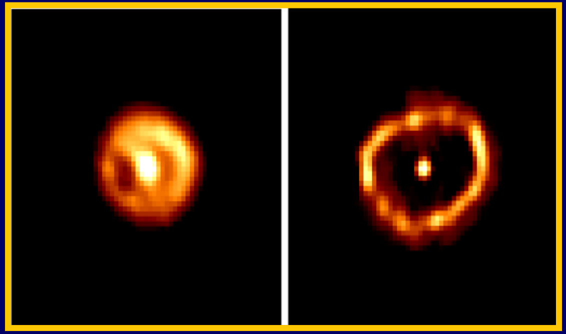
Astrophysics with Radioactive Beams Worldwide

John M. D'Auria
Simon Fraser University

CRAB NEBULA (SN remnant from 1054)

Nova Cygni   Erupted 2/92



NuPac Meeting ISOLDE: CERN
October 10, 2005

Thanks to contributors:

Marialuisa Aliotta, Edinburgh

Carmen Argulo, Louvain-le-Neuve

Jeff Blackmon, ORNL

Lothar Buchmann, TRIUMF

Jac Caggiano, TRIUMF

Jordi Jose, Barcelona

Shigeru Kubono, RIKEN

Ernst Rehm, ANL

Chris Ruiz, TRIUMF

Michael Smith, ORNL

Oliver Sorlin, GANIL

Bob Tribble, Texas A&M

Christof Vockenhuber, TRIUMF

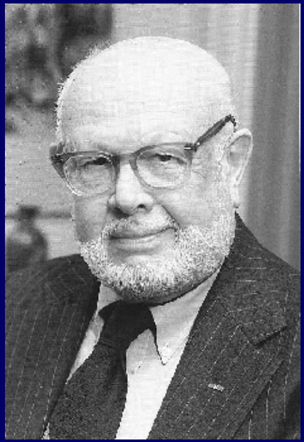
(Michael Wiescher, UND)

Outline

- The Science
  - What needs to be done?
- Role of Radioactive Beams (Accelerated)
  - What is happening and where?
- Examples of Specific Studies?
- Future Plans and Possibilities
- Concluding Remarks

There has been an explosion of important astrophysics studies with RIB performed worldwide, but there is much to do. The essential component are high intensity RB of high purity. ISOLDE has been the benchmark for such beams for many years and needs to now upgrade its facilities to make Important contributions in this exciting area.

