentheorie des Atomkernes.

Von **G. Gamow,** z. Zt. in Göttingen.

Mit 5 Abbildungen. (Eingegangen am 2. August 1928.)

Es wird der Versuch gemacht, die Prozesse der α-Ausstrahlung auf Grund der Wellenmechanik näher zu untersuchen und den experimentell festgestellten Zusammenhang zwischen Zerfallskonstante und Energie der α-Partikel theoretisch zu erhalten.

§ 1. Es ist schon öfters* die Vermutung ausgesprochen worden, daß im Atomkern die nichtcoulombschen Anziehungskräfte eine sehr wichtige Rolle spielen. Über die Natur dieser Kräfte können wir viele Hypothesen machen.

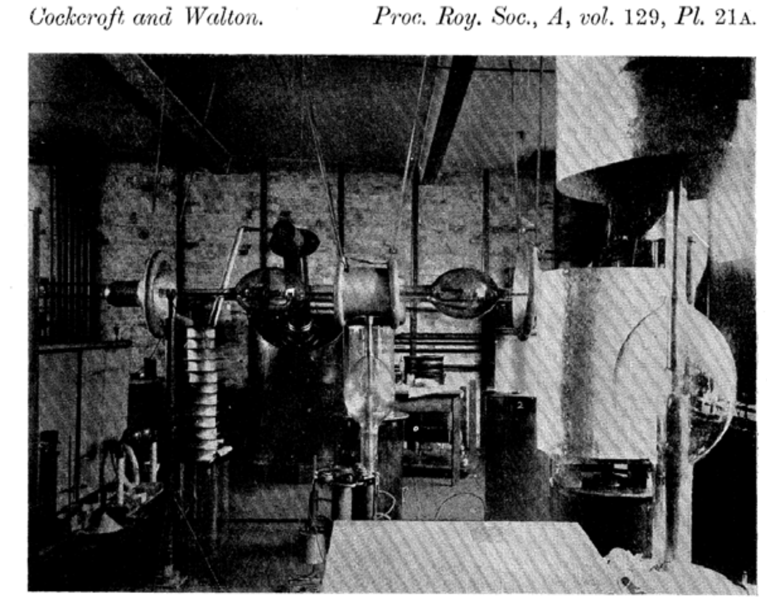
Es können die Anziehungen zwischen den magnetischen Momenten der einzelnen Kernbauelemente oder die von elektrischer und magnetischer Polarisation herrührenden Kräfte sein.

Jedenfalls nehmen diese Kräfte mit wachsender Entfernung vom Kern sehr schnell ab, und nur in unmittelbarer Nähe des Kernes überwiegen sie den Einfluß der Coulombschen Kraft.

Aus Experimenten über Zerstreuung der α-Strahlen können wir schließen, daß, für schwere Elemente, die An-

Fig. 1.

Z. Physik, 52, 510, 1928

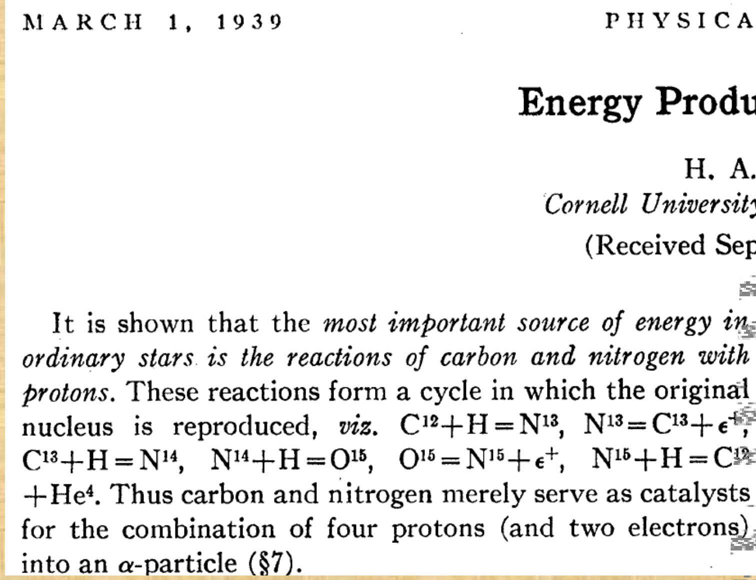


Cockcroft and Walton. *Proc. Roy. Soc., A, vol.* 129, *Pl.* 21A.

First electrostatic accelerator 1930

(Cockcroft-Walton)

First experimental informations about proton-induced reactions



MARCH 1, 1939 PHYSICAL REVIEW VOLUME 55

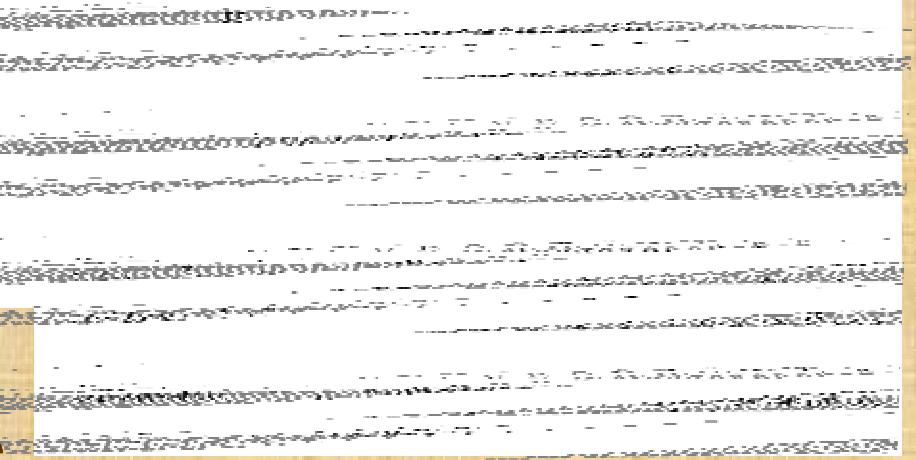
Energy Production in Stars*

H. A. BETHE

Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

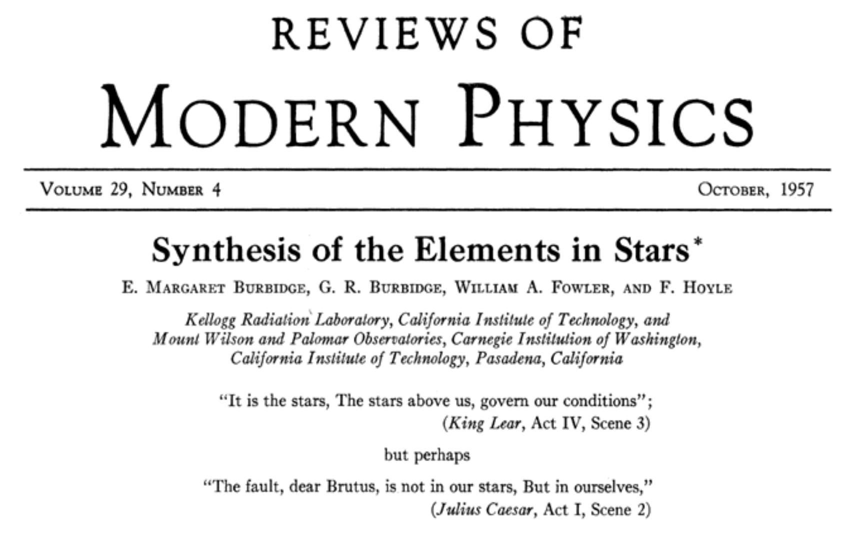


Physikalische Zeitschrift **39**, 633–46, 1938

CNO-cycle

Bethe-Weizsäcker cycle

B^2FH



REVIEWS OF
MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

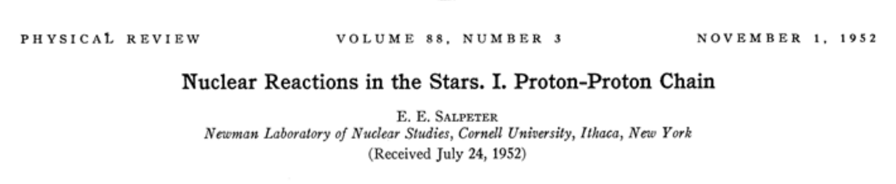
Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)

Also before 1957: Several publications by E.E. Salpeter, W.A. Fowler and others

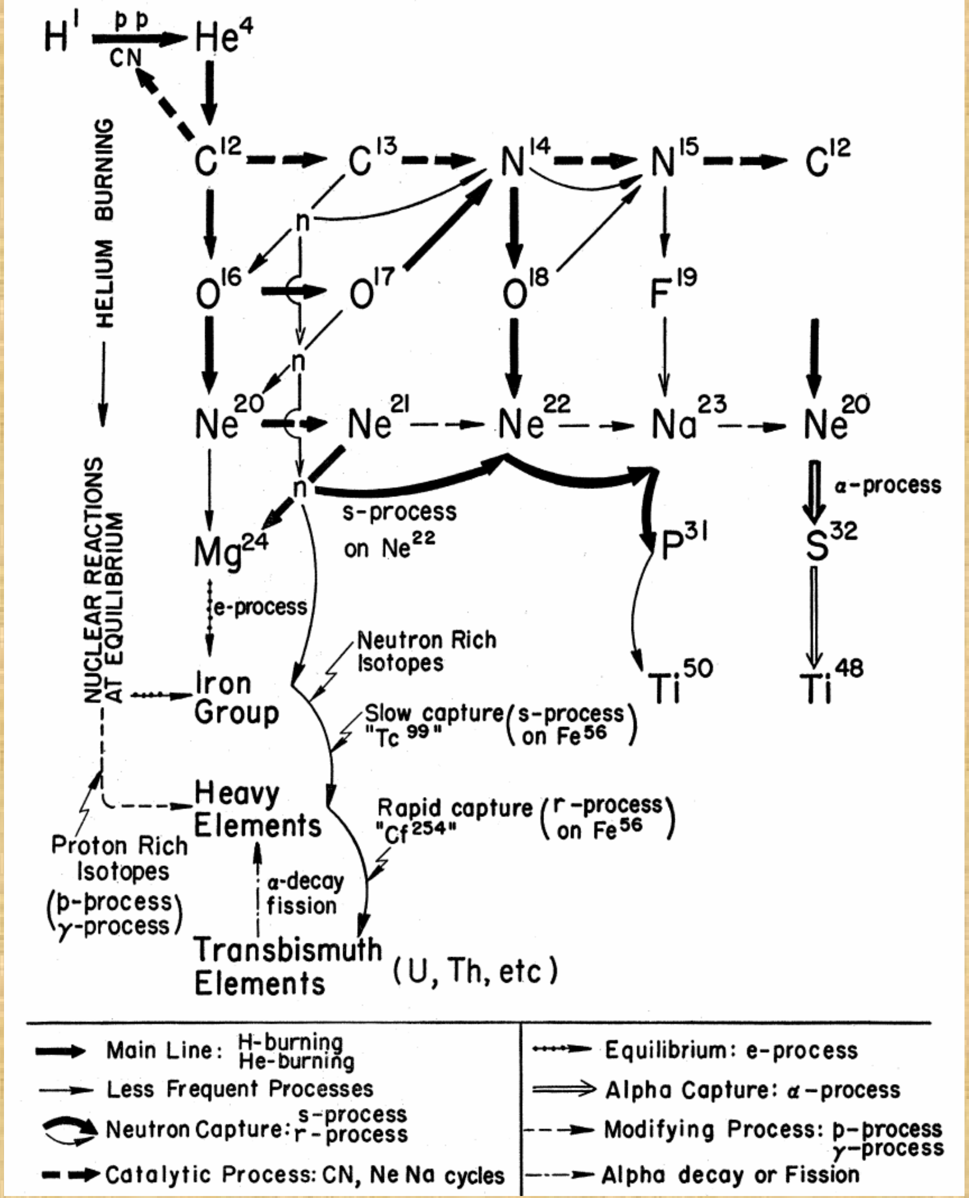


PHYSICAL REVIEW VOLUME 88, NUMBER 3 NOVEMBER 1, 1952

Nuclear Reactions in the Stars. I. Proton-Proton Chain

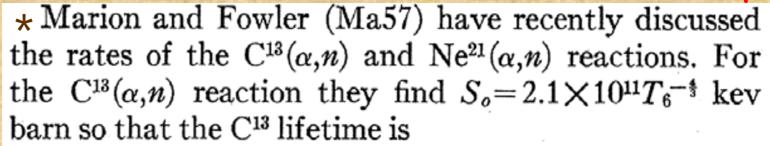
E. E. SALPETER
Newman Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

(Received July 24, 1952)

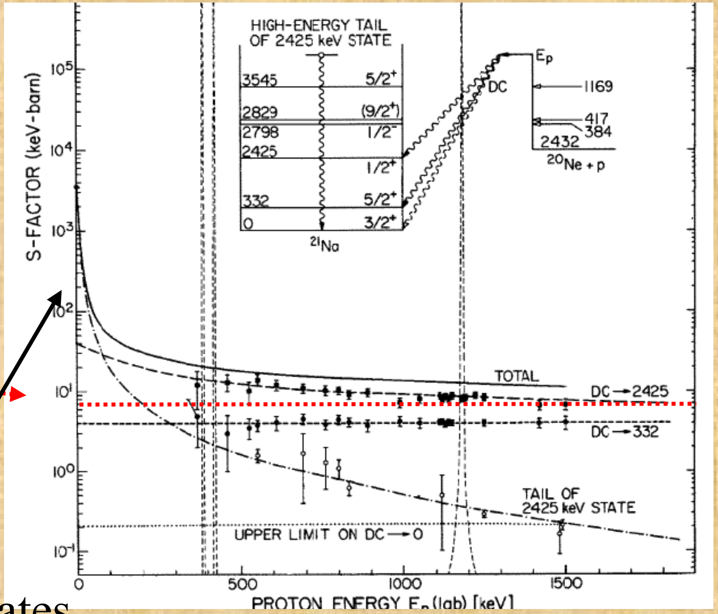


How does B2FH compares to today?

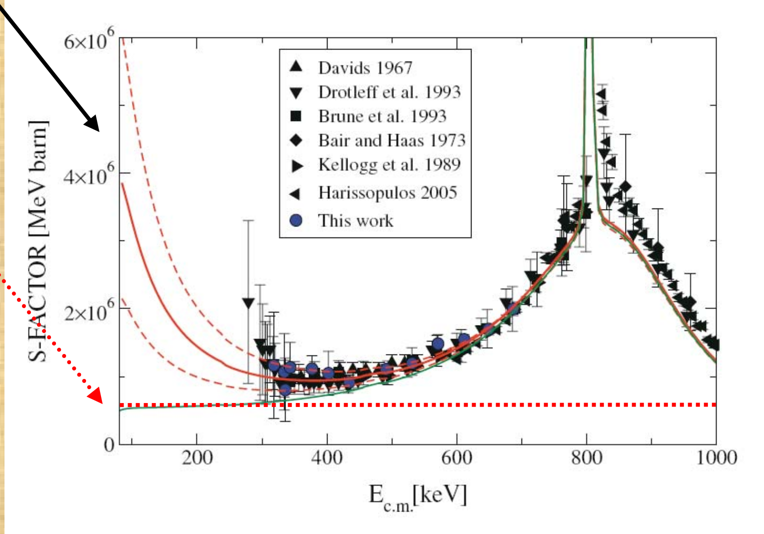
	B^2FH	now
$^{12}C(p,\gamma)$	$S = 1.2 \pm 0.2$	1.6 ± 0.3
$^{14}N(p,\gamma)$	$S = 3.0 \pm 0.6$	1.7 ± 0.1
$^{20}Ne(p,\gamma)$	$S \approx 7$	
$^{12}C(\alpha,\gamma)$	$S_{300} = 345$	150 ± 50
$^{13}C(\alpha,n)$	$S_{190} = 5 \cdot 10^{5*}$	



* Marion and Fowler (Ma57) have recently discussed the rates of the $C^{13}(\alpha,n)$ and $Ne^{21}(\alpha,n)$ reactions. For the $C^{13}(\alpha,n)$ reaction they find $S_o = 2.1 \times 10^{11} T_6^{-\frac{4}{3}}$ kev barn so that the C^{13} lifetime is

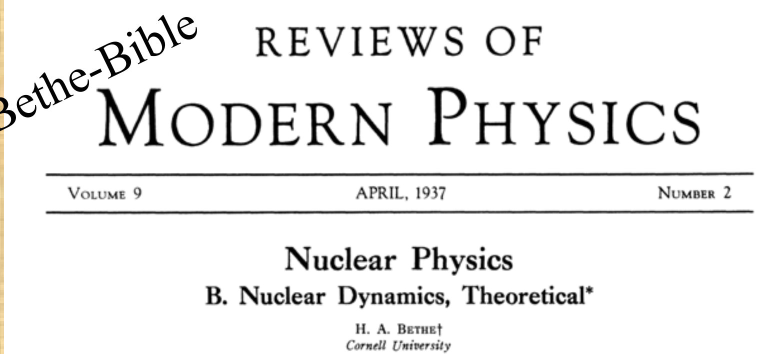


Sub-threshold states



Extrapolation of cross section to energies of interest requires detailed knowledge of nuclear structure !!

Astrophysical S-factor



Bethe-Bible

REVIEWS OF

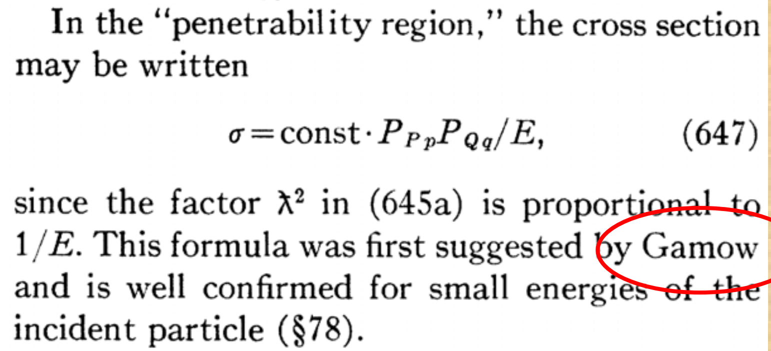
MODERN PHYSICS

VOLUME 9 APRIL, 1937 NUMBER 2

Nuclear Physics

B. Nuclear Dynamics, Theoretical*

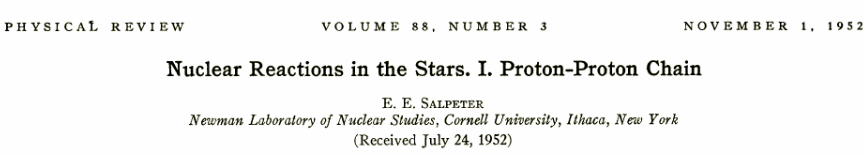
H. A. BETHE†
Cornell University



In the "penetrability region," the cross section may be written

$$\sigma = \text{const} \cdot P_{Pp} P_{Qq} / E, \qquad (647)$$

since the factor $\lambda\!\!\!^{-2}$ in (645a) is proportional to $1/E$. This formula was first suggested by Gamow and is well confirmed for small energies of the incident particle (§78).



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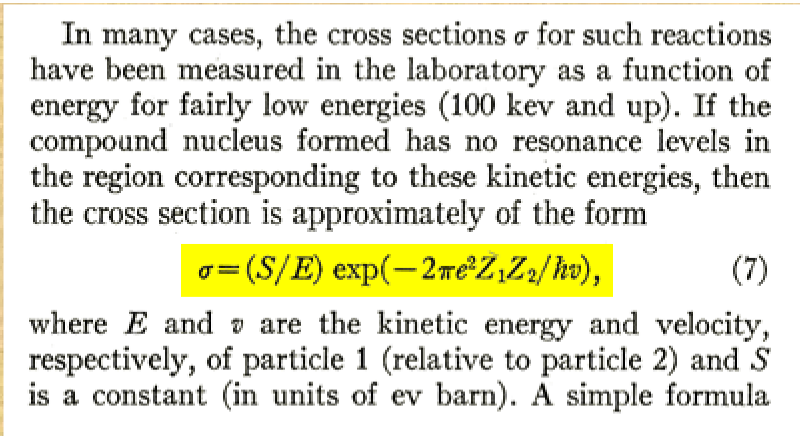
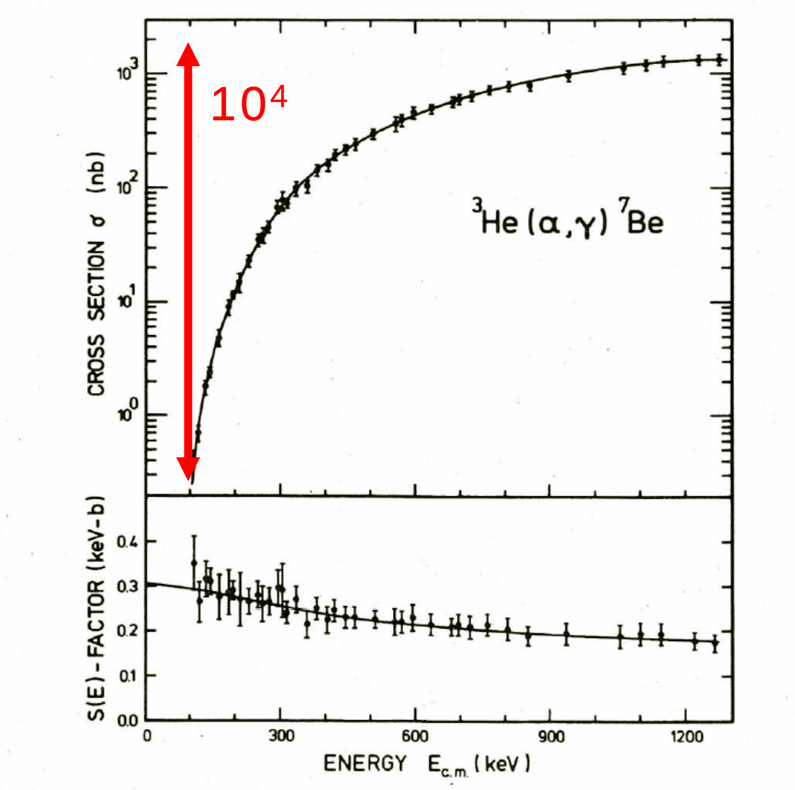


In many cases, the cross sections σ for such reactions have been measured in the laboratory as a function of energy for fairly low energies (100 kev and up). If the compound nucleus formed has no resonance levels in the region corresponding to these kinetic energies, then the cross section is approximately of the form

$$\sigma = (S/E) \exp(-2\pi e^2 Z_1 Z_2 / hv), \qquad (7)$$

where E and v are the kinetic energy and velocity, respectively, of particle 1 (relative to particle 2) and S is a constant (in units of ev barn). A simple formula



$$\sigma(E) \propto \pi \lambda\!\!\!^{-2} \propto \frac{1}{E} .$$

DeBroglie
Wave Length

energy dependencies
of nuclear cross sections

$$\sigma(E) \propto \exp(-2\pi\eta) .$$

SommerfeldParameter

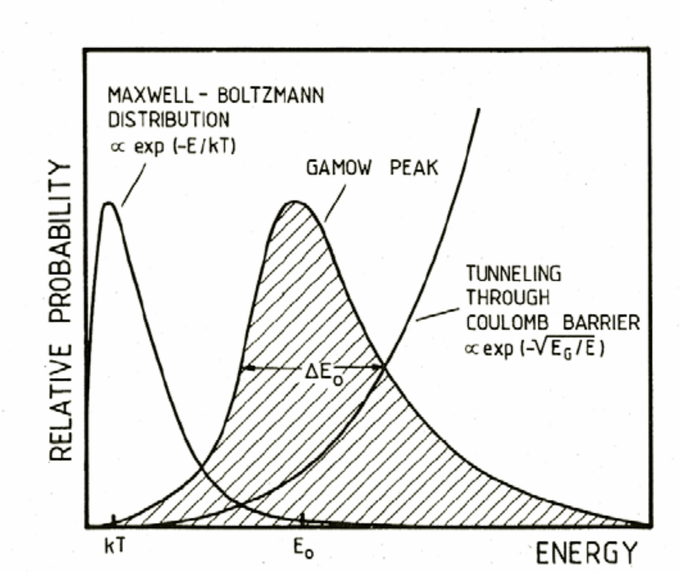
$$2\pi\eta = 31.29 Z_1 Z_2 \left(\frac{\mu}{E}\right)^{1/2}$$

Reaction Rates

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty S(E) \exp\left[-\frac{E}{kT} - \frac{b}{E^{1/2}}\right] dE$$

nonresonant reaction

S(E) ≈ constant



Gamow Peak

resonant reaction

S(E) ≈ Breit-Wigner

Resonance Strength:

$$\omega\gamma = \omega \frac{\Gamma_a \Gamma_b}{\Gamma} .$$

!

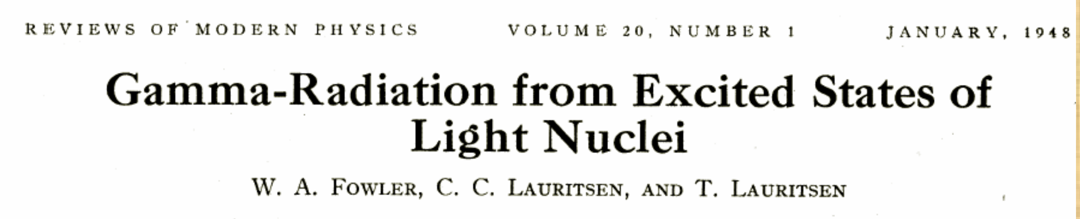
$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar^2 (\omega\gamma)_R \exp\left(-\frac{E_R}{kT}\right)$$

$\Gamma_p(E << E_C) \sim \exp(-k \cdot E_R^{-1/2})$!