“We are all nuclear debris”
Willie Fowler, 1985



Role of Nuclear Astrophysics

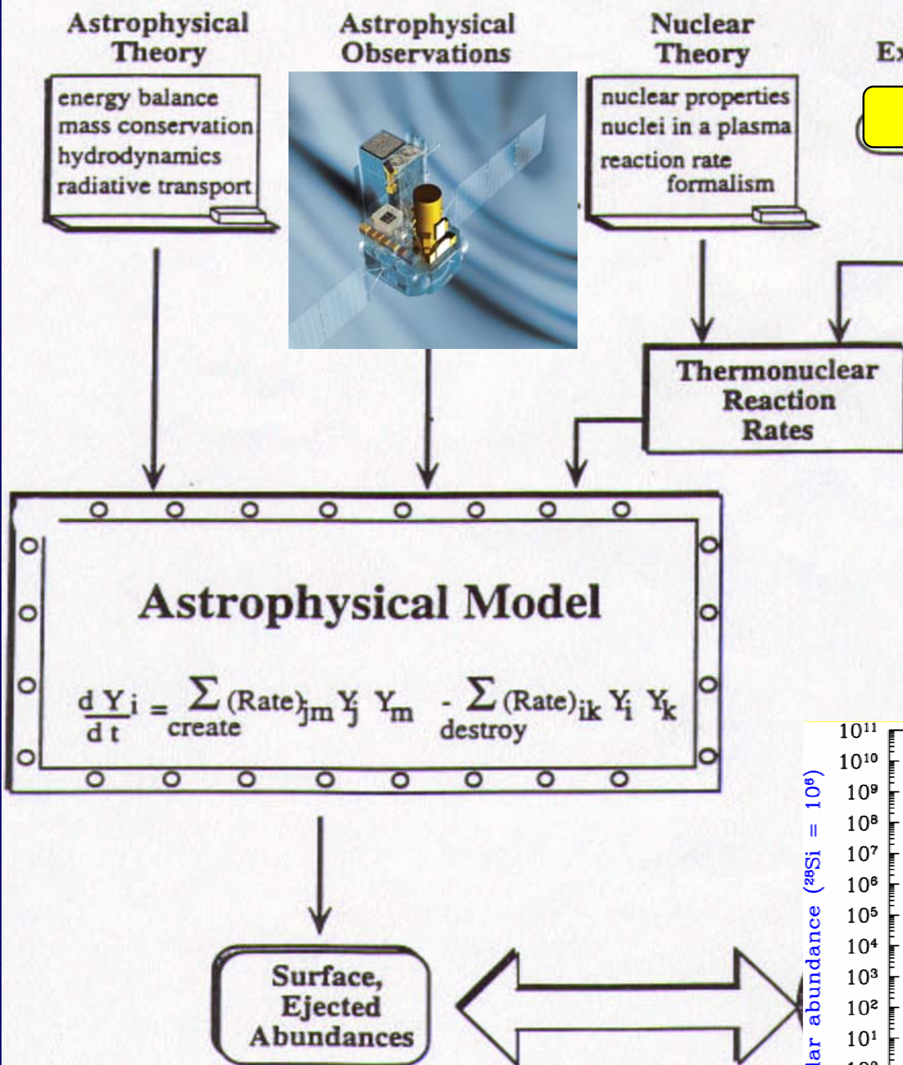
- Nucleosynthesis in stars
- Energy generation in stars

How: Many ways including studies of simple nuclear reactions at low energies using appropriate accelerators

“We stand on the verge of one of those exciting periods which occur in science from time to time. In the past few years, it has become abundantly clear that there is an urgent need for data on the properties and interactions of radioactive nuclei…..for use in **nuclear astrophysics**……At the same time methods for producing radioactive and isomeric nuclei, and for accelerating them in sufficient quantities have been proposed and even brought to the design stage with estimates for performance and cost….**Let’s get on with it!”**

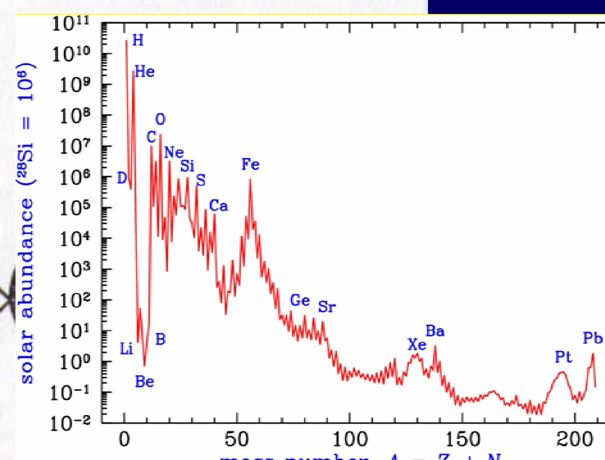
Willie Fowler, Parksville, 1985

The Big Picture



There is no silver bullet experiment but rather a program of difficult and complex studies.

Elemental Abundances



Nick Bateman

Important stellar radioactivities for gamma-ray line astronomy

DECAY CHAIN	MEAN LIFE* (yr)	LINE ENERGIES (MeV) (Branching Ratios)	SITE [Detected]	NUCLEAR PROCESS
^{7}Be→^{7}Li	0.21	0.478 (0.1)	Novae	Expl.H
^{56}Ni→^{56}Co^{+}→^{56}Fe	0.31	<u>0.847</u> (1.) <u>1.238</u> (0.68) 2.598 (0.17) 1.771 (0.15)	SN [SN1987A] [SN1991T]	NSE
^{57}Co→^{57}Fe	1.1	<u>0.122</u> (0.86) <u>0.136</u> (0.11)	SN [SN1987A]	NSE
^{22}Na^{+}→^{22}Ne	3.8	1.275 (1.)	Novae	Expl.H
^{44}Ti→^{44}Sc^{+}→^{44}Ca	89	<u>1.157</u> (1.) <u>0.068</u> (0.95) <u>0.078</u> (0.96)	SN [CasA]	α-NSE
^{26}Al^{+}→^{26}Mg	1.04 10^{6}	<u>1.809</u> (1.)	WR, AGB Novae SNII [inner Galaxy,Vela, Cygnus,Orion]	St.H Expl.H St.Ne Expl.Ne ν
^{60}Fe→^{60}Co→^{60}Ni	2.2 10^{6}	<u>1.332</u> (1.) <u>1.173</u> (1.)	SN [Galaxy]	n-capt
e^{+}	10^{5}-10^{7}	<u>0.511</u>	SNIa... [Galactic bulge]	β^{+}-decay

+ : positron emitters (associated 511 keV line)

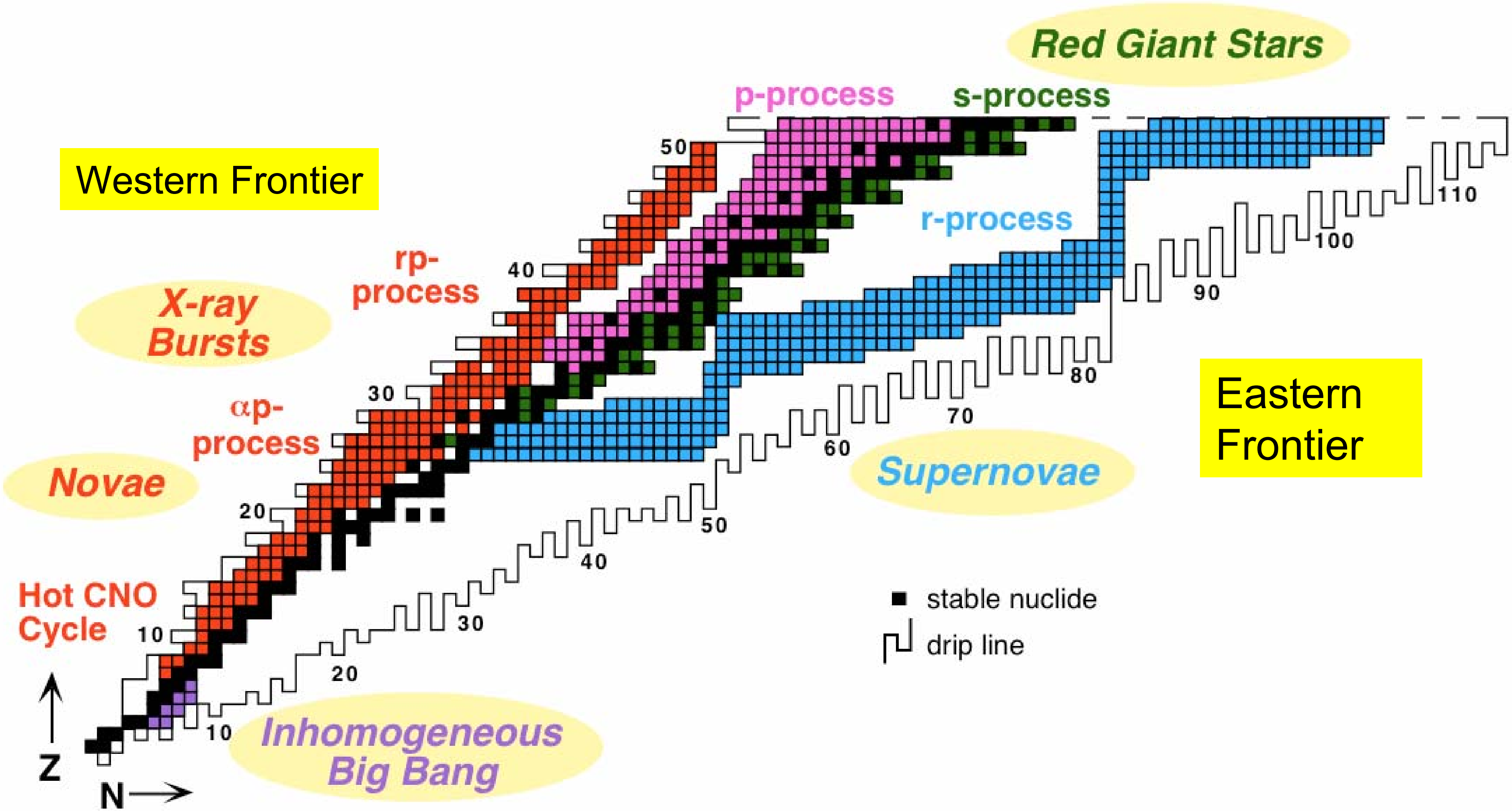
* : Double decay chains: the longest lifetime is given; *Underlined* : lines detected