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

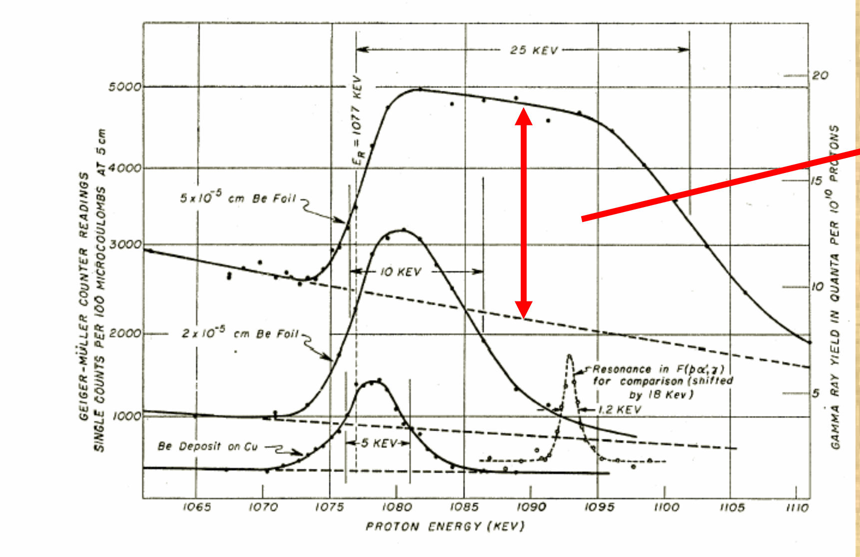
Gamma-Radiation from Excited States of Light Nuclei

W. A. FOWLER, C. C. LAURITSEN, AND T. LAURITSEN

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

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

$\Gamma<<\xi$

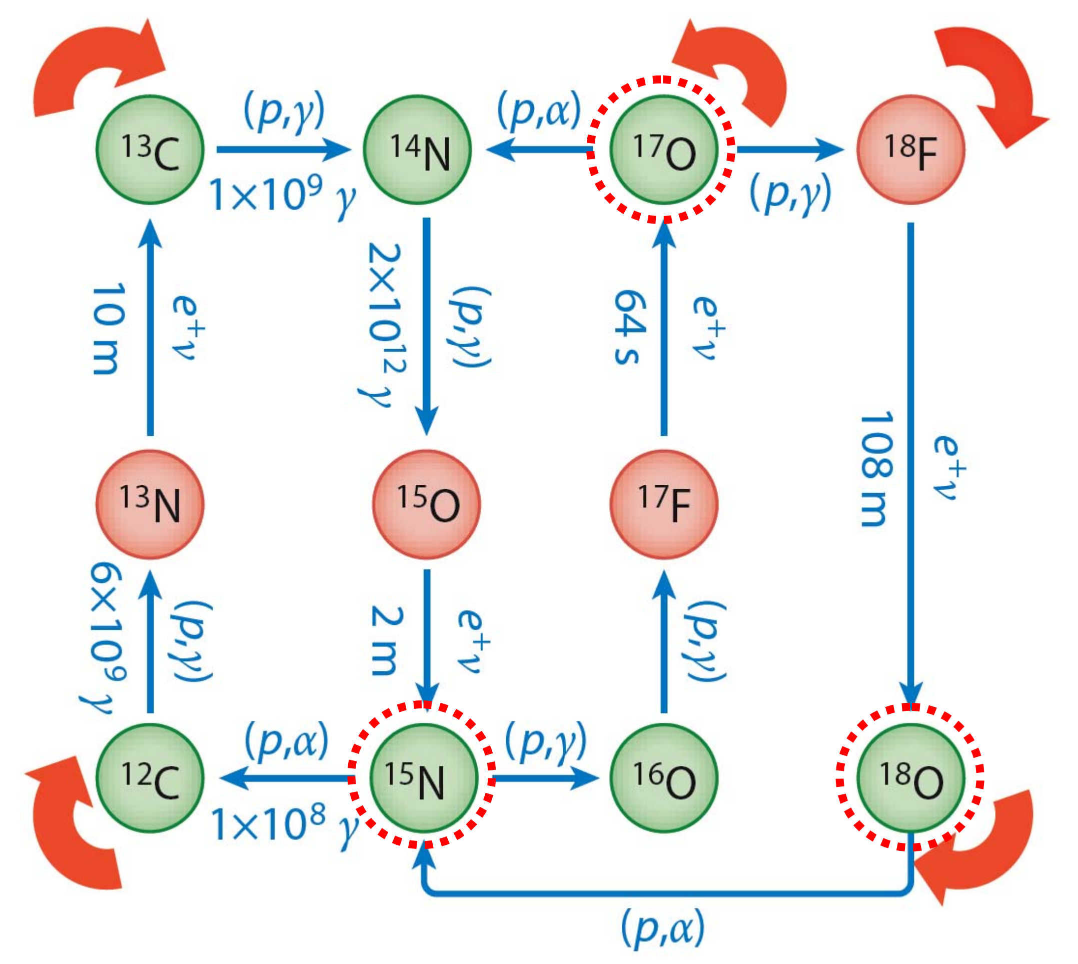


$$Y_{\max}(\infty)=\frac{\pi}{2}\frac{\sigma_R\Gamma}{\epsilon}=\frac{\lambda^2}{2\varepsilon}\,\omega\gamma$$

$\varepsilon = \varepsilon_a + (i/a)\,\varepsilon_i$ (in cm-system!)

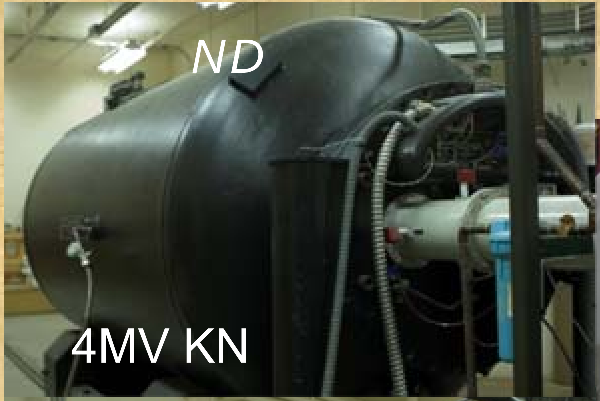
Target = $A_a I_i$

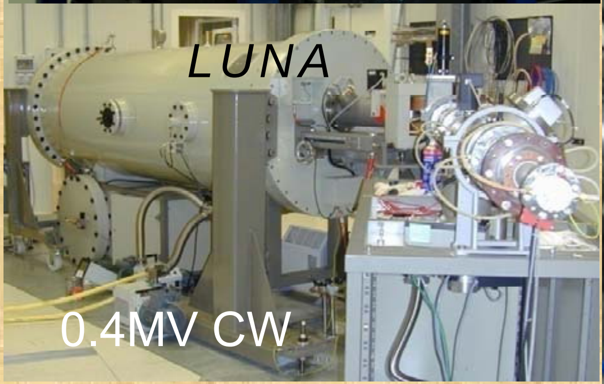
Cold CNO Cycle T < 0.2 GK

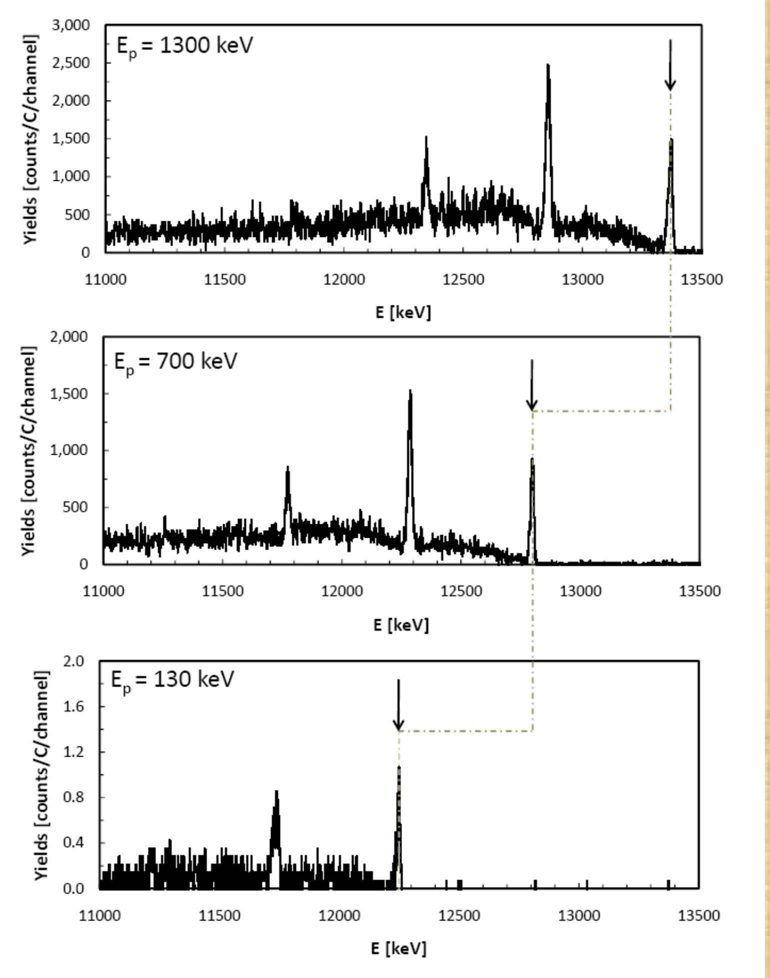


branching point

Measurements of $^{15}N(p,\gamma)^{16}O$

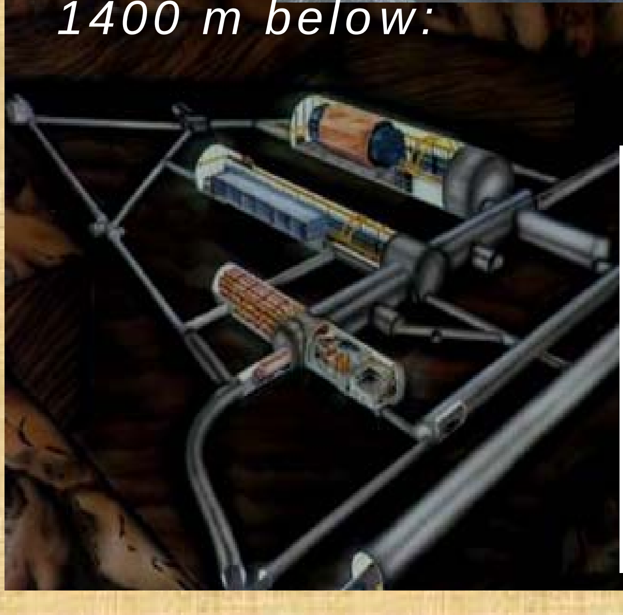




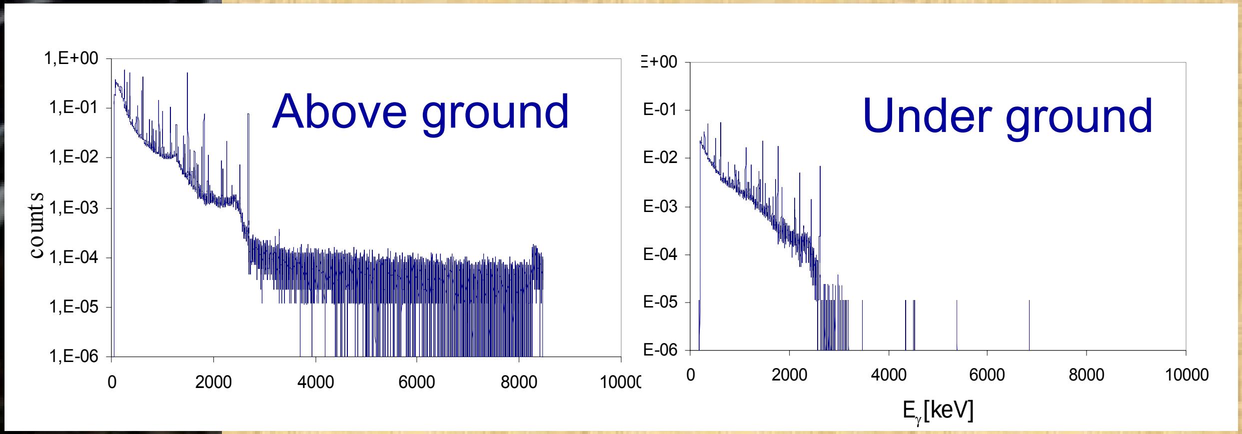


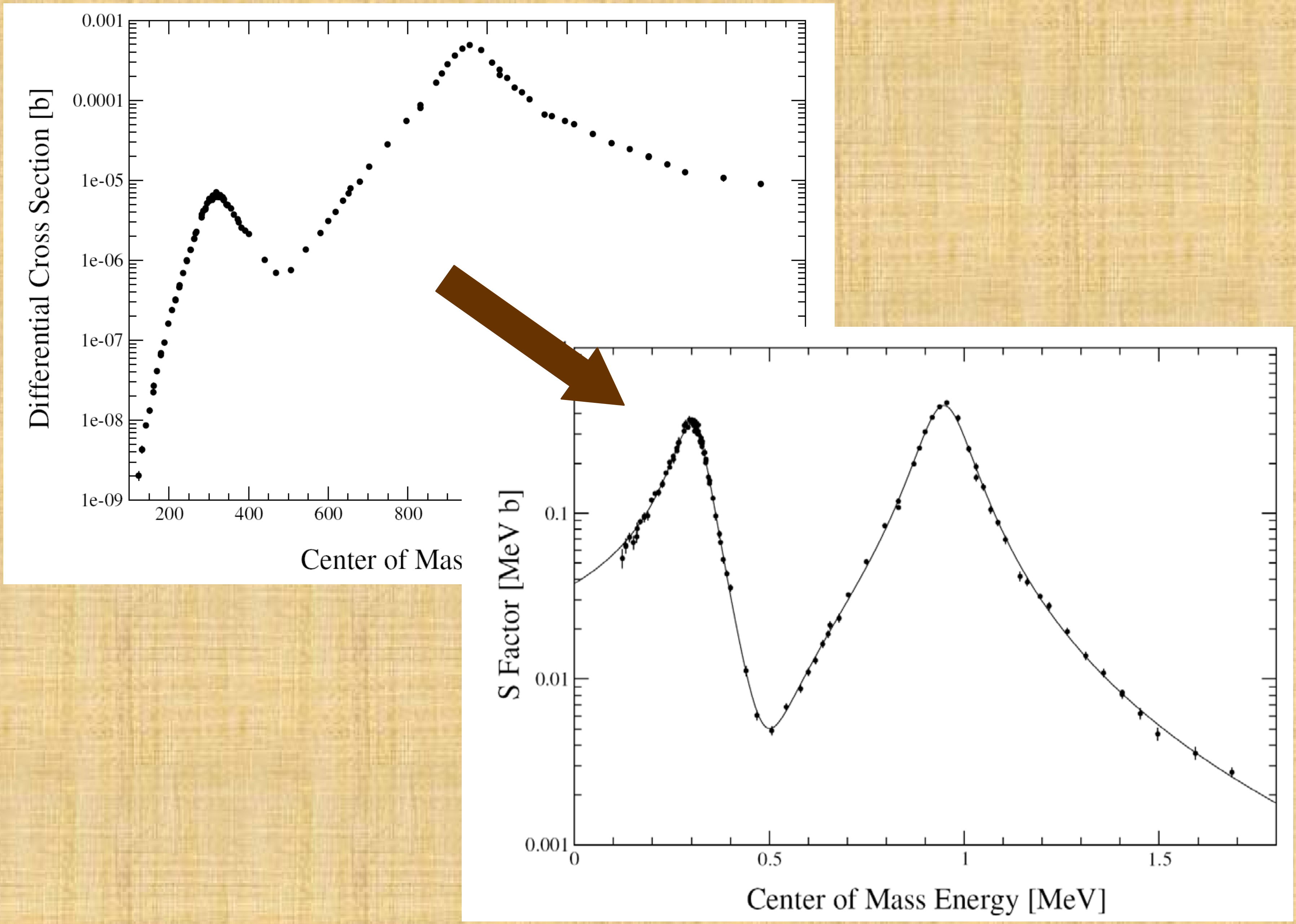
Gran Sasso (elev. 2912m)

1400 m below:



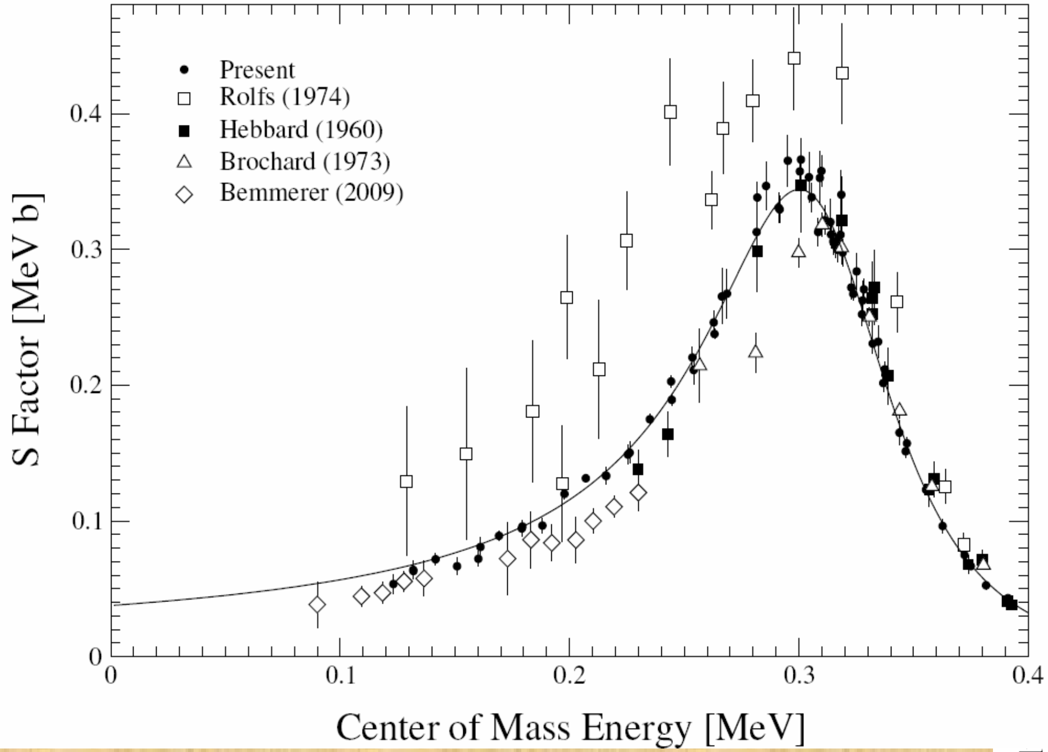
Notre Dame (elev. 212m)

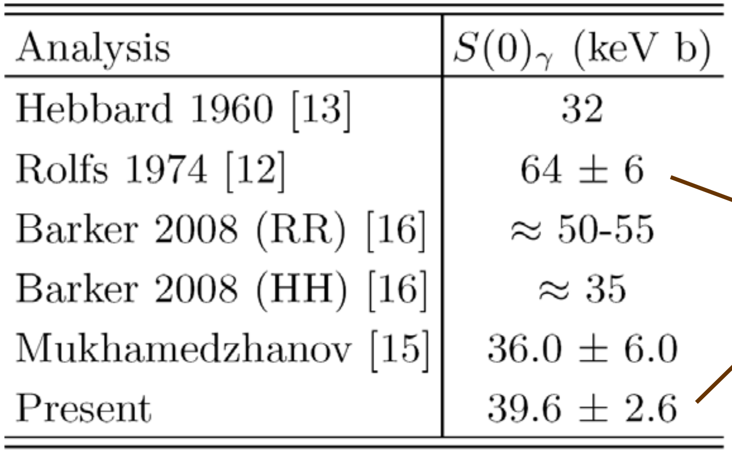



0.001
0.0001
1e-05
1e-06
1e-07
1e-08
1e-09
Differential Cross Section [b]
200
400
600
800
Center of Mas
0.1
0.01
0.001
S Factor [MeV b]
0
0.5
1
1.5
Center of Mass Energy [MeV]

Final Result

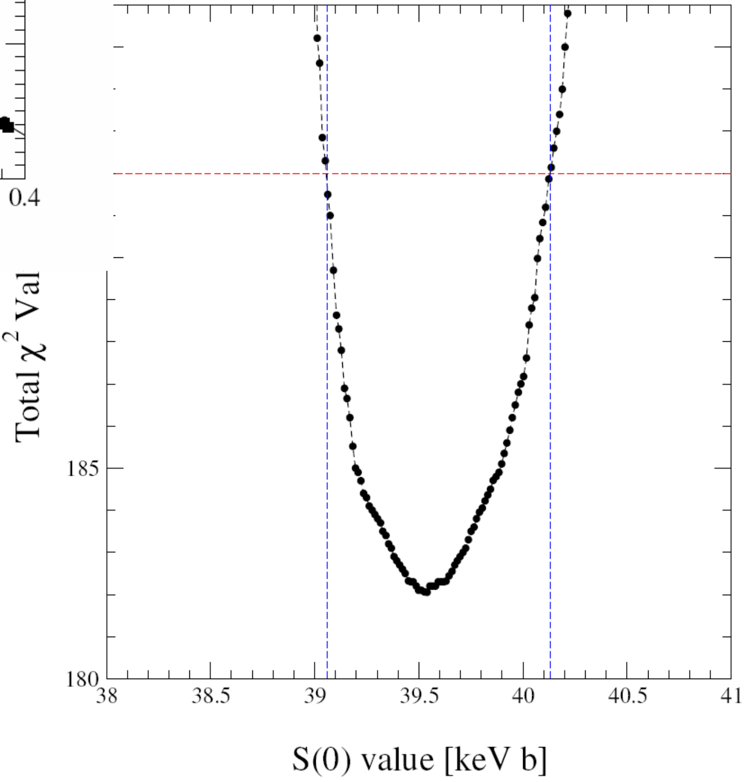
-well constraint by
large energy range



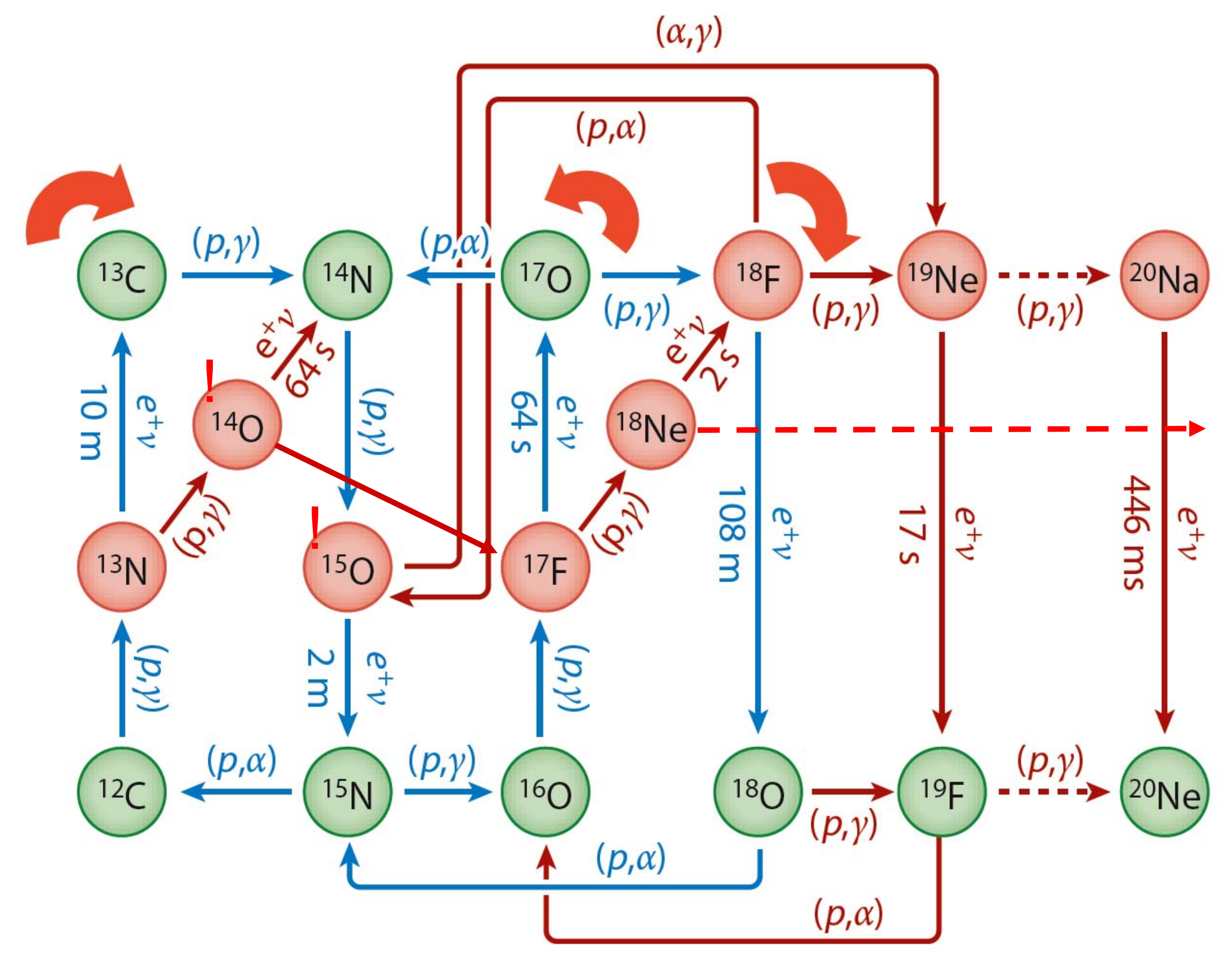


Analysis	$S(0)_\gamma$ (keV b)
Hebbard 1960 [13]	32
Rolfs 1974 [12]	64 ± 6
Barker 2008 (RR) [16]	≈ 50-55
Barker 2008 (HH) [16]	≈ 35
Mukhamedzhanov [15]	36.0 ± 6.0
Present	39.6 ± 2.6

!



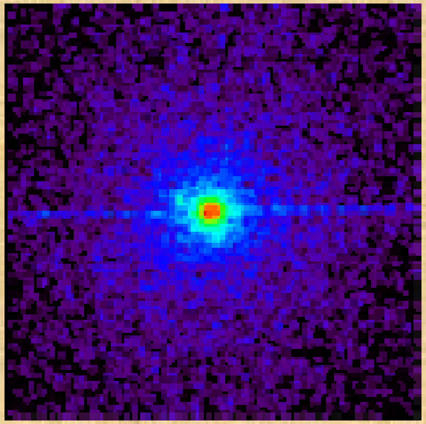
Hot CNO Cycles T > 0.2 GK



Breakout at T > 0.4

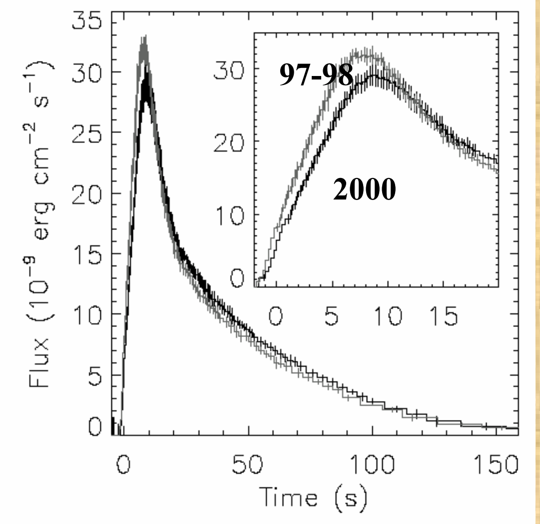
The nuclear trigger of X-ray Bursts

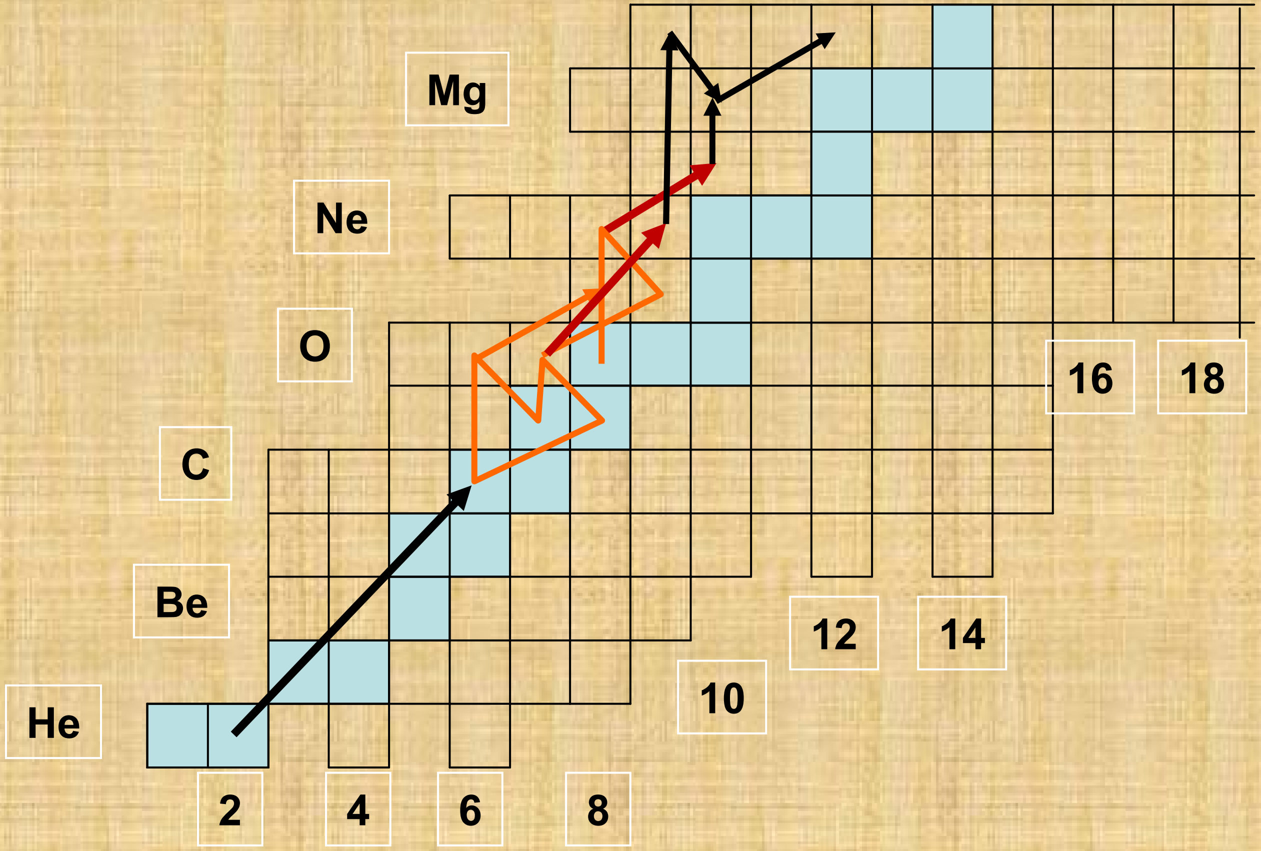
break-out from HCNO cycles: $^{15}O(\alpha,\gamma)^{19}Ne$, $^{18}Ne(\alpha,p)^{21}Na$



Interplay of:
- -CNO feeding by 3α
- -CNO breakout
- -H left after burst

bursts are not
the same





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

- Reaction Rate

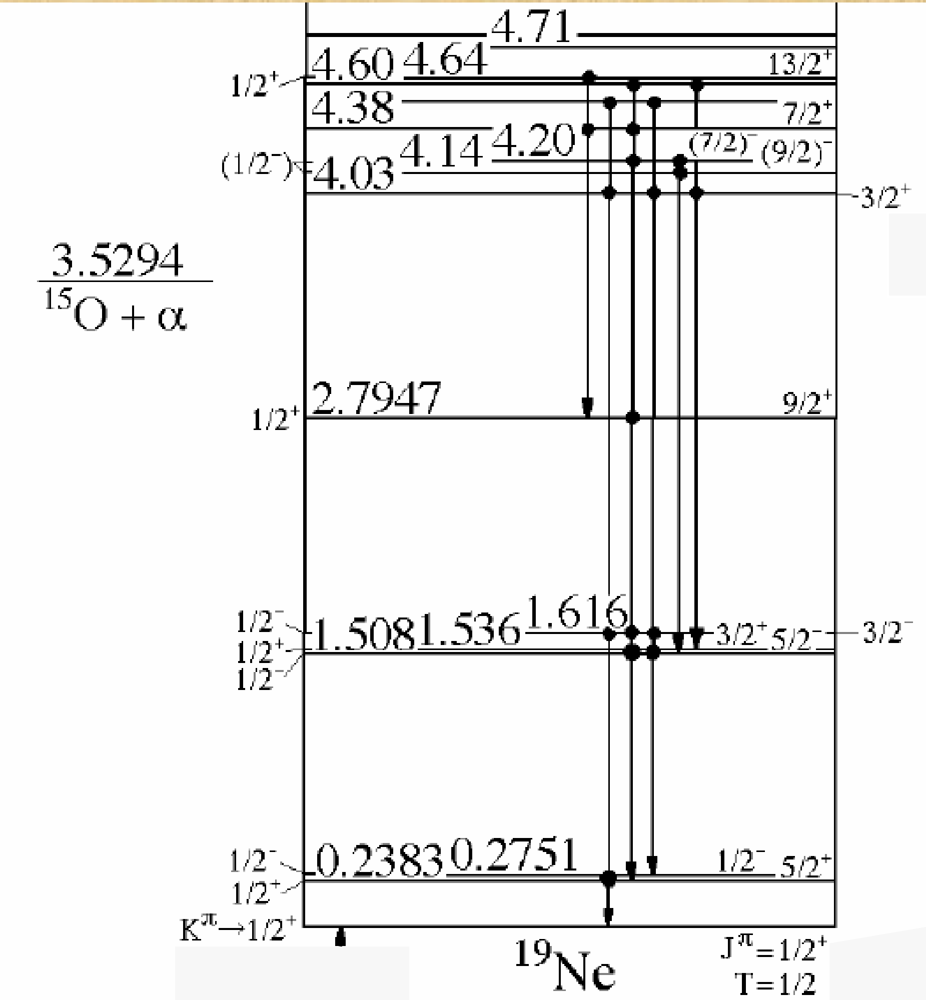
$$N_A < \sigma v > \propto T^{-3/2}\, \omega\gamma\, e^{-E_R/kT}$$

determined by resonance energy E_R and strength $\omega\gamma$

where $$\omega\gamma = \frac{2J_R + 1}{(2J_P + 1)(2J_T + 1)} B_\alpha \Gamma_\gamma$$

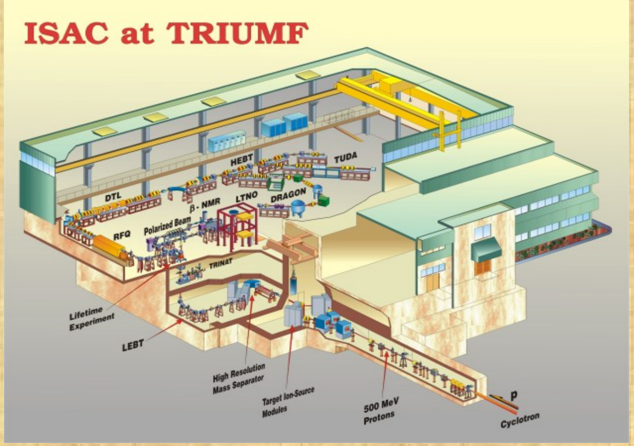
- Three measurable quantities characterize the resonance strength:

J, Γ_γ, and B_α

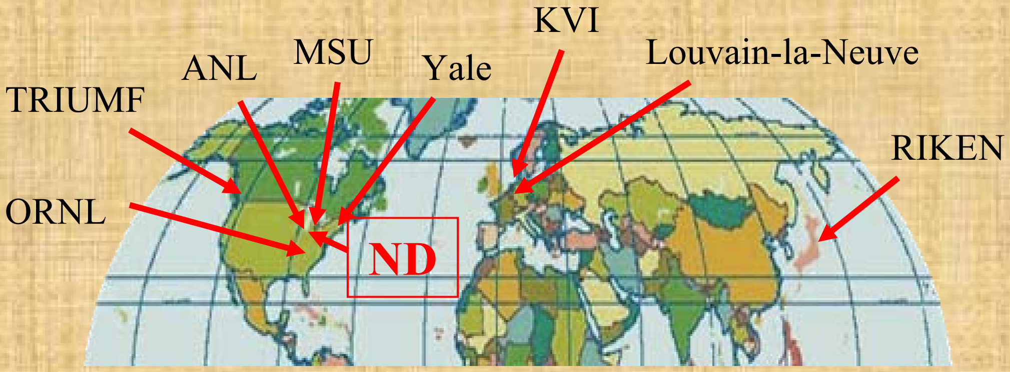


What experimentalists need to do for ^{15}O(α , γ)^{19}Ne

- Direct measurement is difficult!
  - An intense (10^{11} /s) radioactive ^{15}O beam gives a count rate of <1/hr (estimated at ISAC, TRIUMF)



$$\begin{aligned}\omega\gamma &= \frac{2J_R+1}{(2J_P+1)(2J_T+1)}\cdot\frac{\Gamma_\alpha\cdot\Gamma_\gamma}{\Gamma}\\ &\sim B_\alpha\Gamma_\gamma\\ &\sim Y(^{19}Ne)\end{aligned}$$



KVI

MSU

ANL

Yale

Louvain-la-Neuve

TRIUMF

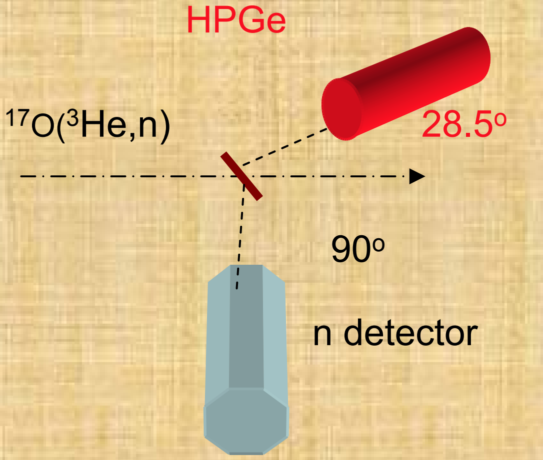
RIKEN

ORNL

ND

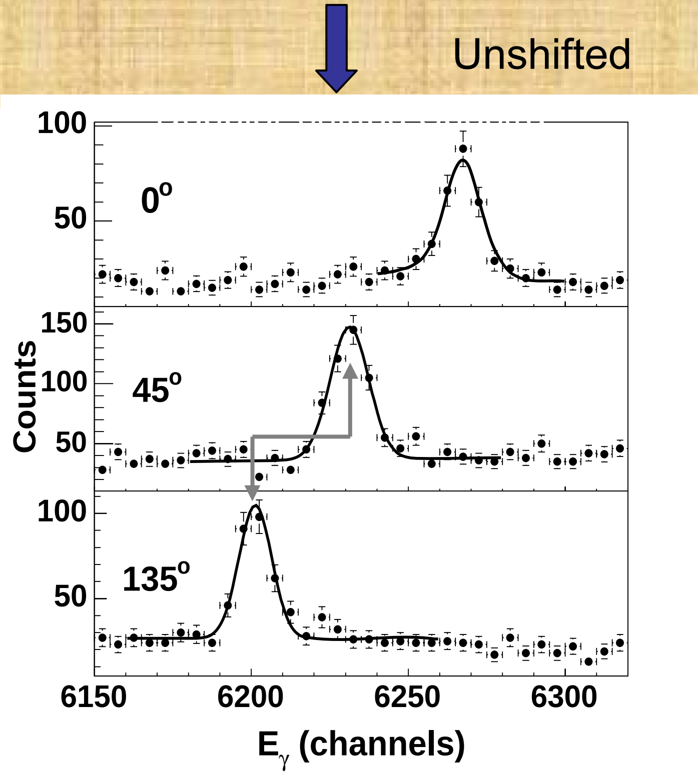
- Indirect method has been approached many times!
  - Populate α -unbound states in ^{19}Ne
  - Measure lifetimes or gamma widths ^{17}O(^{3}He,n- γ)^{19}Ne
  - Measure α -decay branching ratios B_α ^{19}F(^{3}He,t- α)^{19}Ne

“Indirect” approach: lifetime



$$E_\gamma = E_{\gamma_0}(1 + F(\tau)\beta\cos\theta)$$

$E_x = 4034.5 \pm 0.8$ keV



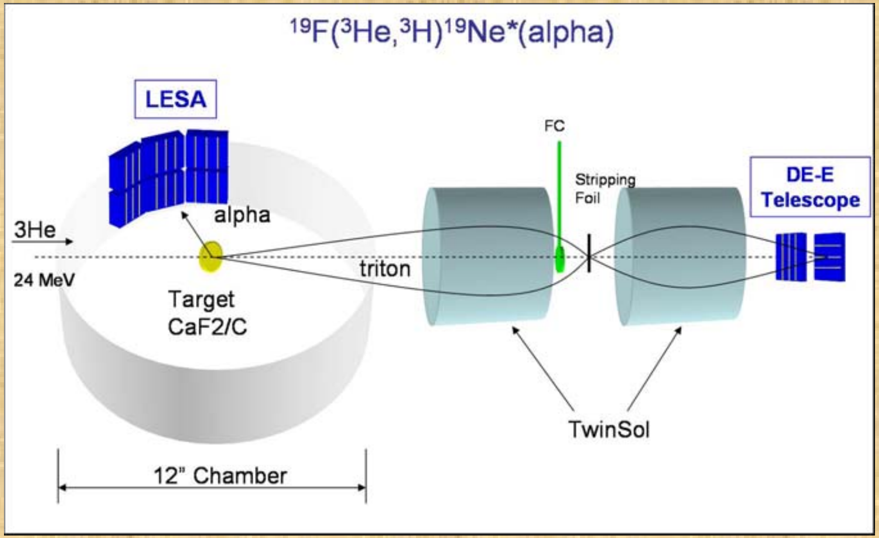
Measured lifetime $\tau = 13 \pm^{9}_{6}$ fs
or $\Gamma = 51 \pm^{43}_{21}$ meV

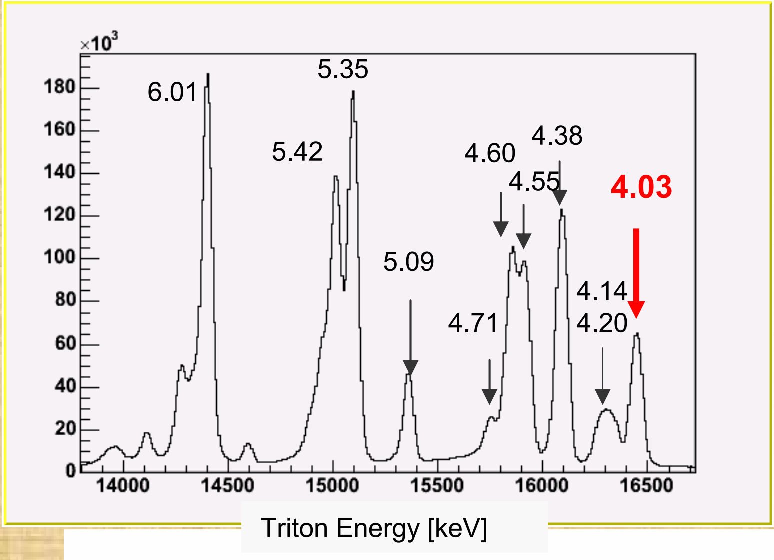
TRIUMF 2006 $\tau = 11 \pm^{8}_{7}$
fs

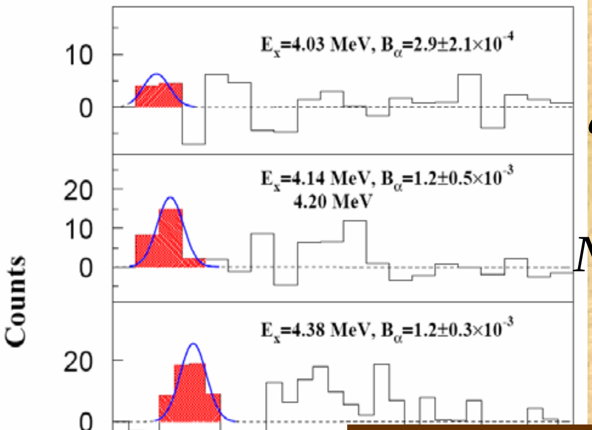
or $\Gamma = 60 \pm^{40}_{25}$ meV

LWEG86: Γ=73 meV

“Indirect” approach: branching ratio B



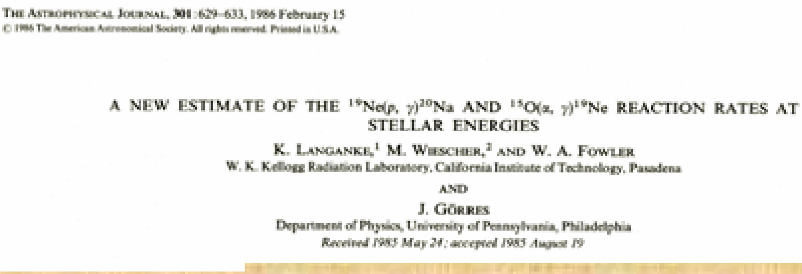




$$\omega\gamma = \frac{2J_R + 1}{(2J_P + 1)(2J_T + 1)} B_\alpha \Gamma_\gamma$$

$$N_A < \sigma v > \propto T^{-3/2}\ \omega\gamma\, e^{-E_R/kT}$$

After 20+ years



THE ASTROPHYSICAL JOURNAL, 301:629–633, 1986 February 15

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A NEW ESTIMATE OF THE $^{19}Ne(p, \gamma)^{20}Na$ AND $^{15}O(\alpha, \gamma)^{19}Ne$ REACTION RATES AT STELLAR ENERGIES

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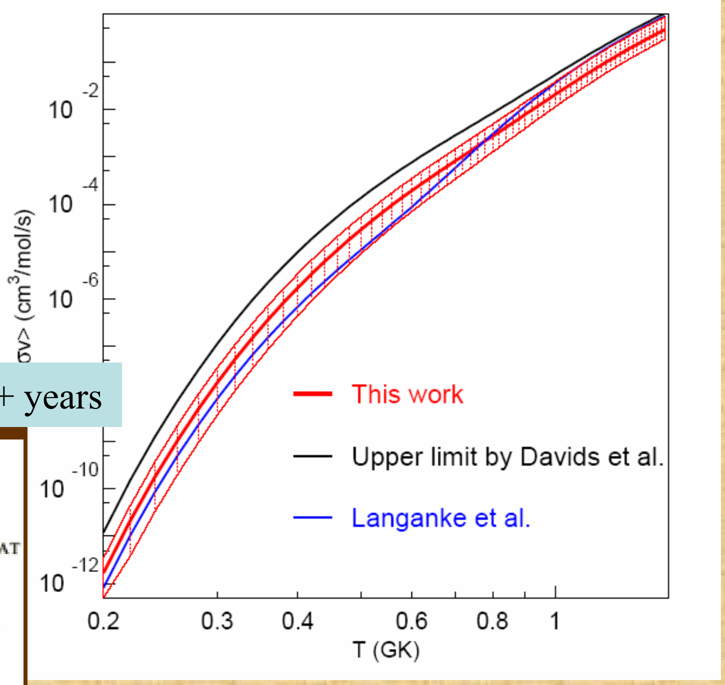


Neutron sources for ~~the~~ s-process

Main Component A>100

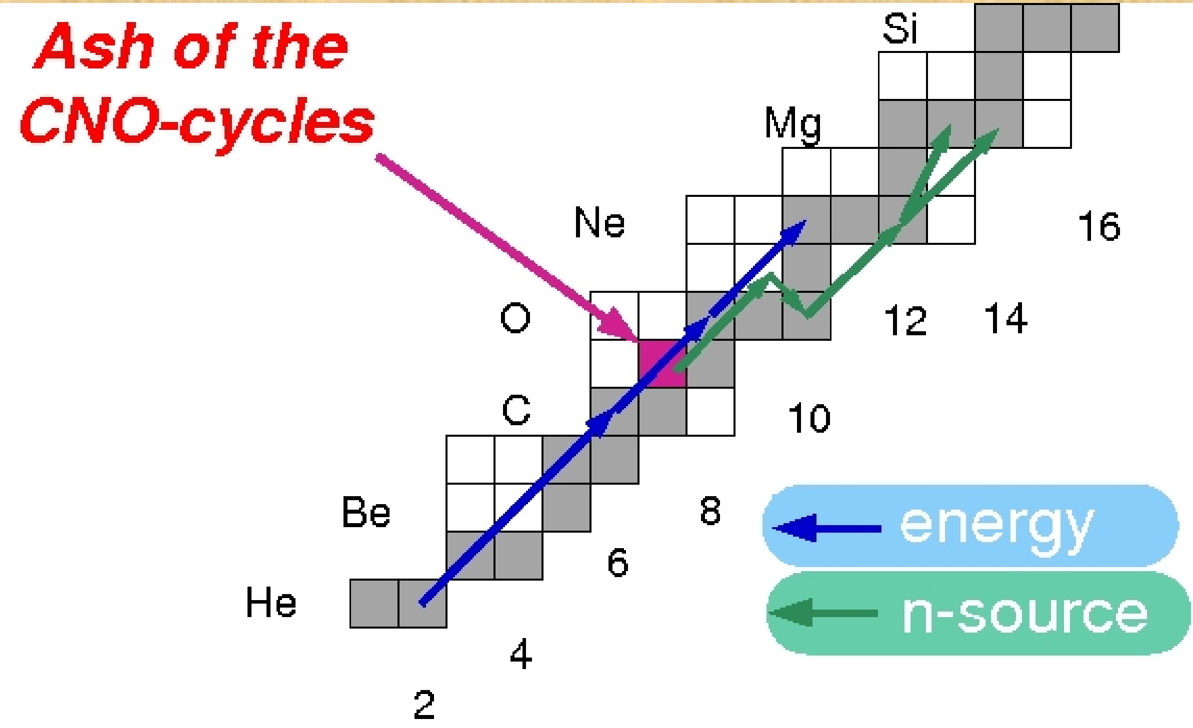
low mass AGB stars
T= 0.1 GK
$N_n \sim 10^7$ /cm^{-3}
s-process at kT=8 keV
Time scale:
a few 10,000 years

Weak Component A< 100

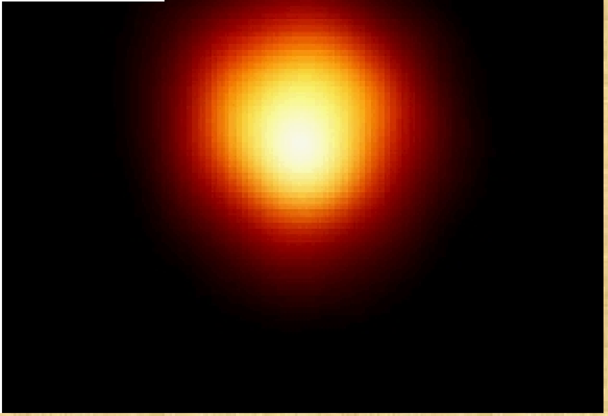
core He burning in massive stars
T=0.3 GK
$N_n \sim 10^6$ /cm^{-3}
s-process at kT=25 KeV
Time scale:
Last few 10,000 years

Shell C burning in massive stars
T=1 GK
$N_n \sim$ up to 10^{12} /cm^{-3}
s-process at kT=90 KeV
Time scale: 1 year
(not the "typical" s-process)