In *parentheses* : branching ratios; In *brackets* : sites of lines detected

St.(Expl.) : Hydrostatic(Explosive) burning; NSE : Nuclear statistical equilibrium

α: α-rich "freeze-out"; n-capt : neutron captures; ν: neutrino-process

R. Diehl et al. (2005)



Role of Radioactive Beams in Nuclear Astrophysics

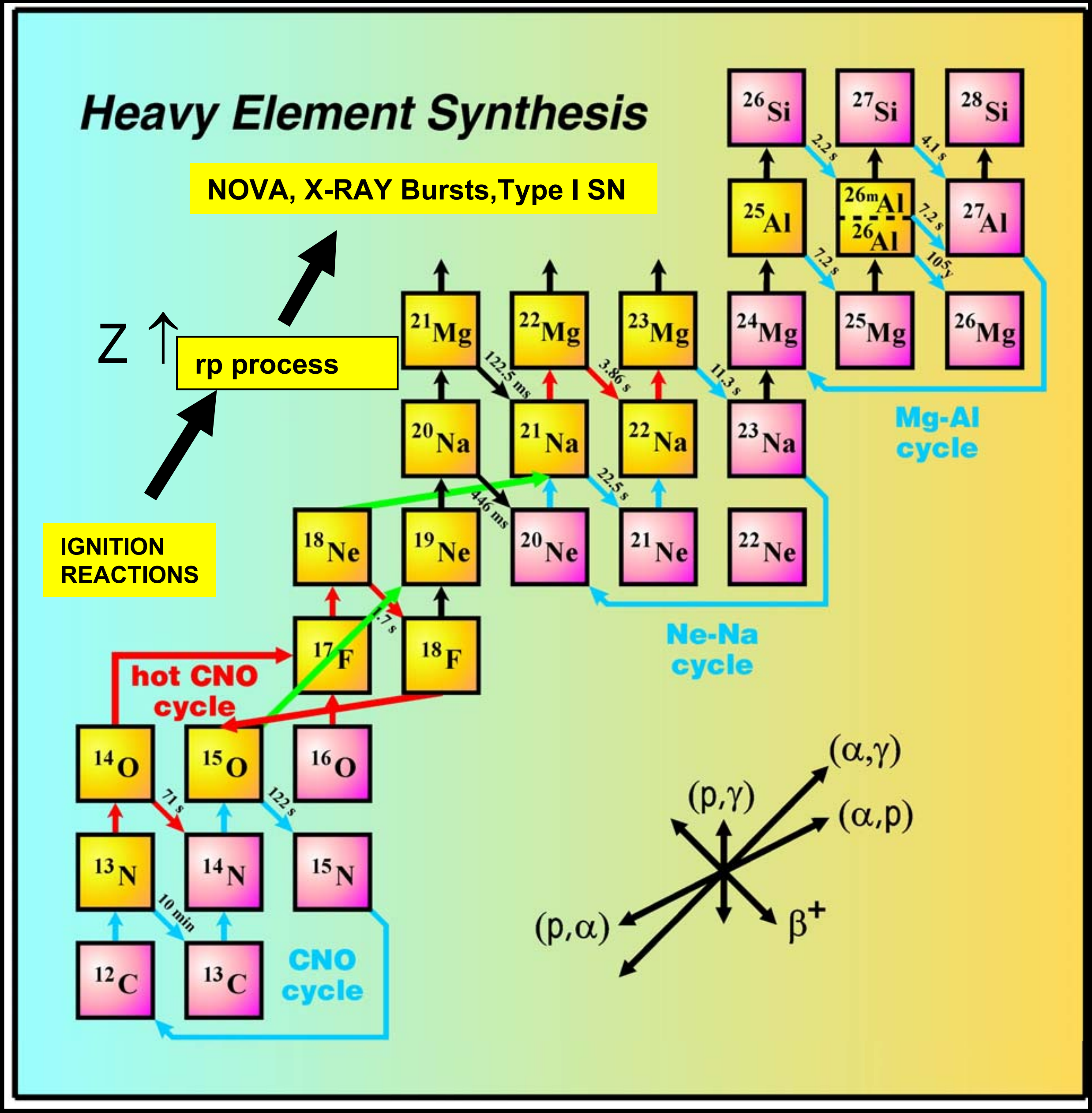
A number of publications including

M. Smith and E. Rehm, Ann. Rev. Nucl. Part. Phys. 51(2001)91

J. Blackmon, C. Angulo, A. Shotter, NP A (in press)

Proceedings of “Nuclei in the Cosmos VIII”,

Many laboratory proposals, e.g. RIA

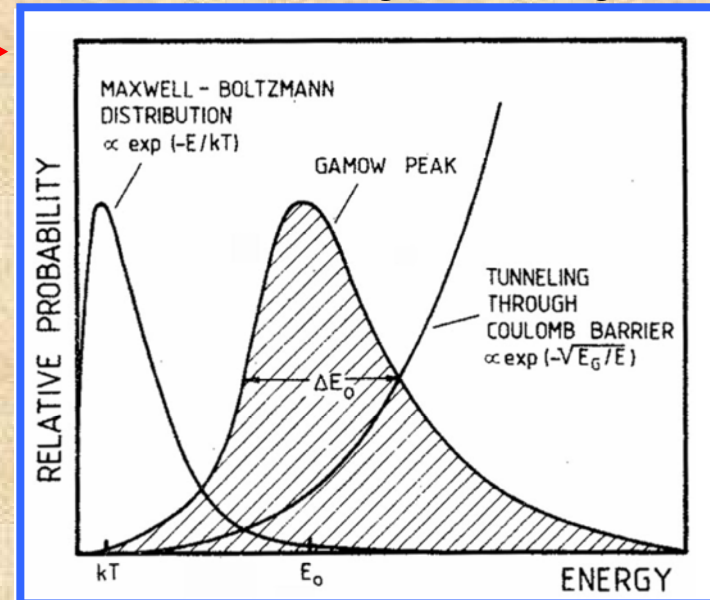