Core Helium Burning

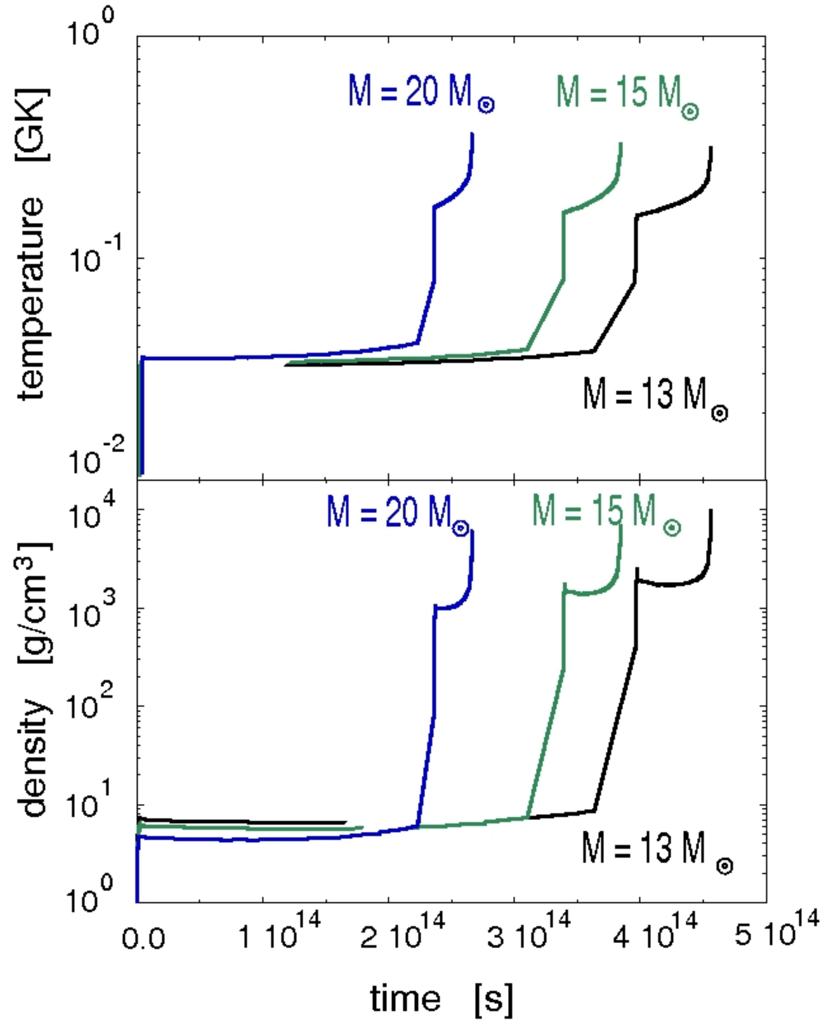


weak component
of s-Process
A<100

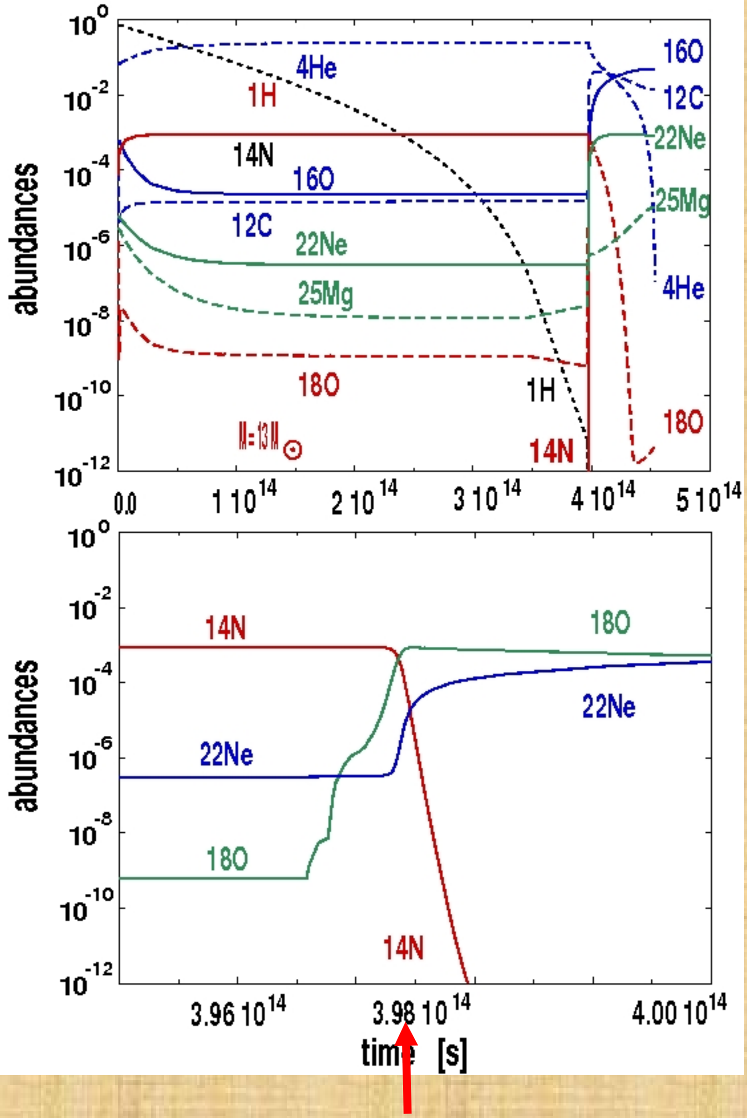


Hubble Space Telescope
Betelgeuse

Simple “1-Zone” Model



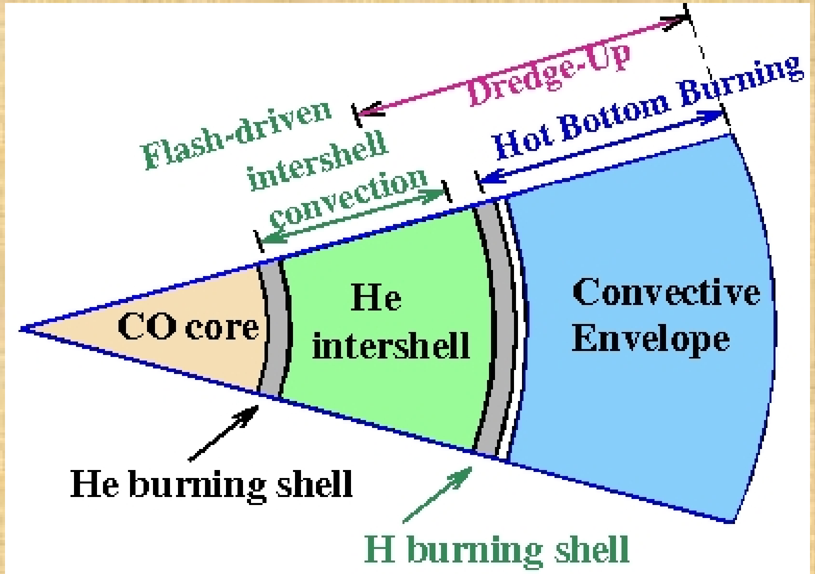
Courtesy Alessandro Chieffi

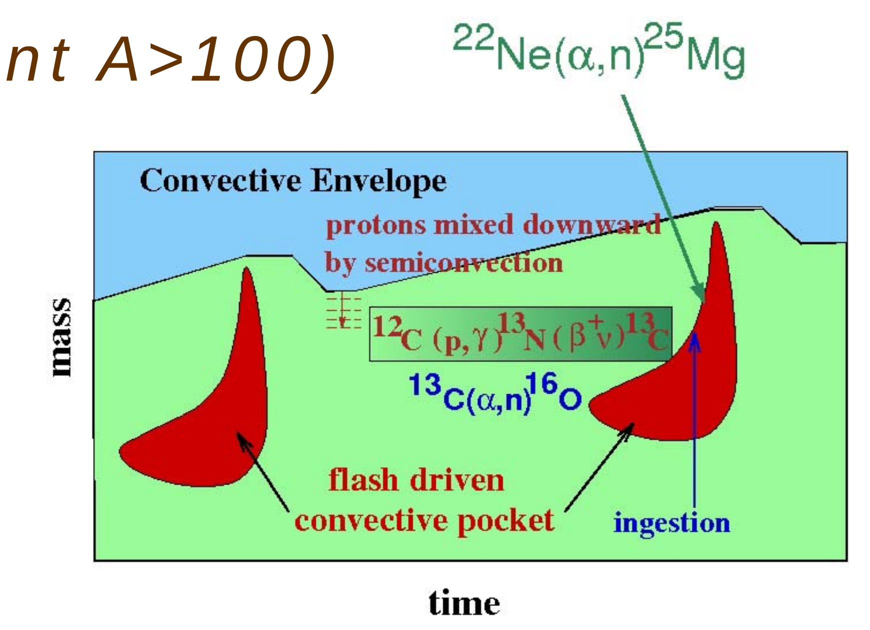


12.6 million years

s-Process (Main Component A>100)

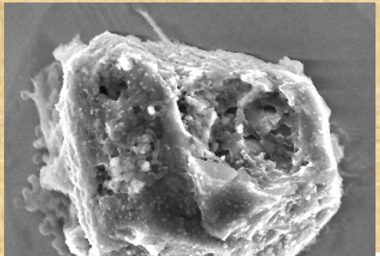
TP-AGB Stars



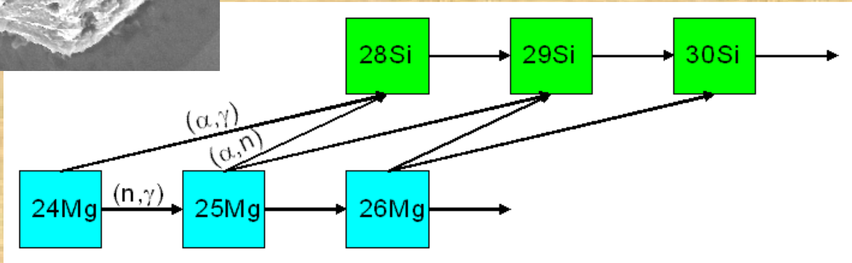


Large Mass Loss ➡ Chemical Evolution

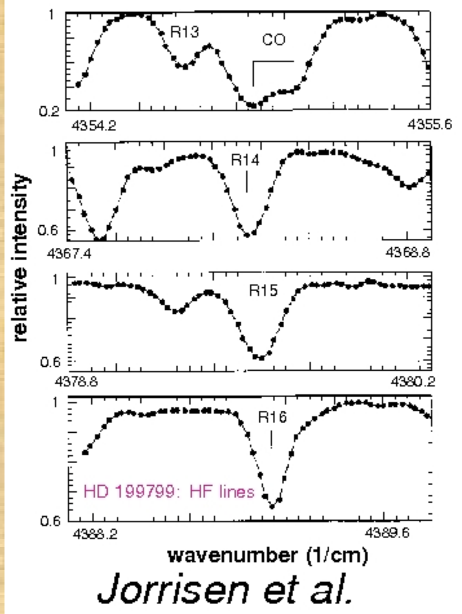
meteorite
inclusions



^{29,30}Si isotope
ratios



Fluorine Lines Observed
On Surface of AGB Star



Jorrisen et al.

Shell Carbon Burning

burns on the ashes of He-Burning
^{12}C, ^{16}O, $^{20,22}Ne$ and $^{25,26}Mg$

main energy source: $^{12}C+^{12}C$

$$^{12}C+^{12}C \begin{cases} ^{20}Ne+\boldsymbol{\alpha} \\ ^{23}Na+\mathbf{p} \end{cases}$$

!

p/α-ratio

main neutron source: $^{22}Ne(\alpha,n)$

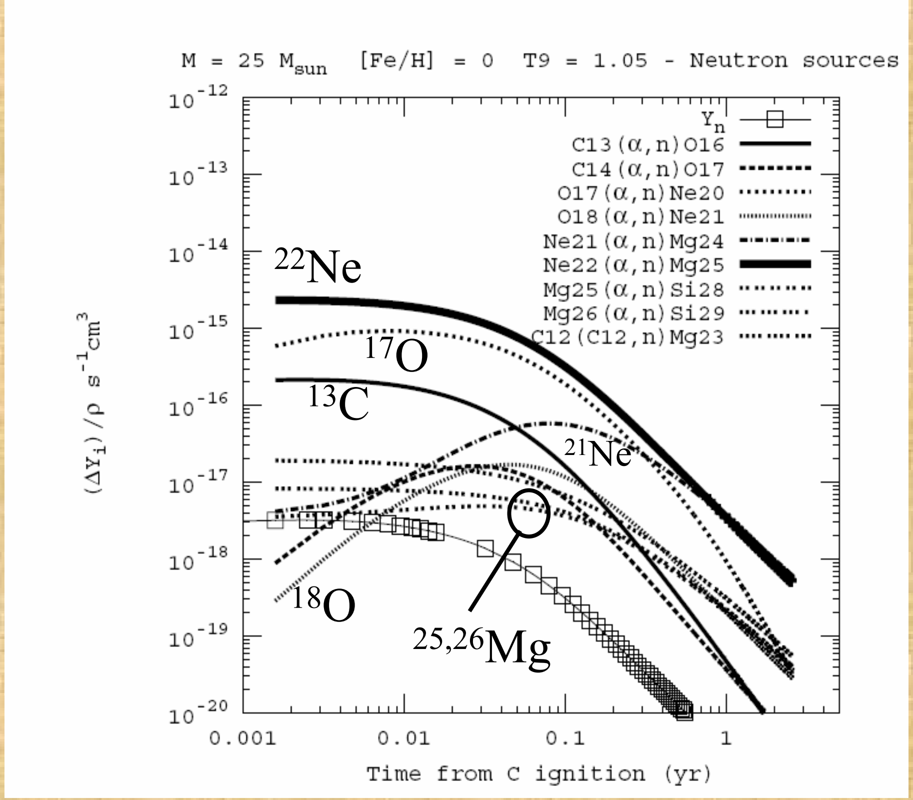
well known at 1GK
residual from He burning
→how much is left at end of He burning?
Small production branch:
$^{20}Ne(p,\gamma)^{21}Na(\beta^{+})^{21}Ne(p,\gamma)^{22}Na(\beta^{+})$

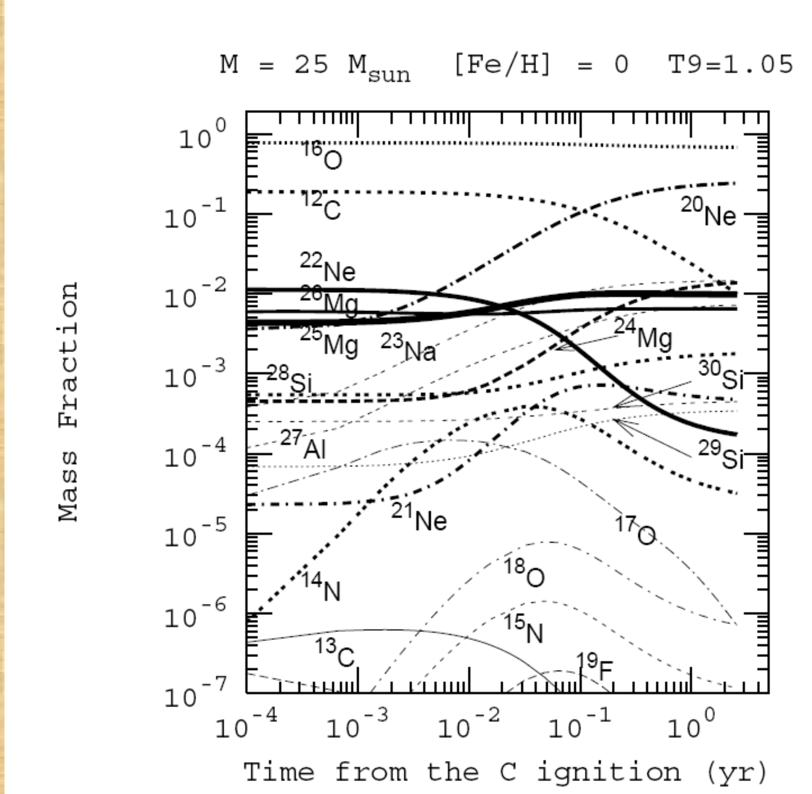
possible neutron source at end of burning: $^{25,26}Mg(\alpha,n)$

Most abundant isotopes at end of burning:
^{16}O, ^{20}Ne, ^{23}Na and ^{24}Mg

Neutron sources (Flux)

Light element nucleosynthesis: $^{16}O, ^{20}Ne, ^{23}Na, ^{24}Mg$





M. Pignatari, PhD Thesis

C shell poisons

Neutron poisons:
^{16}O,^{22}Ne,^{25}Mg,^{26}Mg(n,γ)

but

^{17}O(α,n),(α, γ)

^{17}O(n,α)

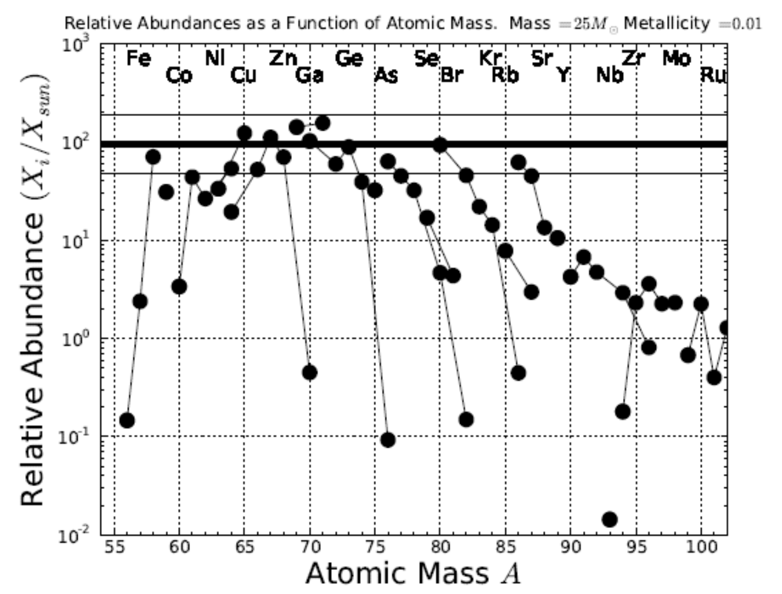
^{17}O(p,α)

(similar for ^{21}Ne)

competition of reaction channels determines neutron recycling efficiency

alpha “poisons”:
^{16}O,^{20}Ne(α,γ),^{22}Ne(α.n)

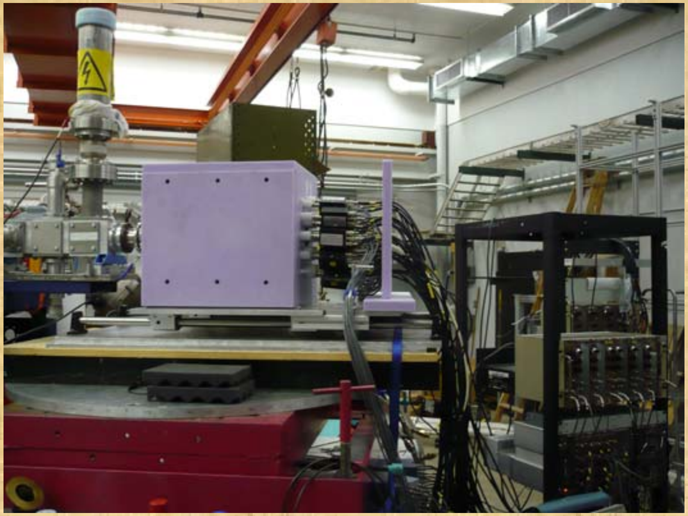
proton “poisons”:
^{17}O,^{23}Na(p,α),
^{22}Ne,^{25}Mg(p,γ)
NOT ^{12}C(p,γ)
(photodissociation!)

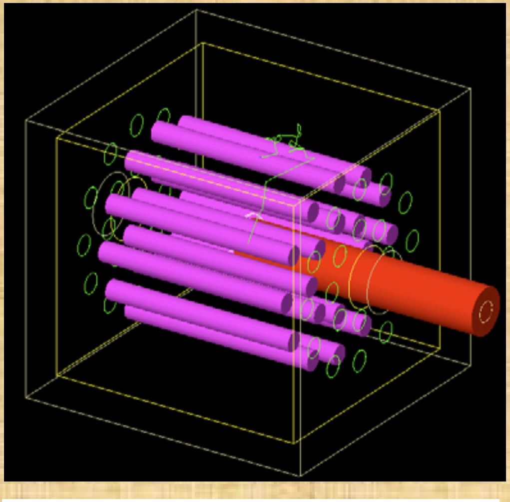


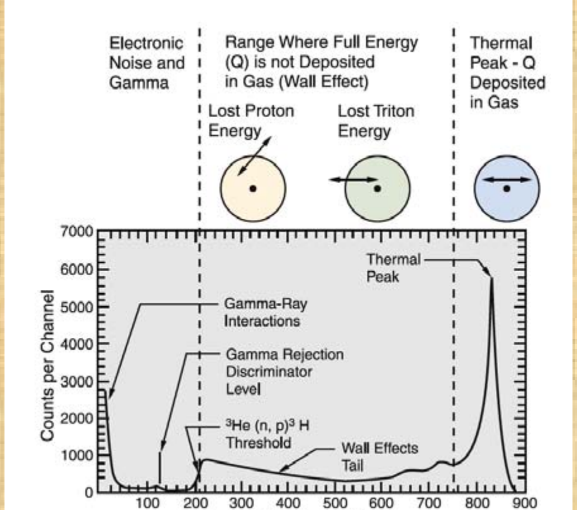
S-process distribution
at the end of the C shell

Pignatari 2009

Experiment at Notre Dame: ^{17}O+alpha







Canberra

^{3}He detector system

-thermalization of neutrons

-^{3}He(n,p) reaction

Q = 764 keV

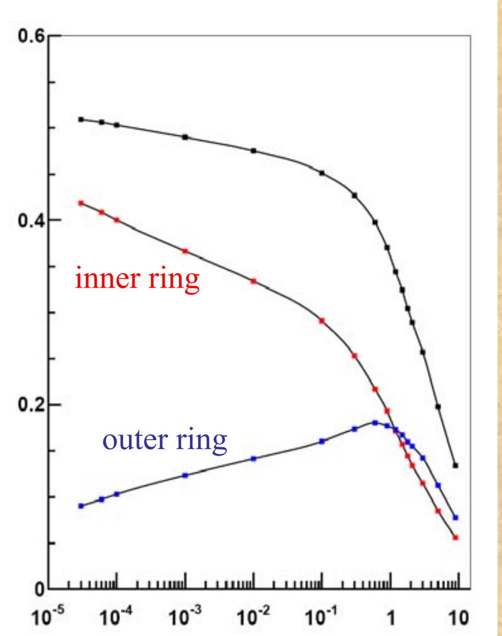
- 8 tubes in inner ring

-12 tubes in outer ring

Target: Ta_2O_5

enriched water >97 %

(17O: $2000/ml)

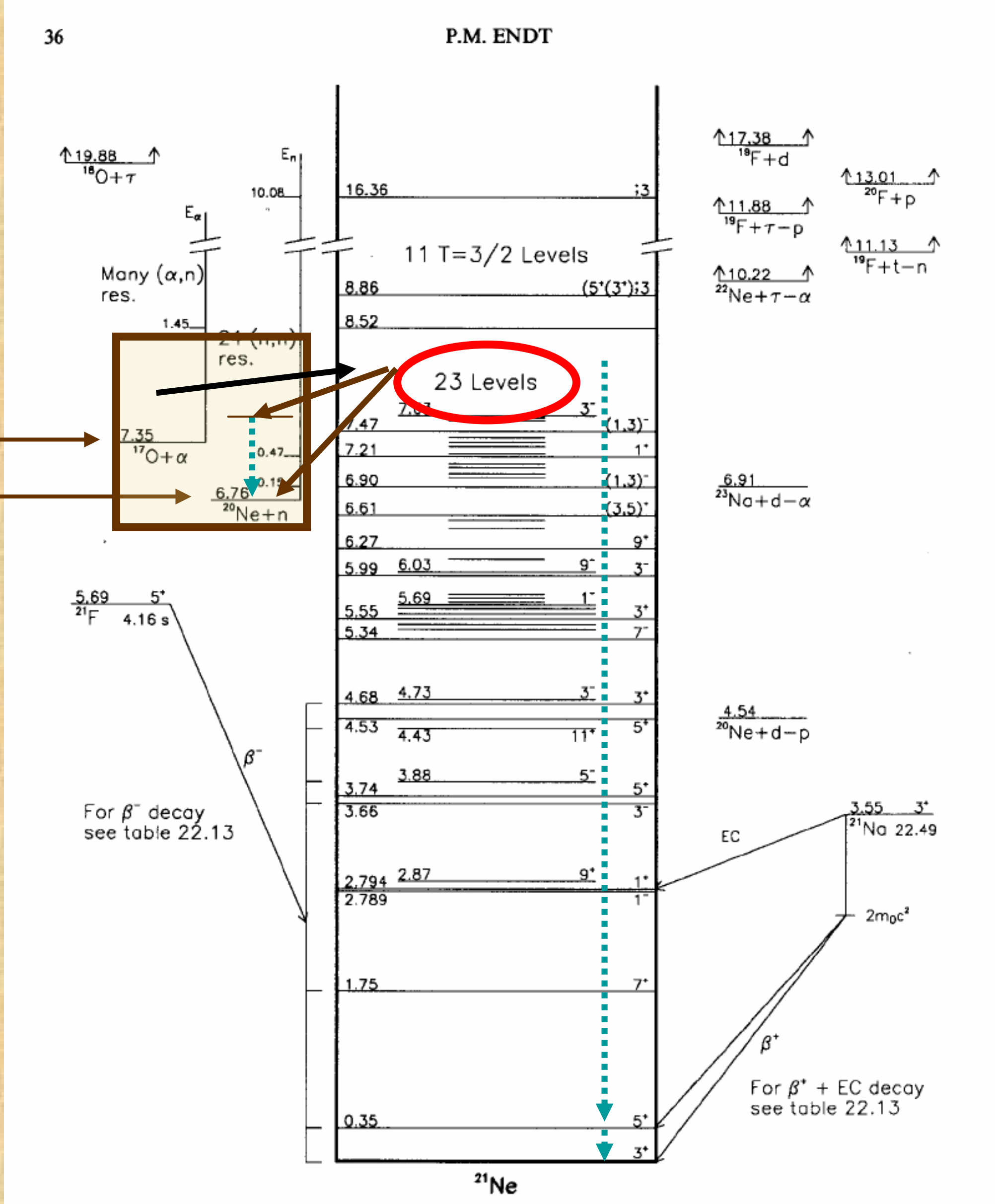


$^{17}O(\alpha,n)^{20}Ne$

Q= 0.59 MeV

S_α =7.35 MeV

S_n =6.76 MeV



Previous work:

Bair and Haas 1973

1.4-5.3 MeV

Anodized Ta:

$^{17}O(15\%)/^{18}O(5\%)$

^{17}O implanted

Denker PhD Thesis 1994

0.8-2.0 MeV

Gas target

$^{17}O(50\%)/^{18}O(29\%)$

gamma

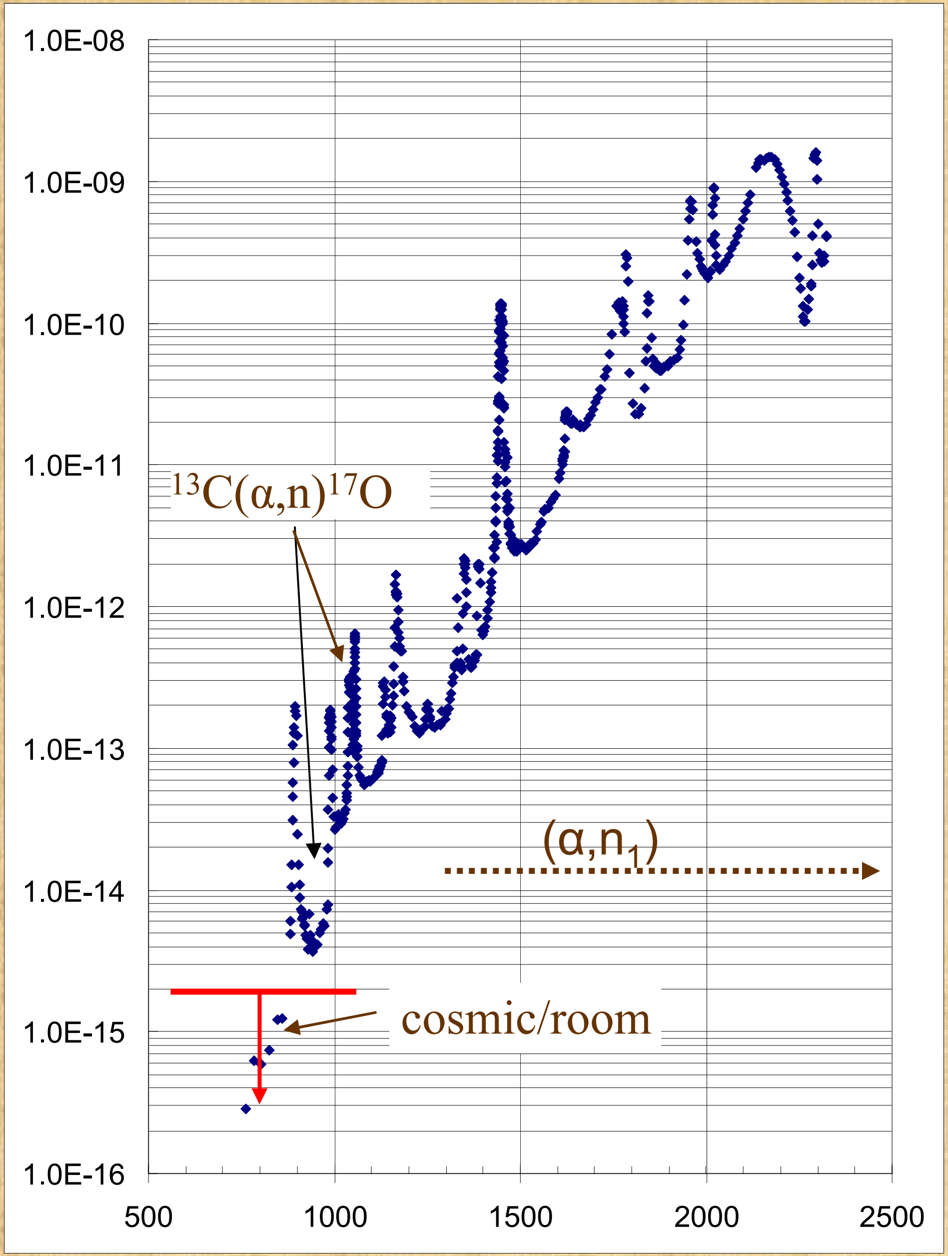
neutron

Preliminary results
$^{17}O(\alpha,n)^{20}Ne$

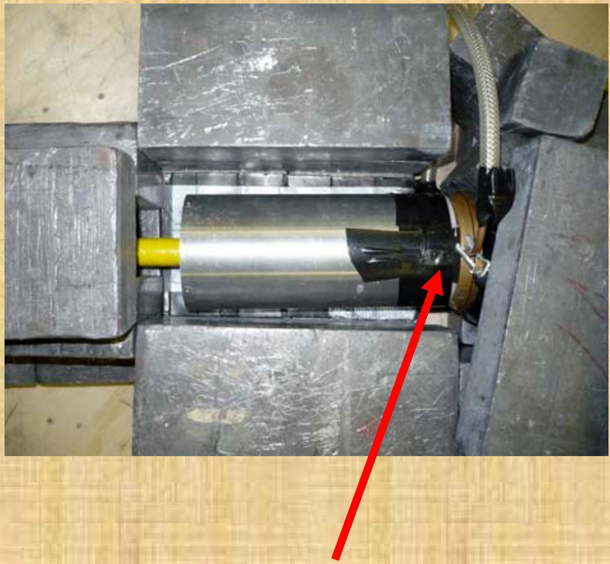
Good agreement
with Denker
Correct for (α,n_1)!!

Measurement below
900 keV hampered
by cosmic/room background

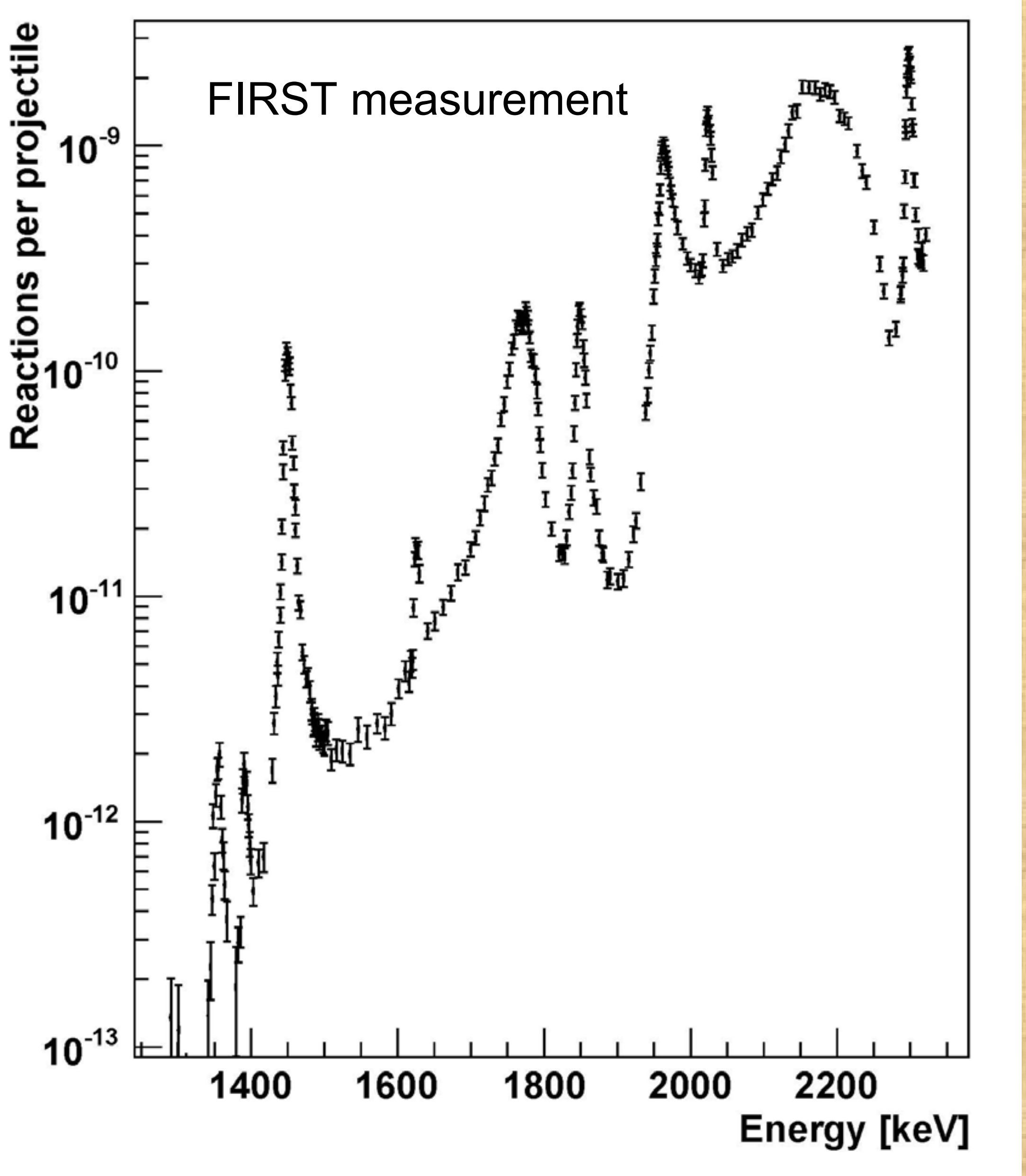
Up to now:
NO experimental
information for
$^{17}O(\alpha,n_1/\gamma)$



Preliminary results
$^{17}O(\alpha,n_1\gamma)^{20}Ne$



PVC neutron “shield”



Preliminary results
$^{17}O(\alpha,\gamma)^{21}Ne$

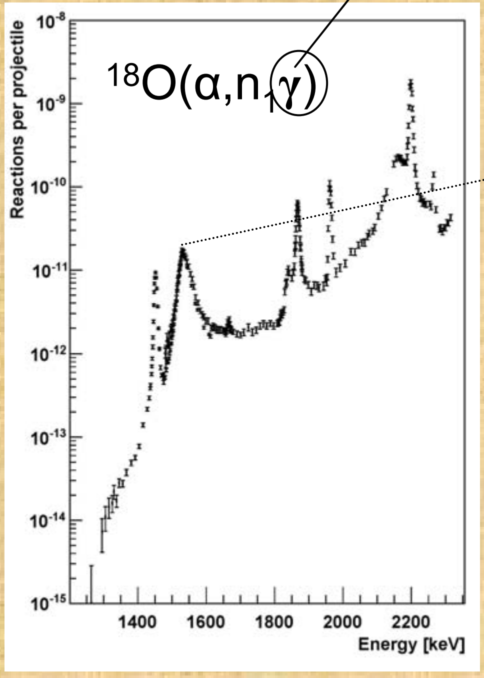
(α,n)/(α,γ)

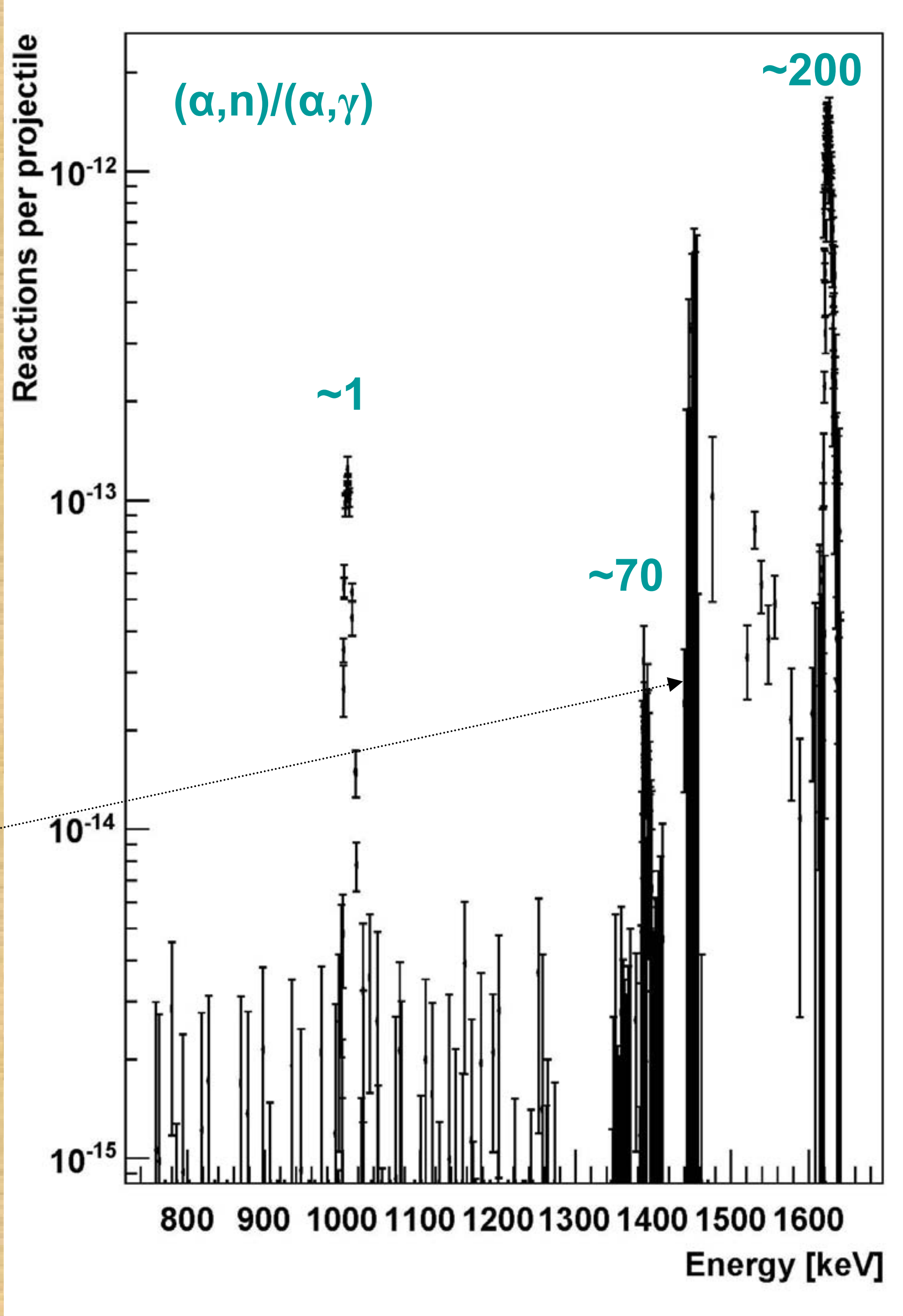
Fowler: ~10

Descouvemont ~10000
(theory)

?

will be continued with large Ge detector array…

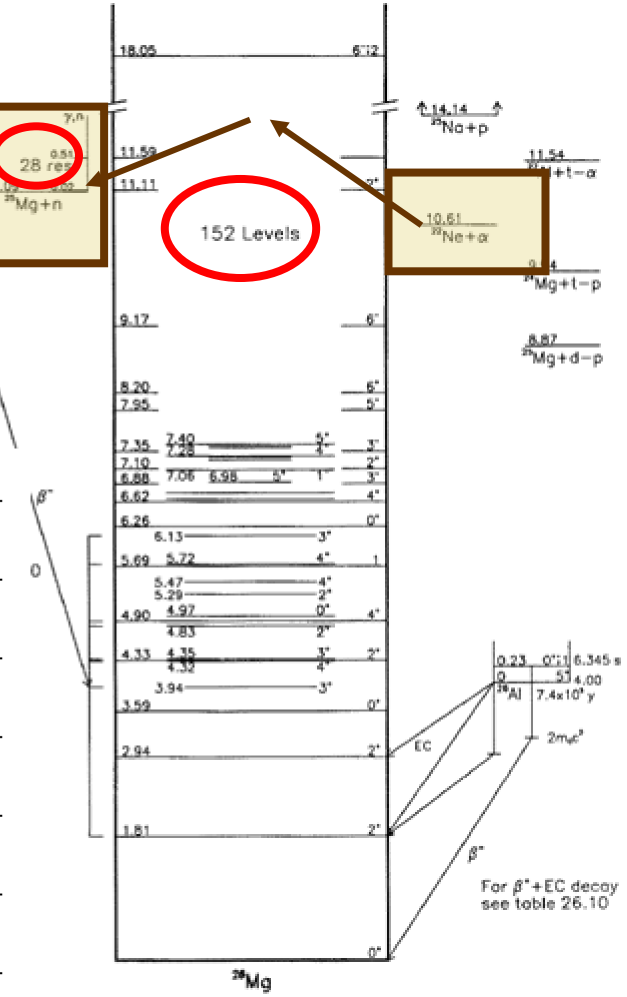


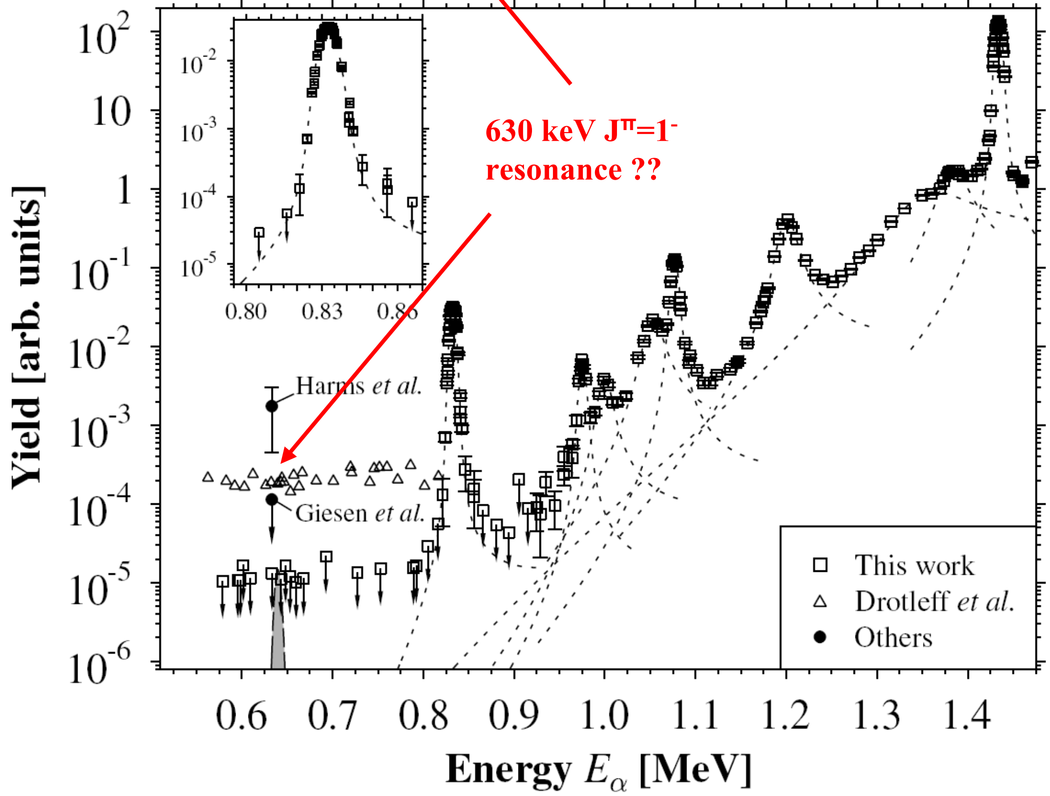


$^{22}Ne(\alpha,n)$, the main neutron source

Q= -0.48 MeV

$^{26}Mg(\gamma,\gamma')$ to search for state and its spin!



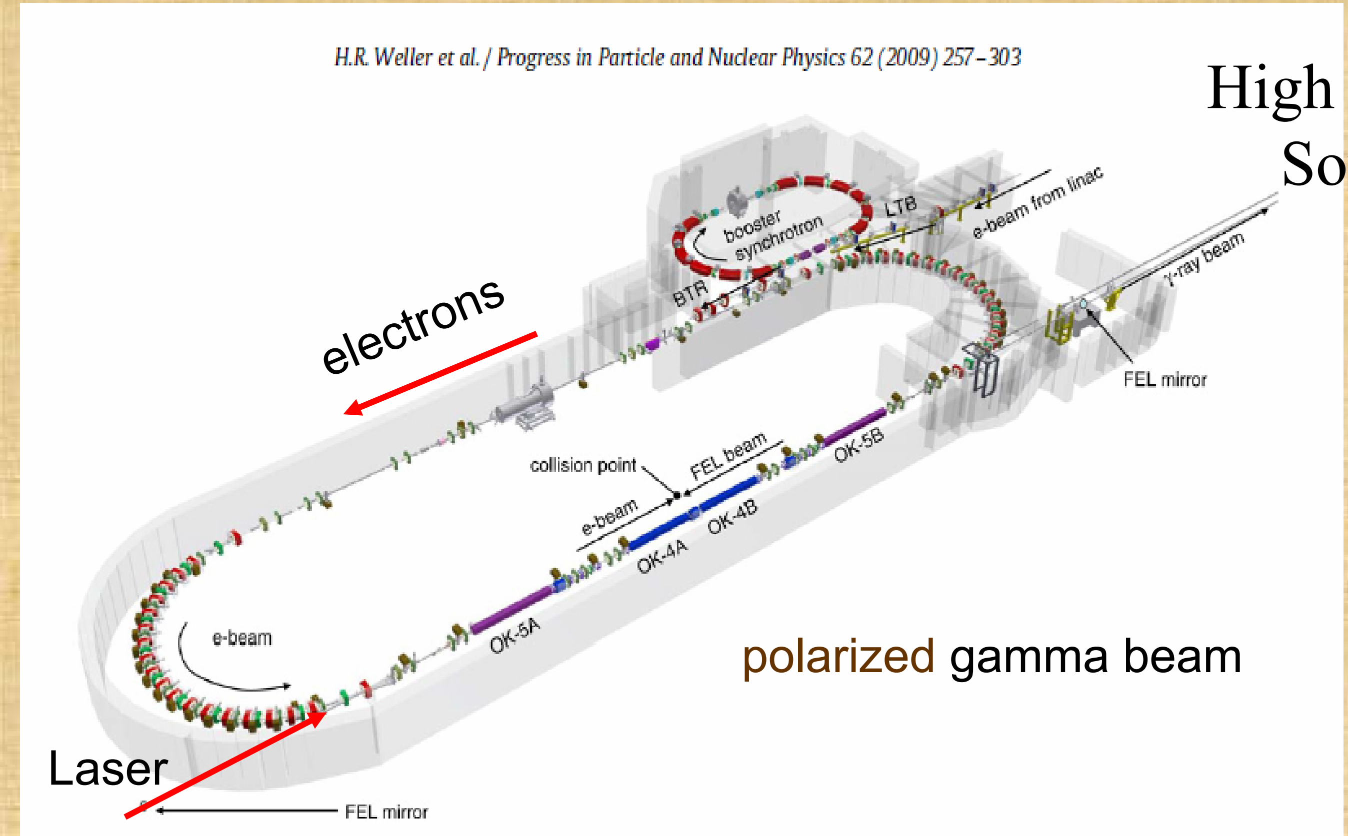


630 keV $J^\pi=1^-$ resonance ??

present upper limit: < 50 neV

Experiment at HIGS

High Intensity γ-ray Source (HIγS)



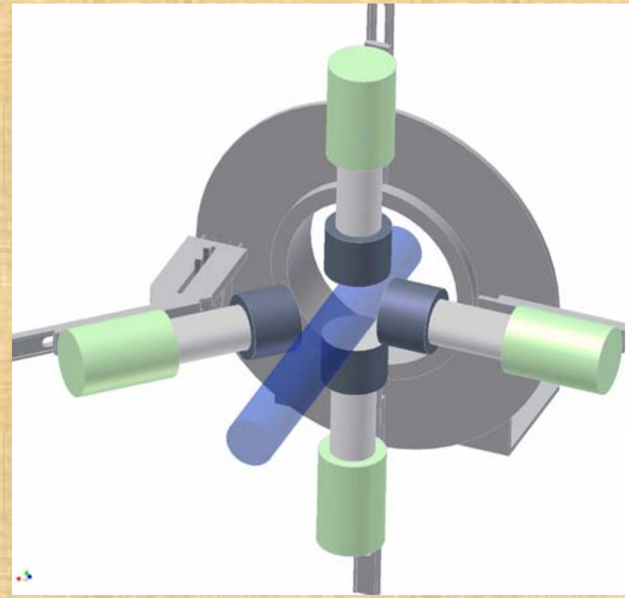
H.R. Weller et al. / Progress in Particle and Nuclear Physics 62 (2009) 257–303

electrons

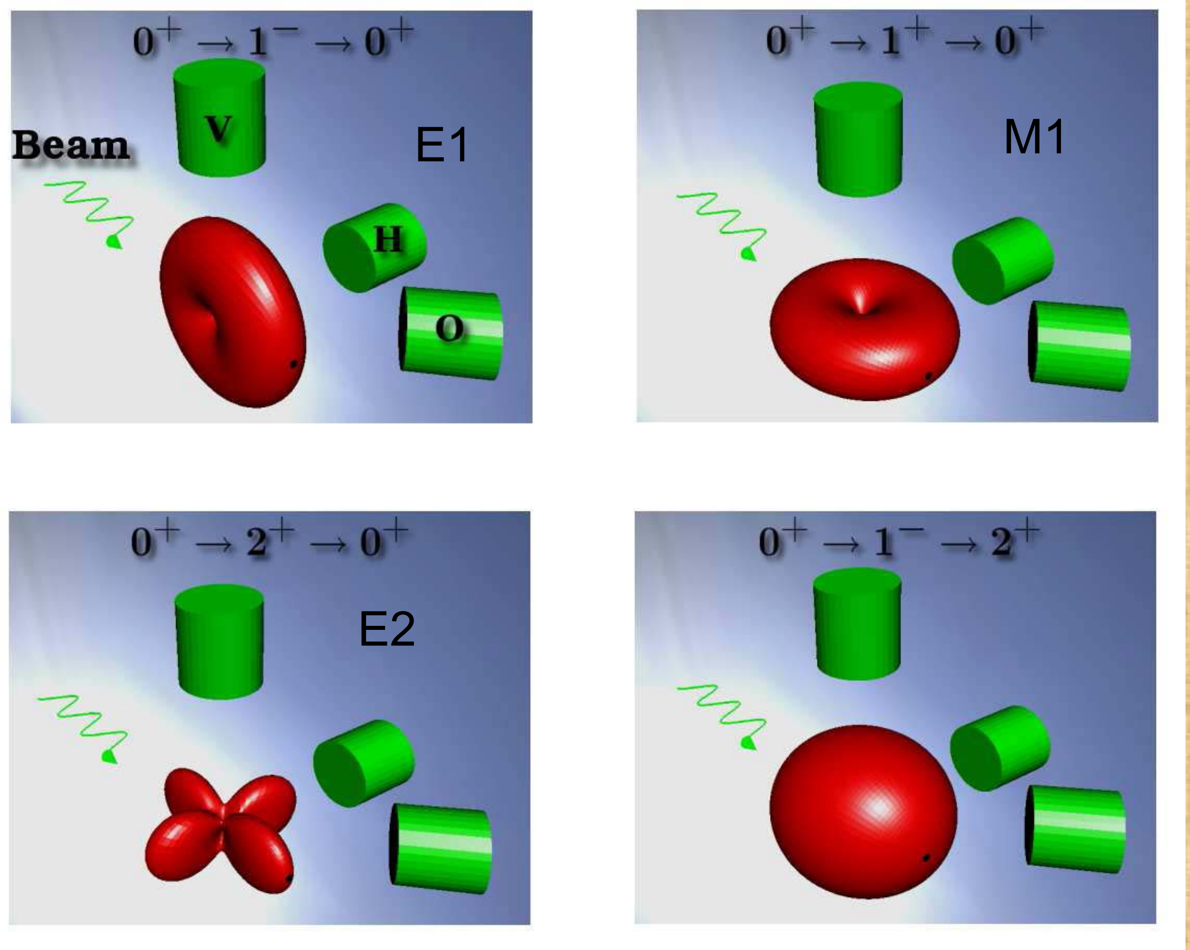
Laser

polarized gamma beam

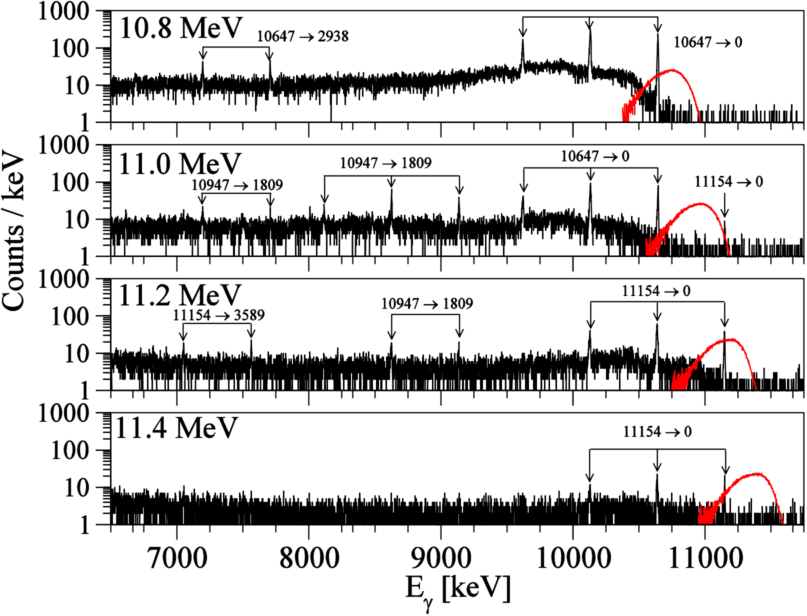
Target: 10 g(!) ^{26}Mg
Market value $100000 ($10/mg)
On loan for 10% of value per year



Unique spin and parity assignment
But strong ground state transition
is required



Results



630 keV Resonance(?)

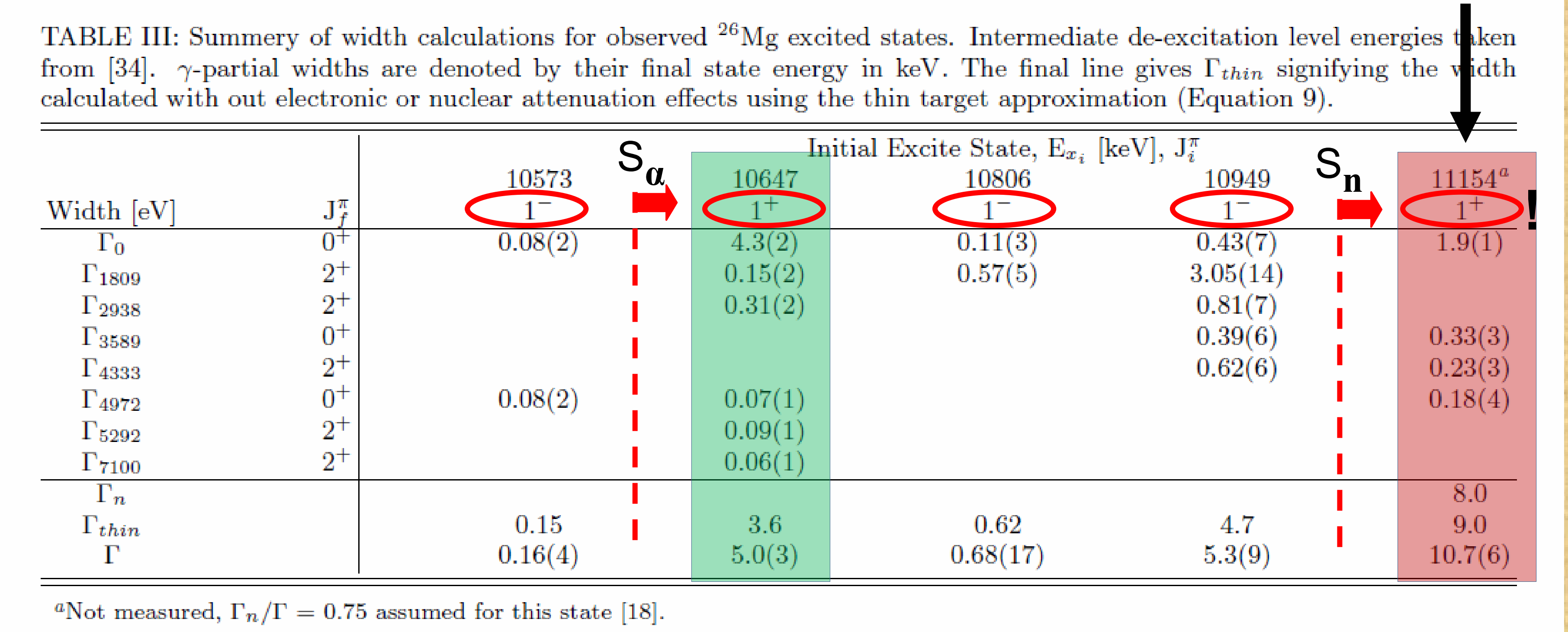
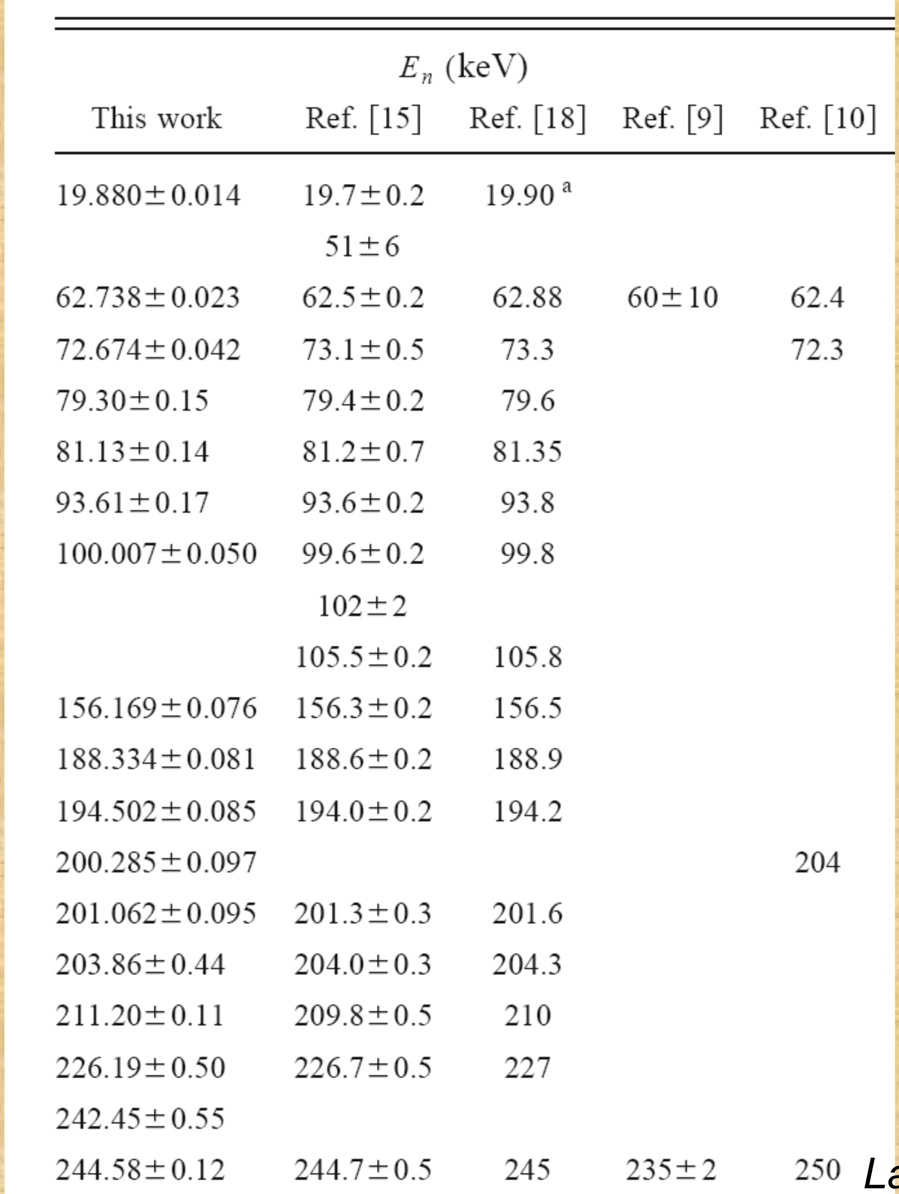


TABLE III: Summery of width calculations for observed ^{26}Mg excited states. Intermediate de-excitation level energies taken from [34]. γ-partial widths are denoted by their final state energy in keV. The final line gives Γ_{thin} signifying the width calculated with out electronic or nuclear attenuation effects using the thin target approximation (Equation 9).

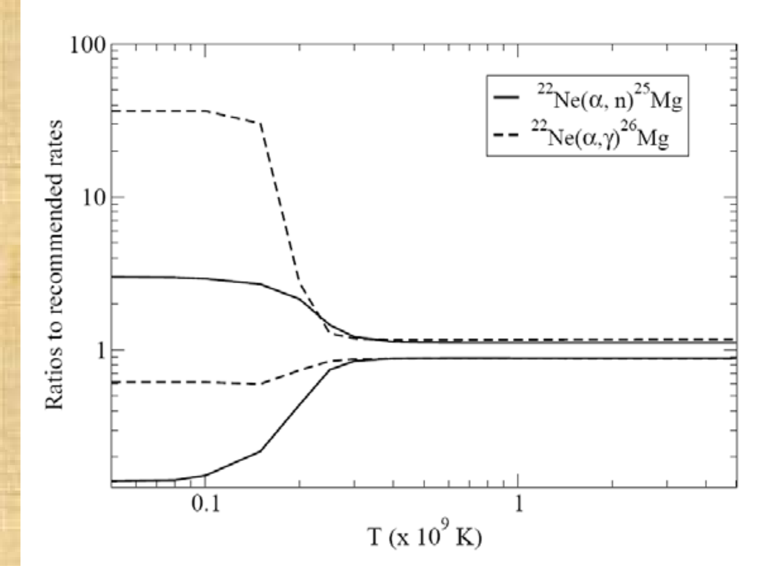
		Initial Excite State, E_{x_i} [keV], J_i^π				
		10573	10647	10806	10949	11154[a]
Width [eV]	J_f^π	1^-	1^+	1^-	1^-	1^+
Γ_0	0^+	0.08(2)	4.3(2)	0.11(3)	0.43(7)	1.9(1)
Γ_{1809}	2^+		0.15(2)	0.57(5)	3.05(14)	
Γ_{2938}	2^+		0.31(2)		0.81(7)	
Γ_{3589}	0^+				0.39(6)	0.33(3)
Γ_{4333}	2^+				0.62(6)	0.23(3)
Γ_{4972}	0^+	0.08(2)	0.07(1)			0.18(4)
Γ_{5292}	2^+		0.09(1)			
Γ_{7100}	2^+		0.06(1)			
Γ_n						8.0
Γ_{thin}		0.15	3.6	0.62	4.7	9.0
Γ		0.16(4)	5.0(3)	0.68(17)	5.3(9)	10.7(6)

[a] Not measured, $\Gamma_n/\Gamma = 0.75$ assumed for this state [18].

^{25}Mg+n: Evaluation from Koehler



E_n (keV)				
This work	Ref. [15]	Ref. [18]	Ref. [9]	Ref. [10]
19.880±0.014	19.7±0.2	19.90 [a]		
	51±6			
62.738±0.023	62.5±0.2	62.88	60±10	62.4
72.674±0.042	73.1±0.5	73.3		72.3
79.30±0.15	79.4±0.2	79.6		
81.13±0.14	81.2±0.7	81.35		
93.61±0.17	93.6±0.2	93.8		
100.007±0.050	99.6±0.2	99.8		
	102±2			
	105.5±0.2	105.8		
156.169±0.076	156.3±0.2	156.5		
188.334±0.081	188.6±0.2	188.9		
194.502±0.085	194.0±0.2	194.2		
200.285±0.097				204
201.062±0.095	201.3±0.3	201.6		
203.86±0.44	204.0±0.3	204.3		
211.20±0.11	209.8±0.5	210		
226.19±0.50	226.7±0.5	227		
242.45±0.55				
244.58±0.12	244.7±0.5	245	235±2	250



Karakas et al., ApJ 643, 471 (2006)

Uncertainties from resonances below the detection limit of direct measurement !

Next month: complimentary (γ,n) reaction at HIγS

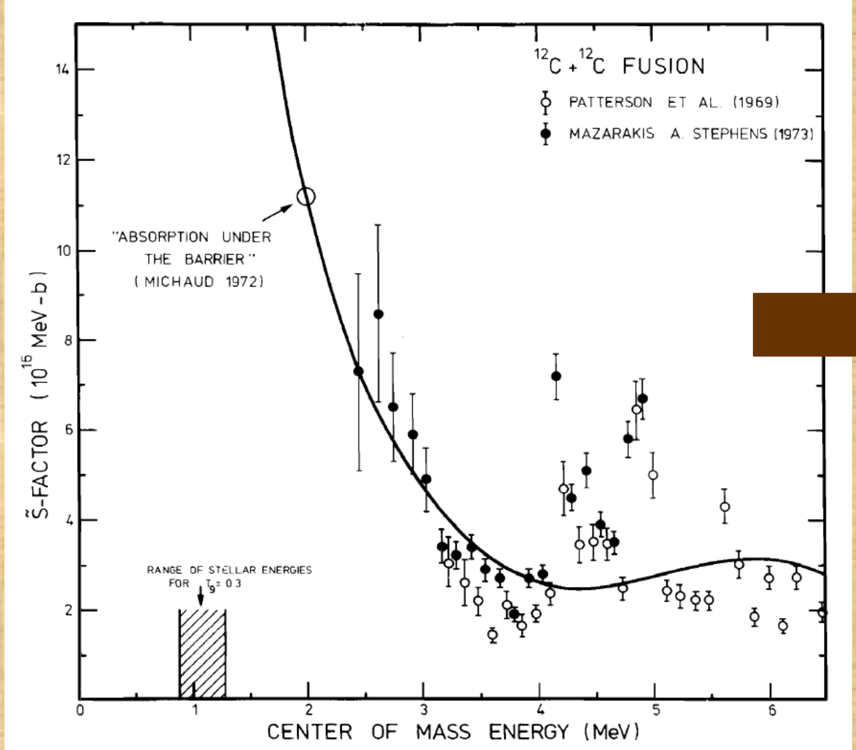
Last known resonance at 832 keV

Uncertainties in the $^{12}C+^{12}C$ fusion rate?

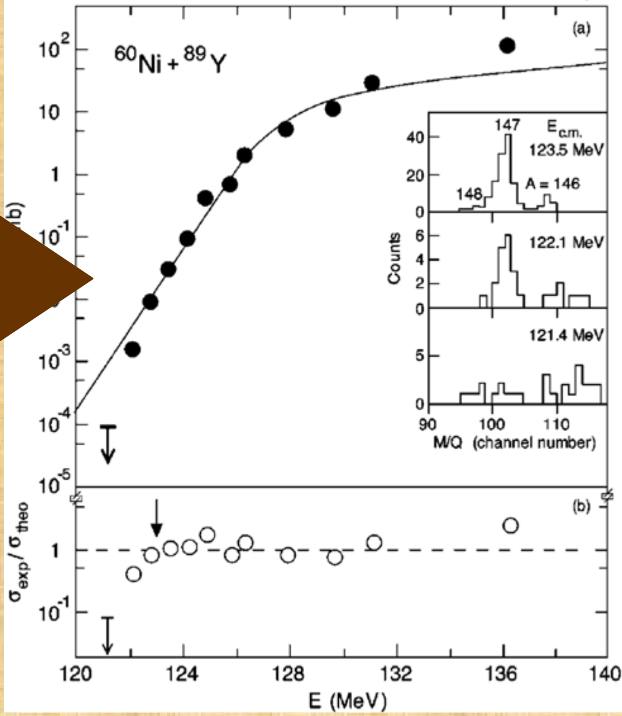
Consequences for:

- Stellar Carbon burning
- Type Ia supernova ignition
- Superburst ignition conditions

Absorption under the barrier - 1973

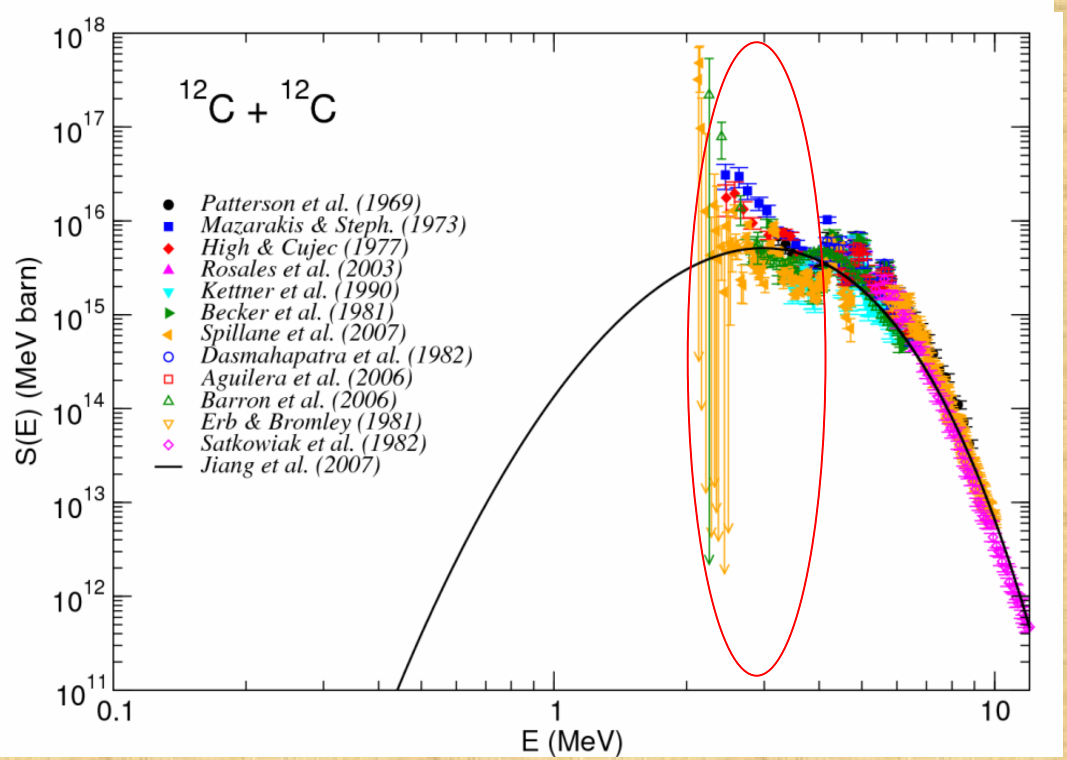


Hindrance at extreme sub-barrier energies – 2002



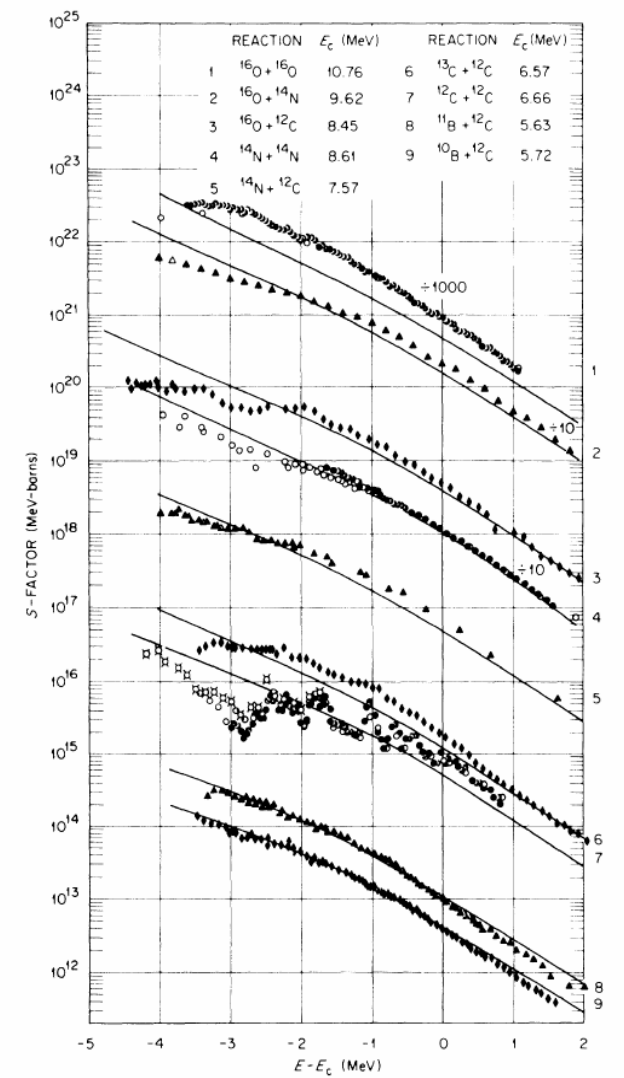
Different potential models lead to different ways to extrapolate the low energy cross section (S-factor).