Western Frontier

The western frontier

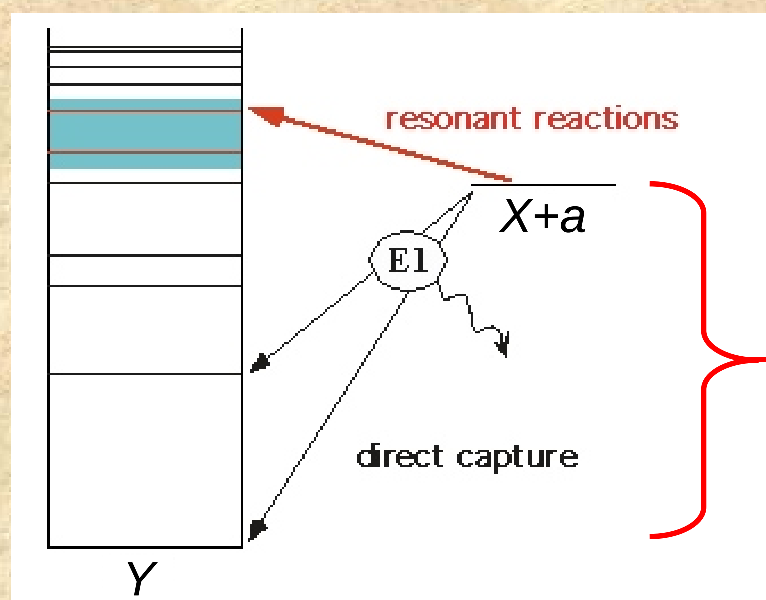
Energies are high: T, Z

Broader range of energies



$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi \mu}} (kT)^{3/2} \int_0^\infty S e^{-b/\sqrt{E}} e^{-E/(kT)} dE$$

Direct Capture



Lower binding energy for radioactive nuclei

Lower level density & broad states

$\rightarrow E_x, J^\pi, \Gamma_a$ or C^2S_a (Indirect Studies)

$$N_A \langle \sigma v \rangle = 1.54 \times 10^{11} (\mu T_9)^{-3/2} \omega\gamma \exp[-11.605 \, E_R/T_9]$$

Resonance Reactions

Thick Target Yield = ½ $\lambda_2 \omega\gamma (M_b + M_t)/M_t \varepsilon$