- standard potential model
- hindrance potential model

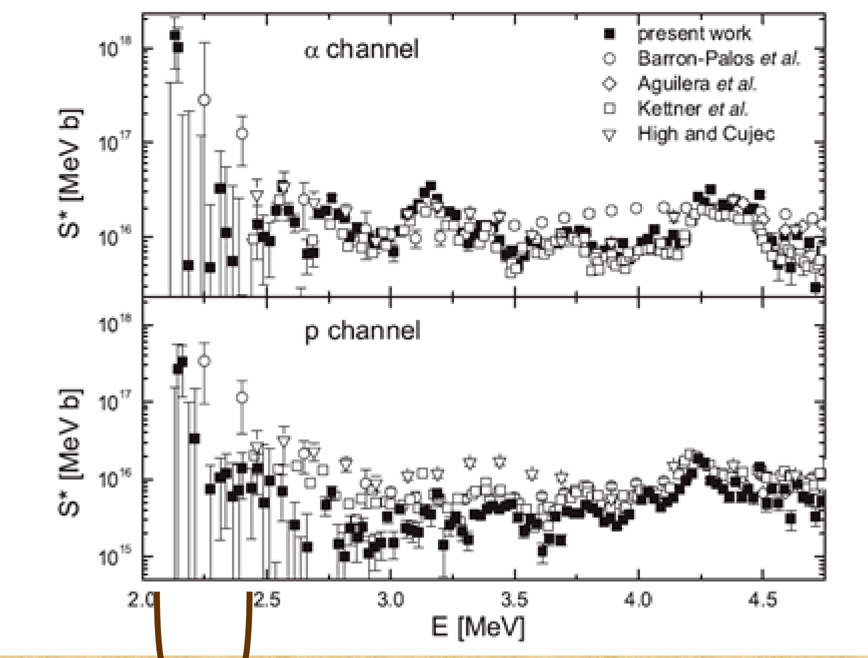


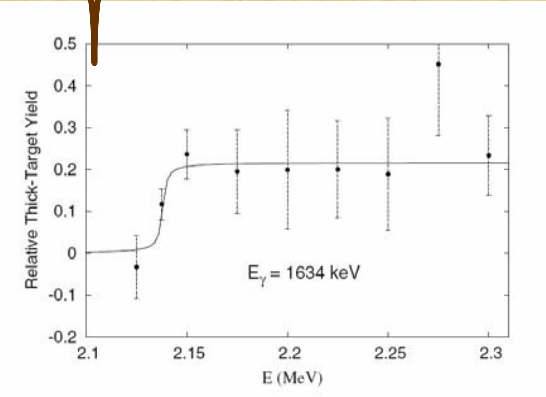
Caughlan & Fowler ADND 1988
Gasques et al. PRC 2005
Yakovlev et al. PRC 2006
Jiang et al. PRC 2007

Resonance structure in $^{12}C+^{12}C$



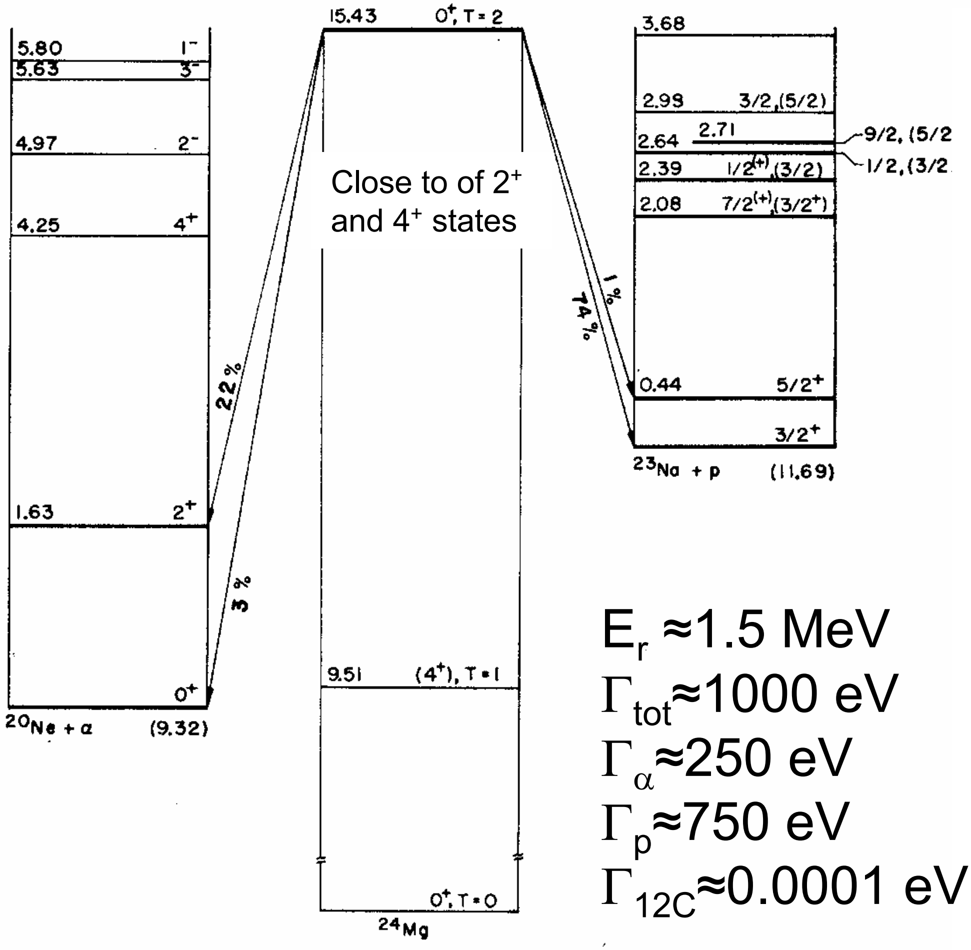
Stokstad, 1976





Spillane, 2007

^{12}C-^{12}C cluster configuration?



Close to of 2^+ and 4^+ states

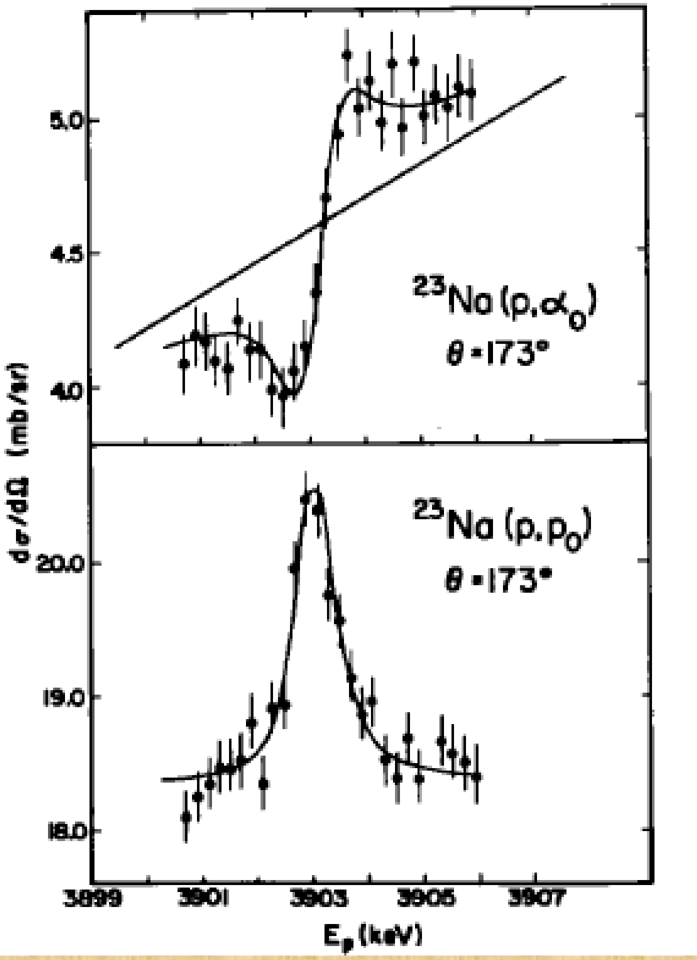
$E_r \approx 1.5$ MeV

$\Gamma_{tot} \approx 1000$ eV

$\Gamma_\alpha \approx 250$ eV

$\Gamma_p \approx 750$ eV

$\Gamma_{12C} \approx 0.0001$ eV?

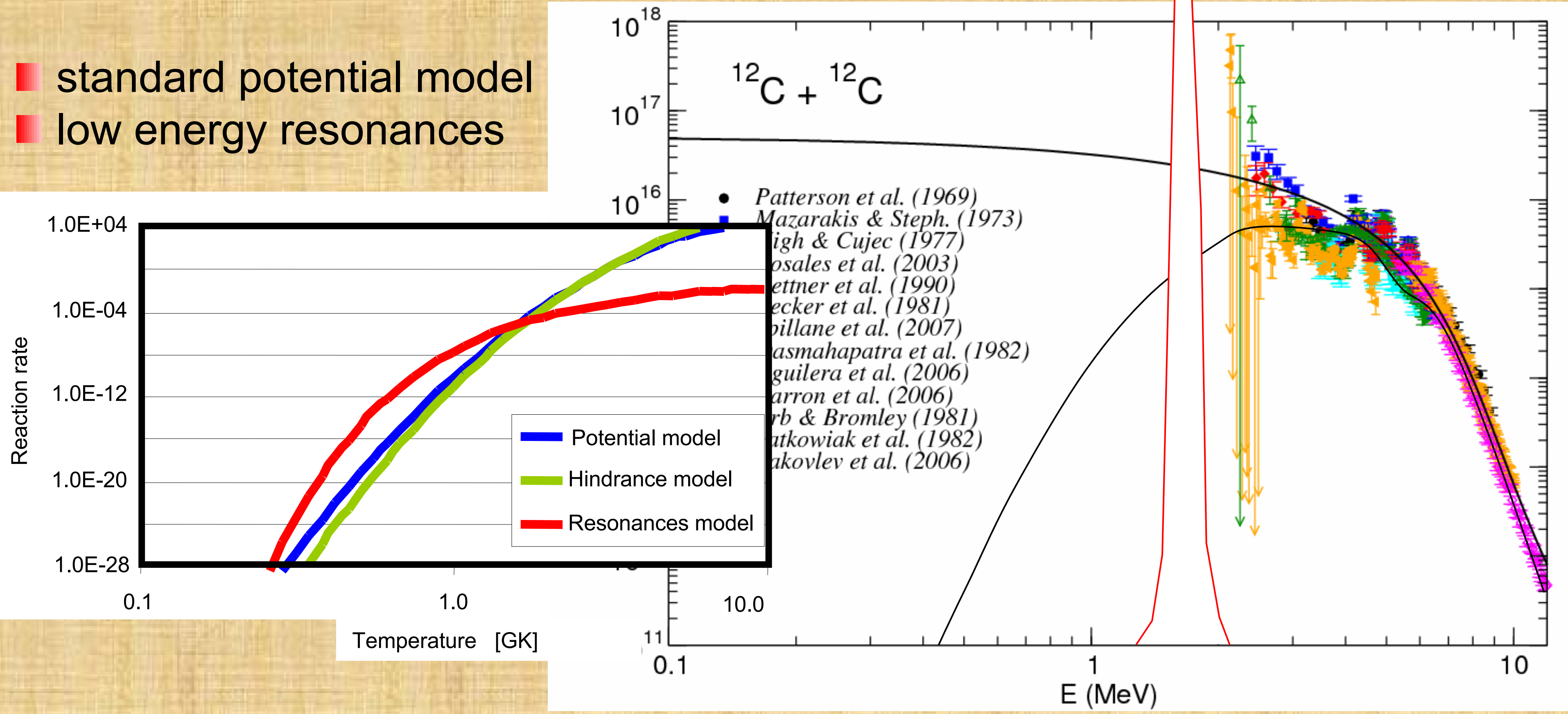


~1 count per day!

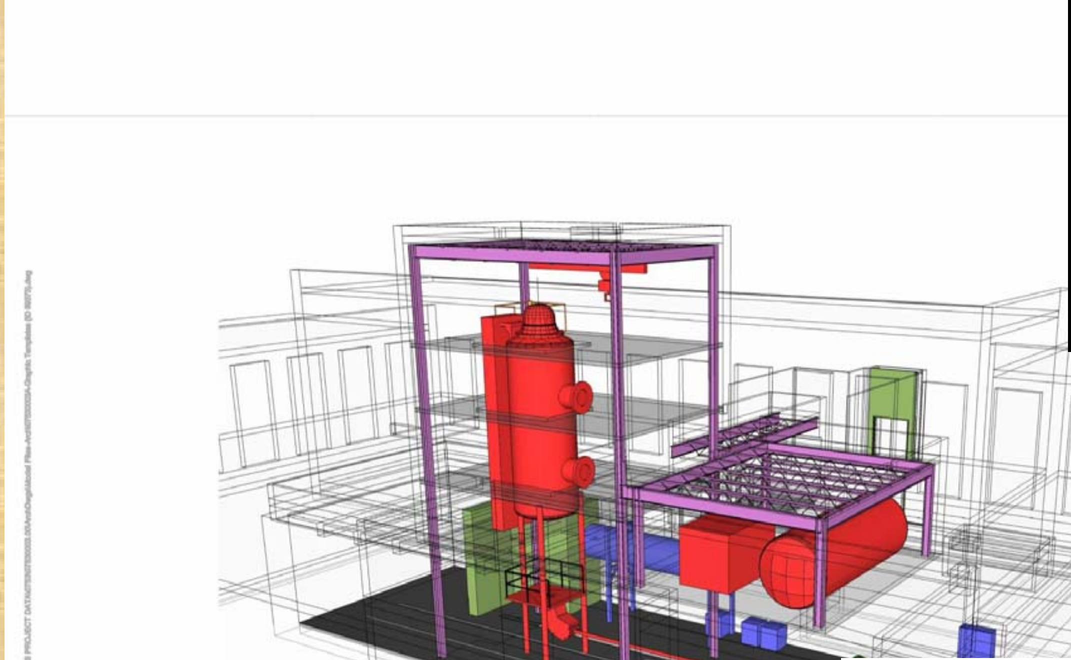
Influence of hypothetical 1.5 MeV resonance

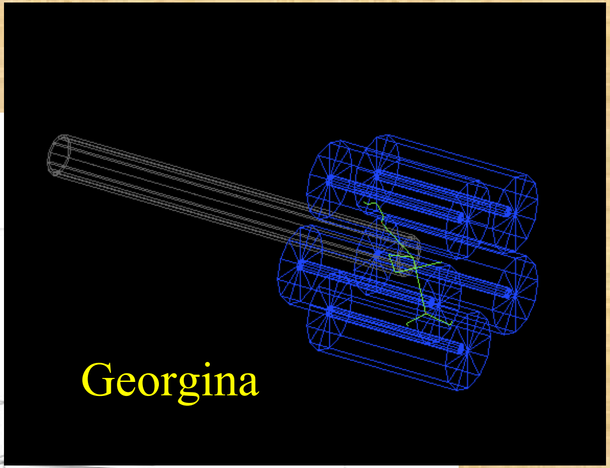
Strong, molecular $^{12}C+^{12}C$ resonance causes enormous enhancement of S-factor and reaction rate at stellar burning conditions

- standard potential model
- low energy resonances



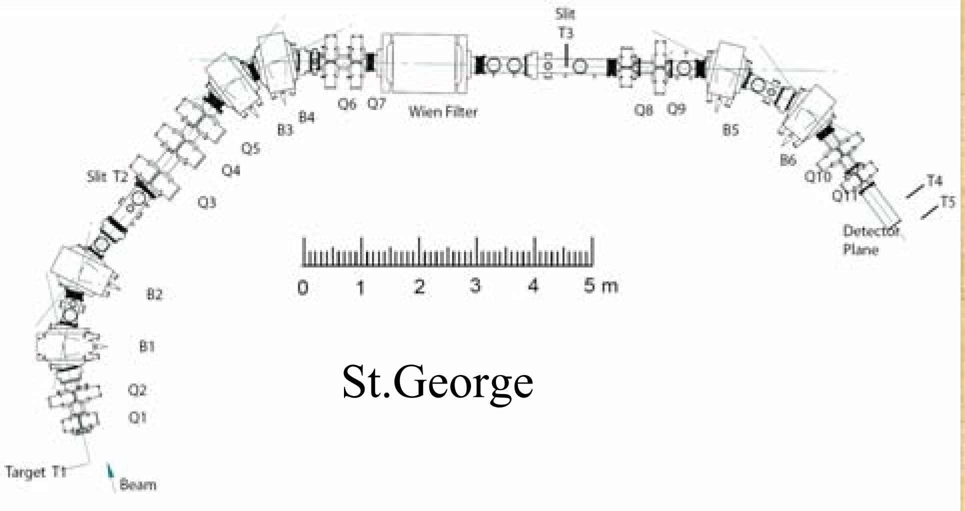
Future





Georgina

DUSEL

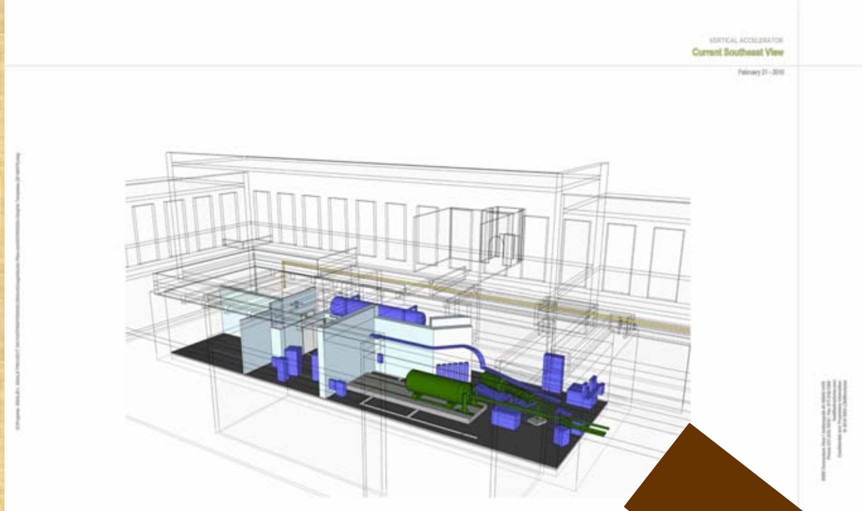


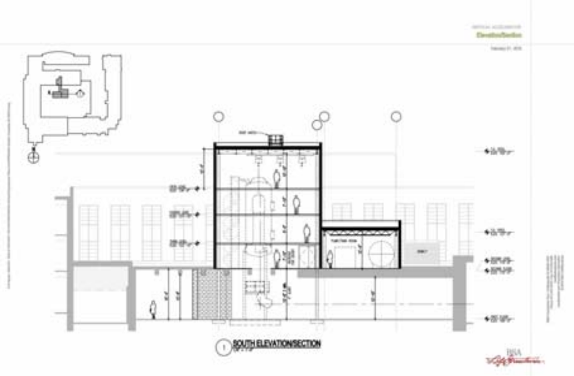
St.George

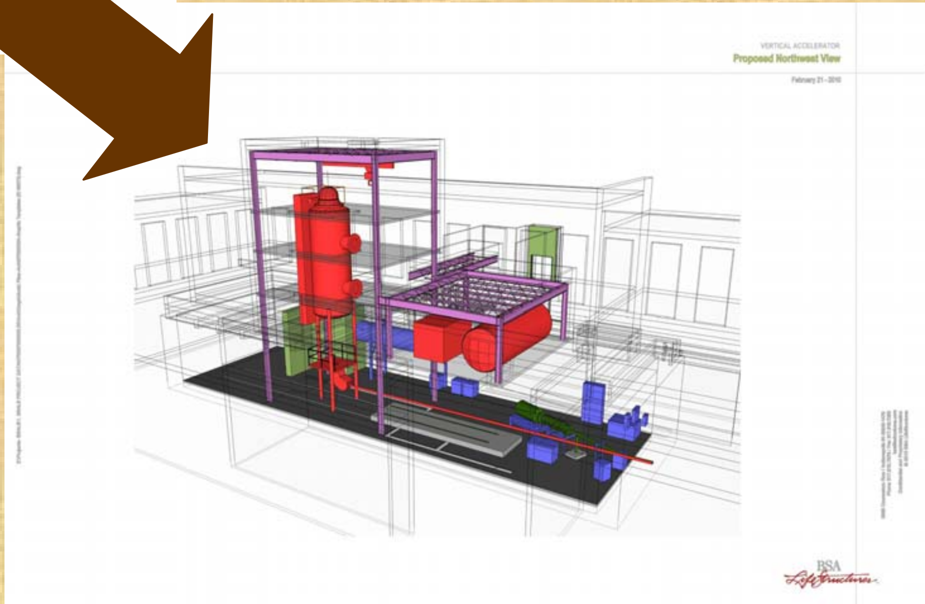
Future: 5 MV heavy ion accelerator Santa Ana

Provide intense heavy ion beams for St. George

Provide intense proton and alpha beams for direct experiemnts



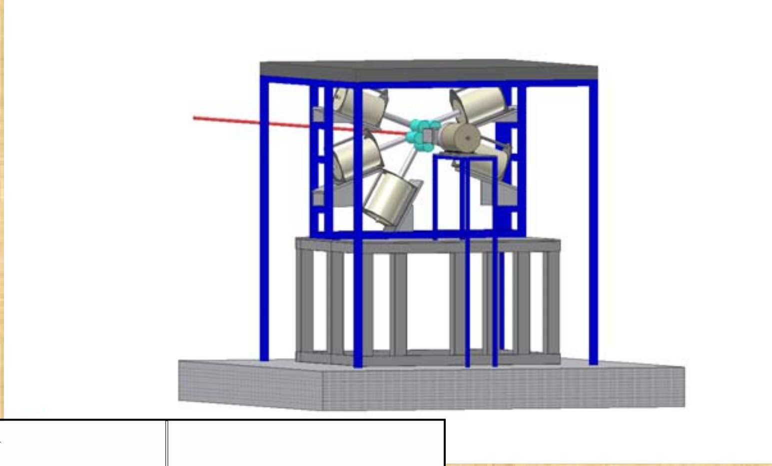


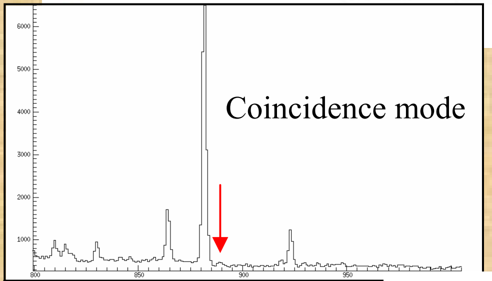


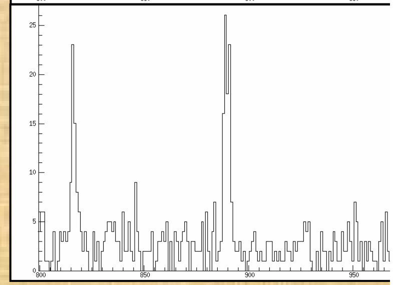
Future: Georgina Ge array

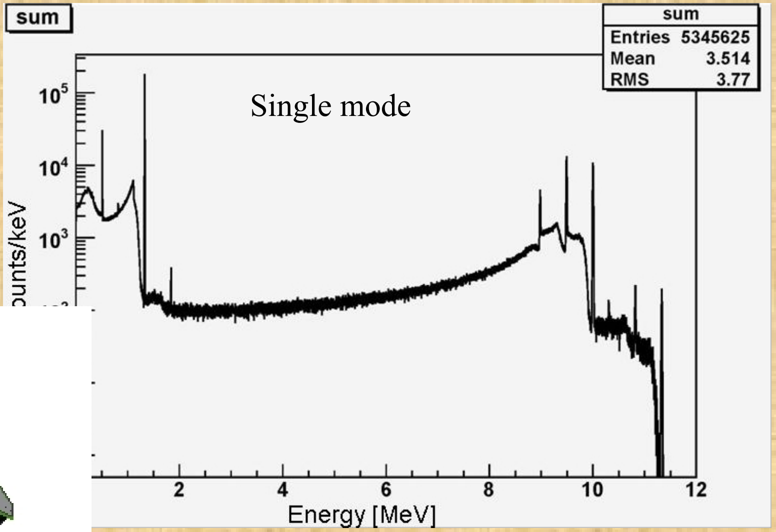
5 100% Ge detectors

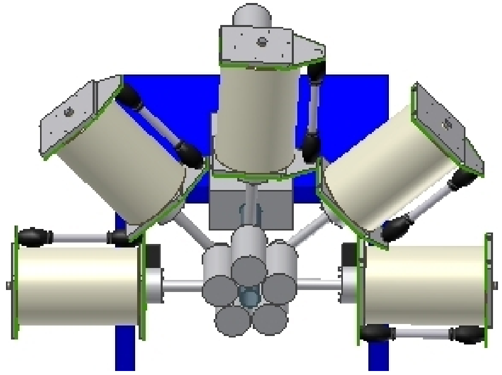
1. Large efficiency up to 12 MeV.
2. Compact design to fit into tight spaces and to allow effective shielding (e.g., with cosmic ray veto detector).
3. Versatility to adopt the array to a wide variety of experimental needs (e.g., in combination with Si-detector arrays or other γ-detectors).
4. Modest granularity; in most experiments of interest the γ-ray multiplicity will be ≤3.




Coincidence mode




Single mode



36% geometrical solid angle

Monte Carlo simulation

sum efficiency:

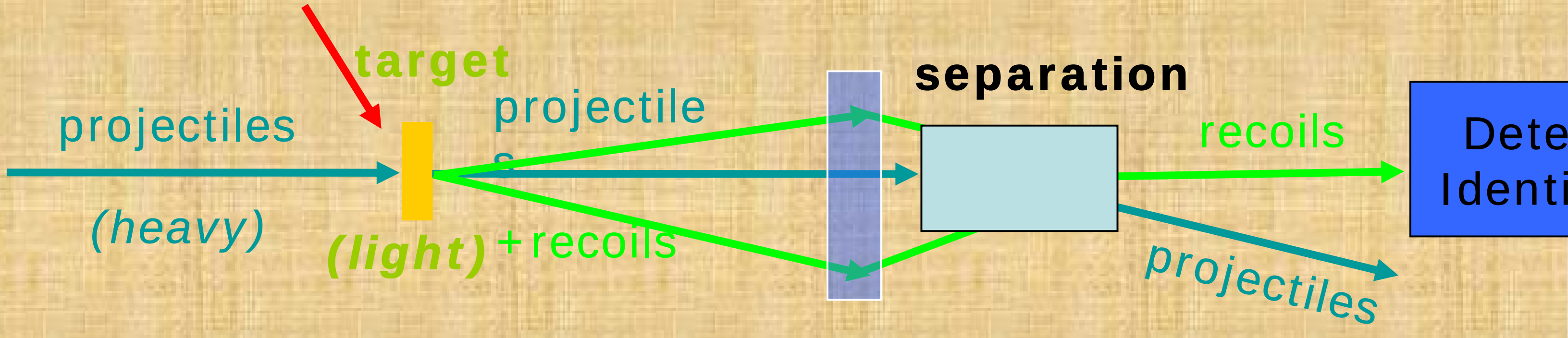
1.33 MeV 6.7% (GS 9%)

10.0 MeV 1.0% 1.6% addback

Future: recoil separator St. George

Design goal: alpha capture reactions
with Q ~ 10 MeV

Recoil separator: Principle



γ detector

target

projectiles

(heavy)

(light)

projectiles
+ recoils

separation

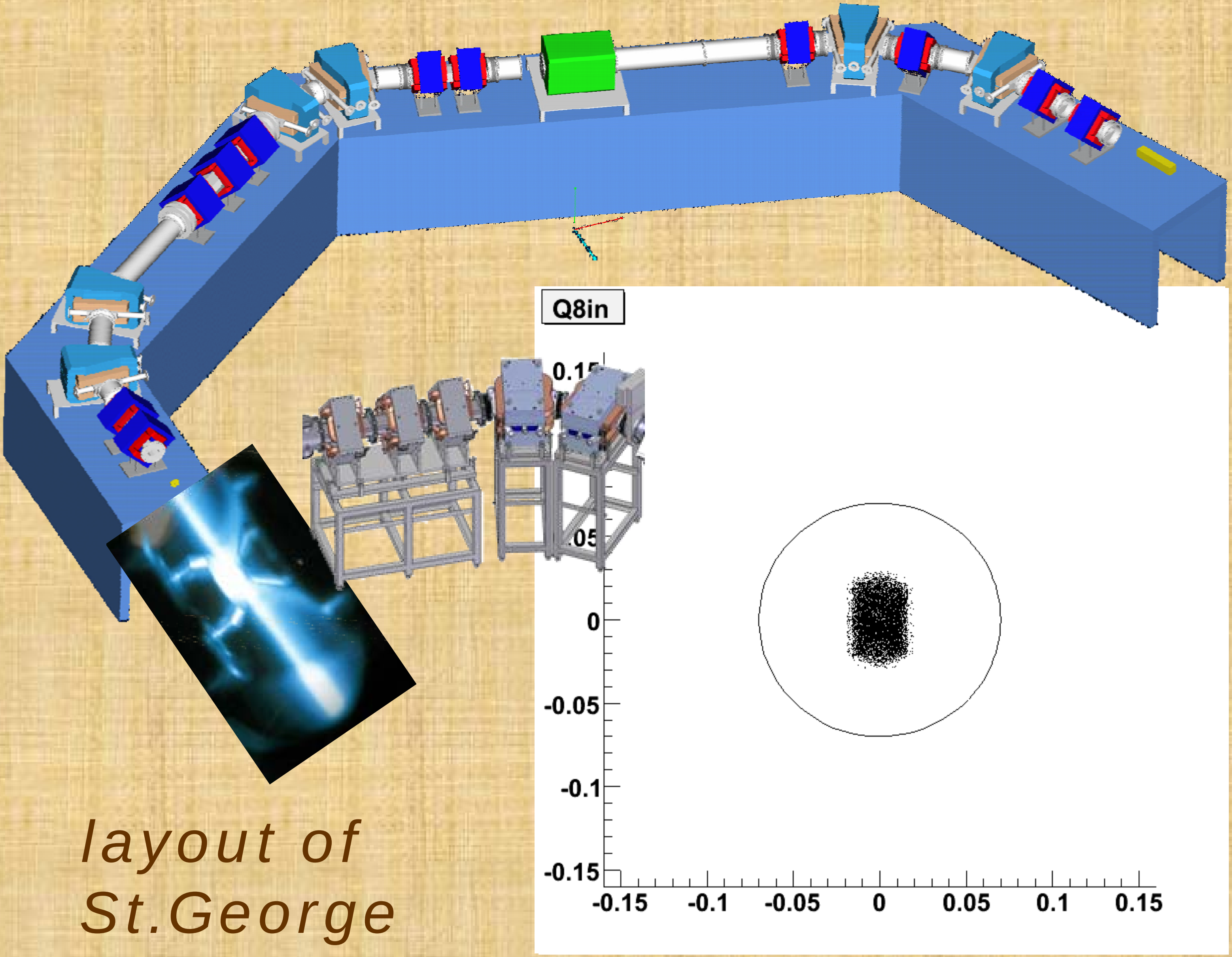
recoils

projectiles

Detection
Identification

**focusing
and charge
selection**

Drawings from D. Schürmann

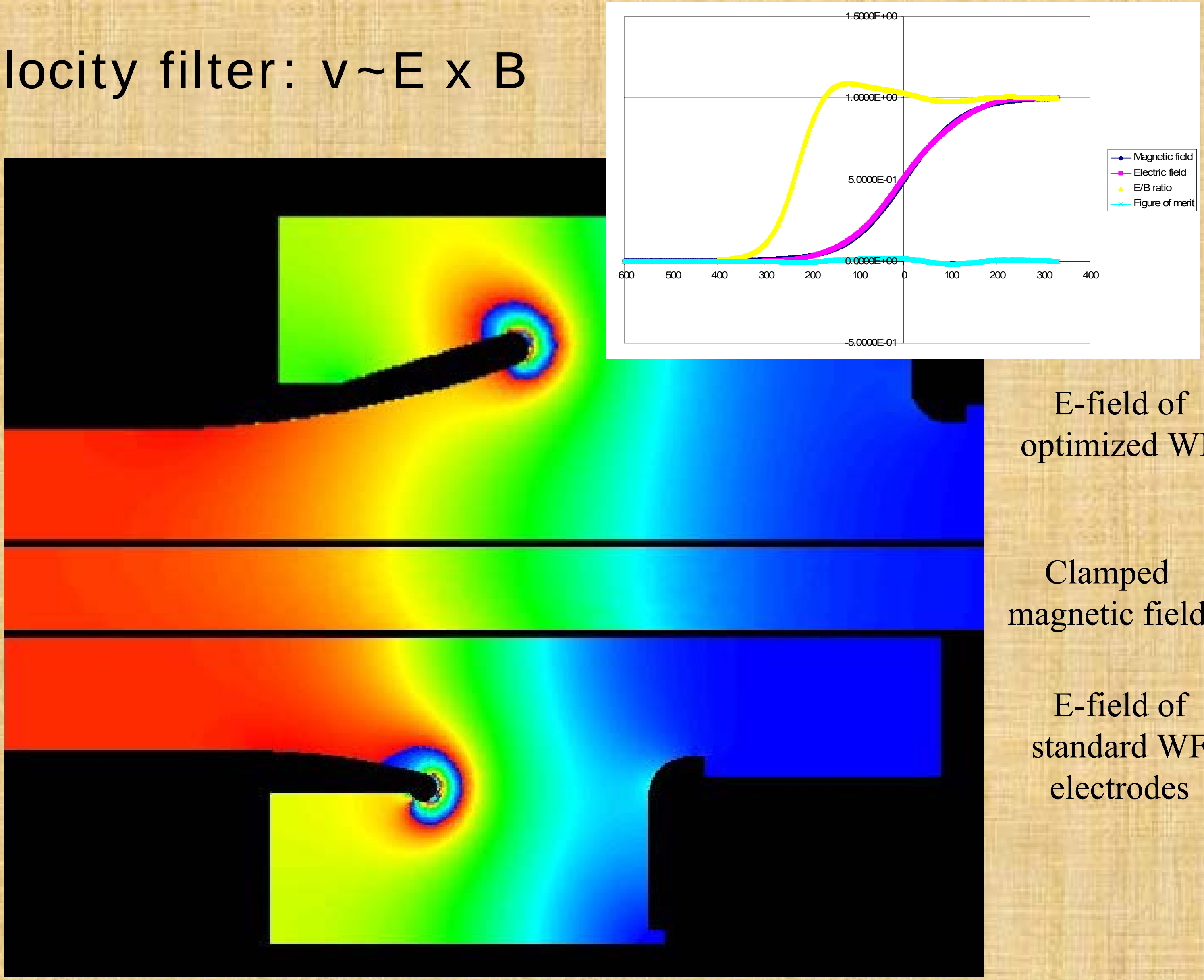


layout of St.George

^{24}Mg(α,γ)^{28}Si

Wien filter electrostatic fringe field

Velocity filter: v~E x B



E-field of optimized WF

Clamped magnetic field

E-field of standard WF electrodes

It’s Coming !

Plans for St. George

DIRECT

$^{17}O, ^{22}Ne(\alpha,\gamma)$

$^{22}Ne(\alpha,n)$**(!)**

Q<0

sorry, no $^{17}O(\alpha,n)$

(Q>0)

INDIRECT

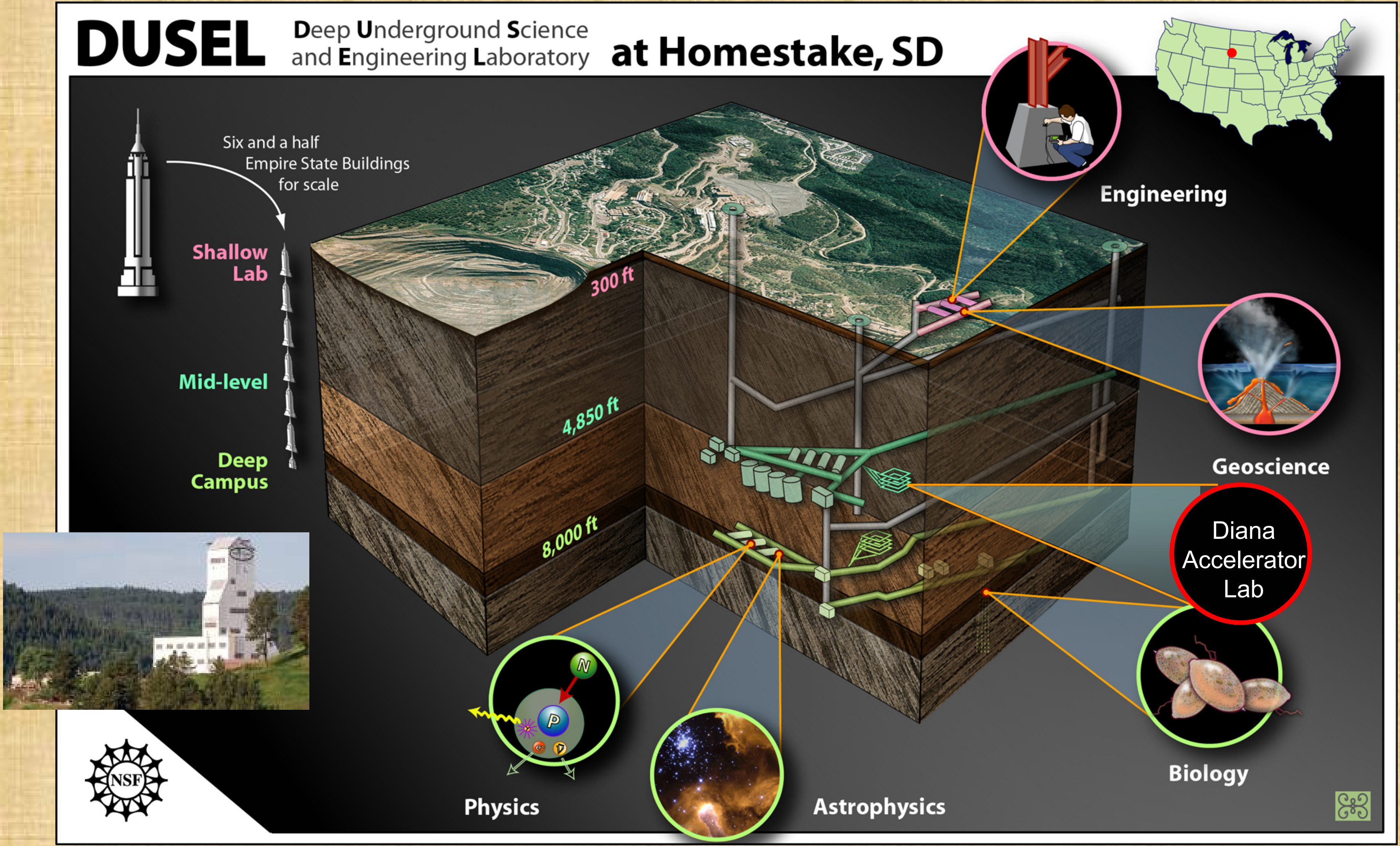
alpha-transfer reactions

at sub-Coulomb energies

- evaluate resonances too weak for DIRECT
- locate exact energies of resonances for Direct

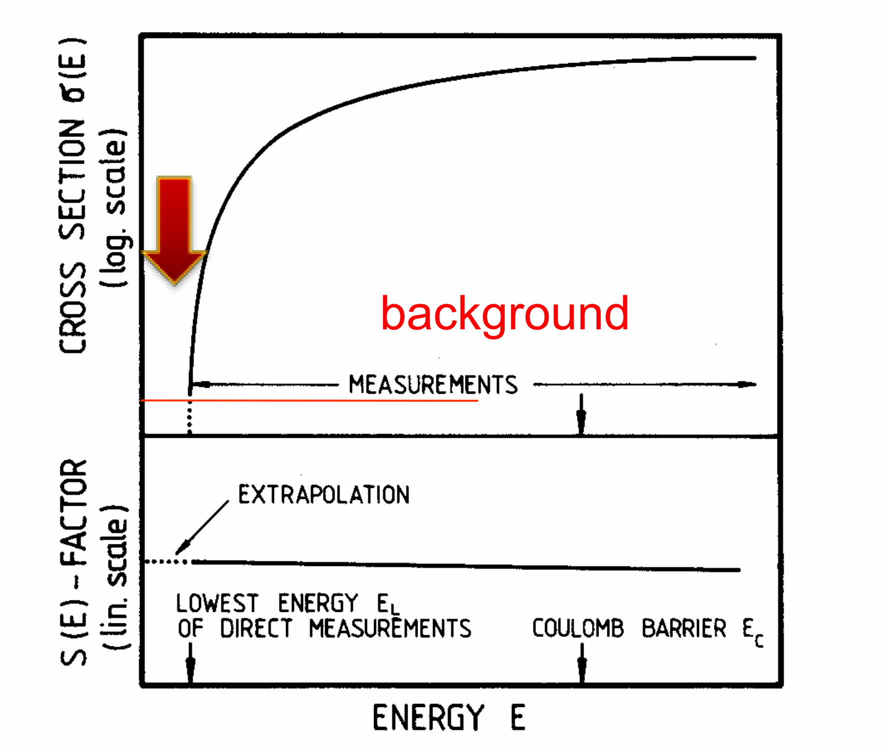
("misuse" St.George as
0 degreee spectrometer)

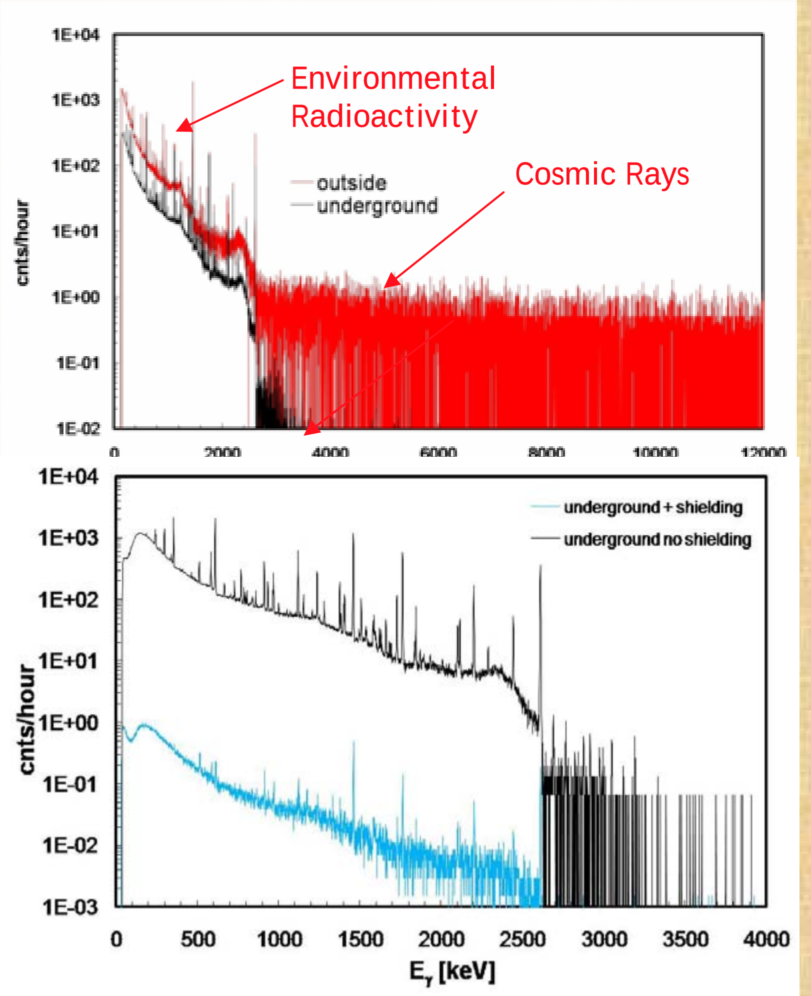
Future: Underground Accelerator Laboratory



Diana Accelerator Lab

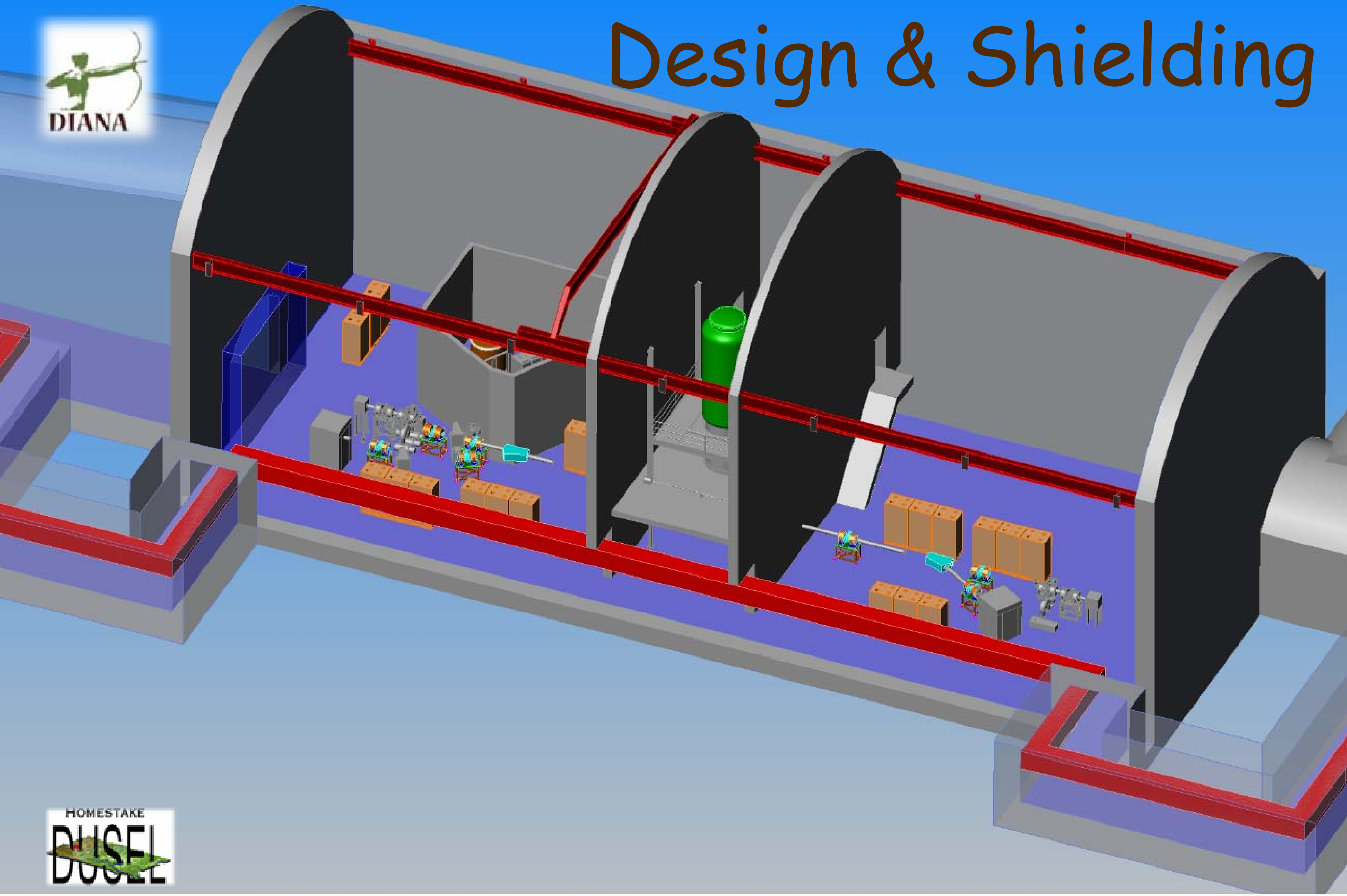
Why going underground?





For low Q-value reaction: Local shielding (Pb) is more effective when the muon flux is reduced!

Design & Shielding



DIANA

HOMESTAKE DUSEL

UNIVERSITY OF NOTRE DAME

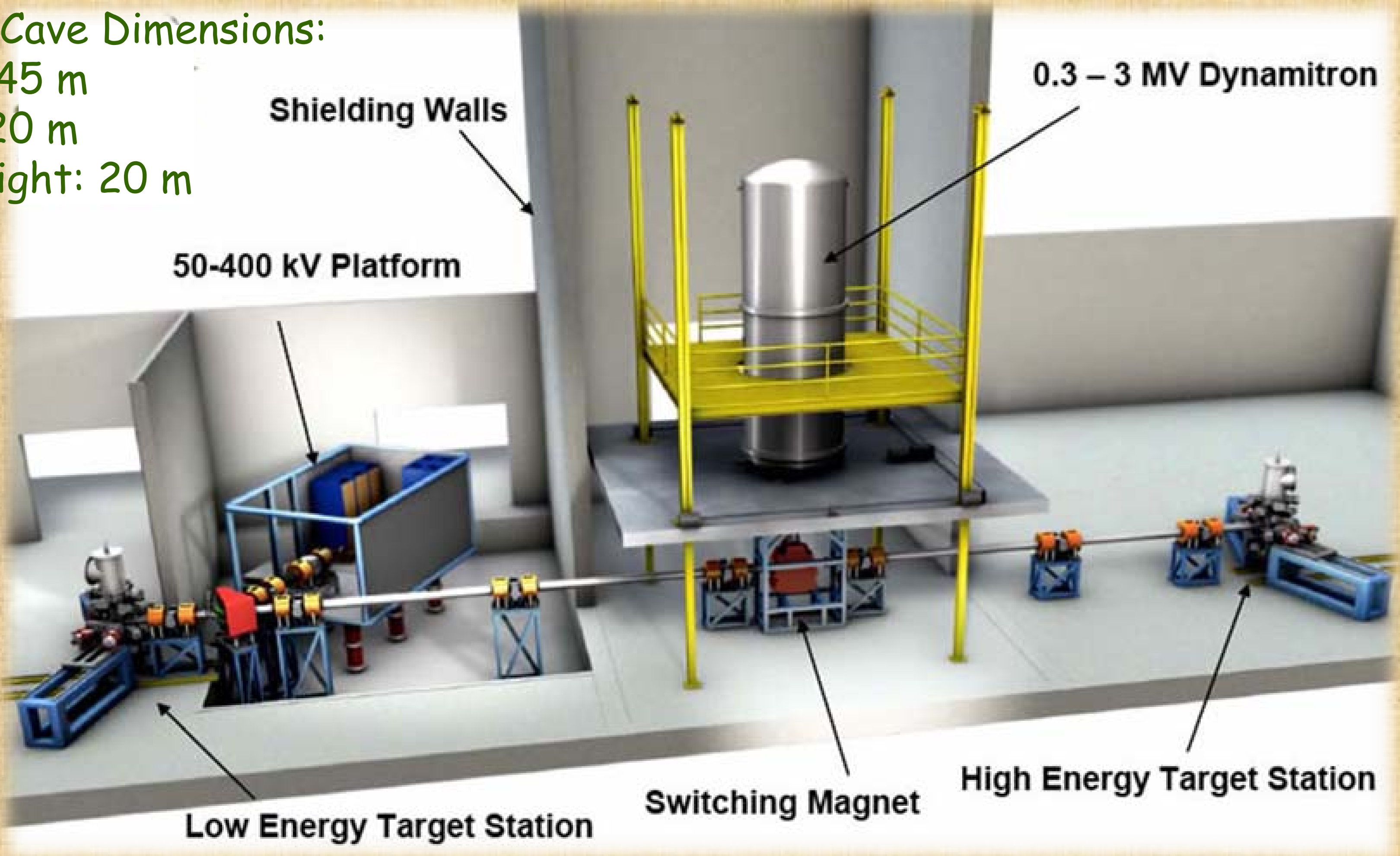
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

BERKELEY LAB

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

Laboratory Lay-Out

Approx. Cave Dimensions:
Length: 45 m
Width: 20 m
Max. Height: 20 m



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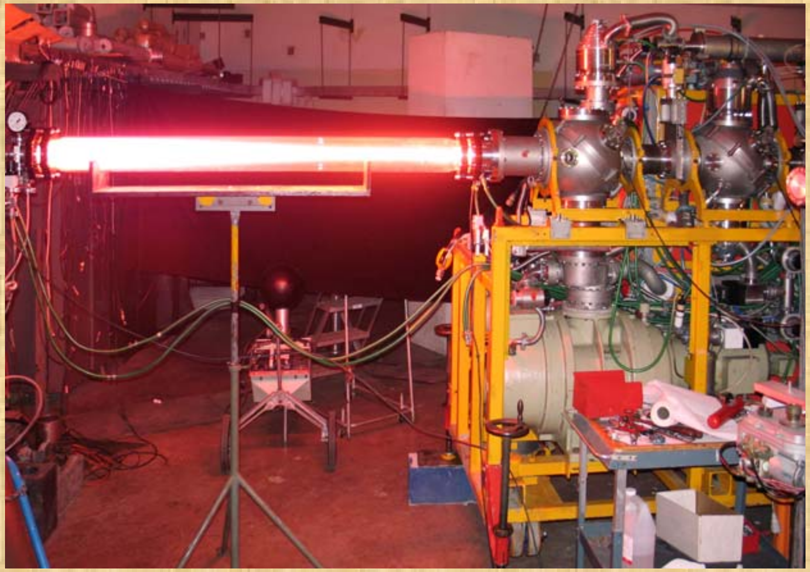

^{22}Ne(α,n)