Jeff Blackmon

Indirect Techniques (mostly) with RIBs [focus on reaction rates]

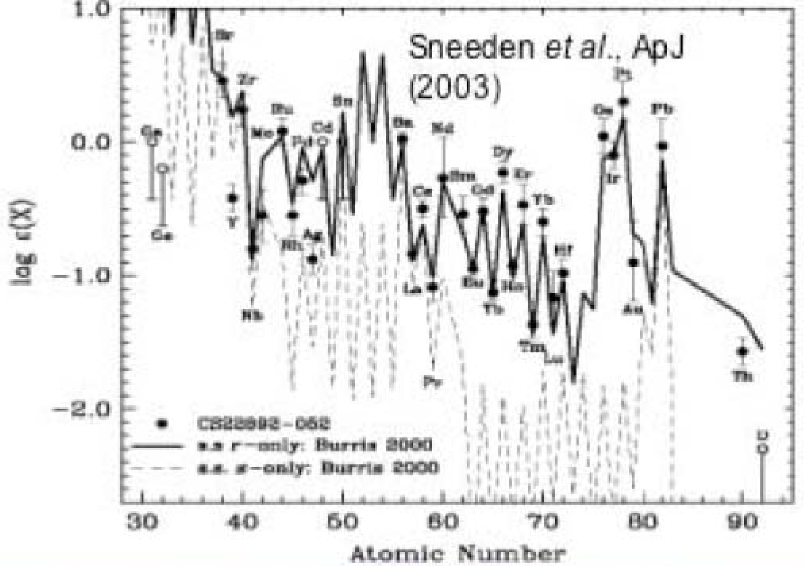
- **Radiative widths** for resonance rates

  - populate resonance state and measure decay
- **Locate resonance energies – E_R**
- **Coulomb dissociation (need high energy fragmentation beam)**

  [$^{7}Be(p,\gamma)^{8}B$, $^{8}B(p,\gamma)^{9}C$, $^{11}C(p,\gamma)^{12}N$, $^{22}Mg(p,\gamma)^{23}Al$]
- **Trojan Horse** (**no time to cover!**)

  - unique way to understand screening
- **Asymptotic Normalization Coefficients**

  - stable and radioactive beams

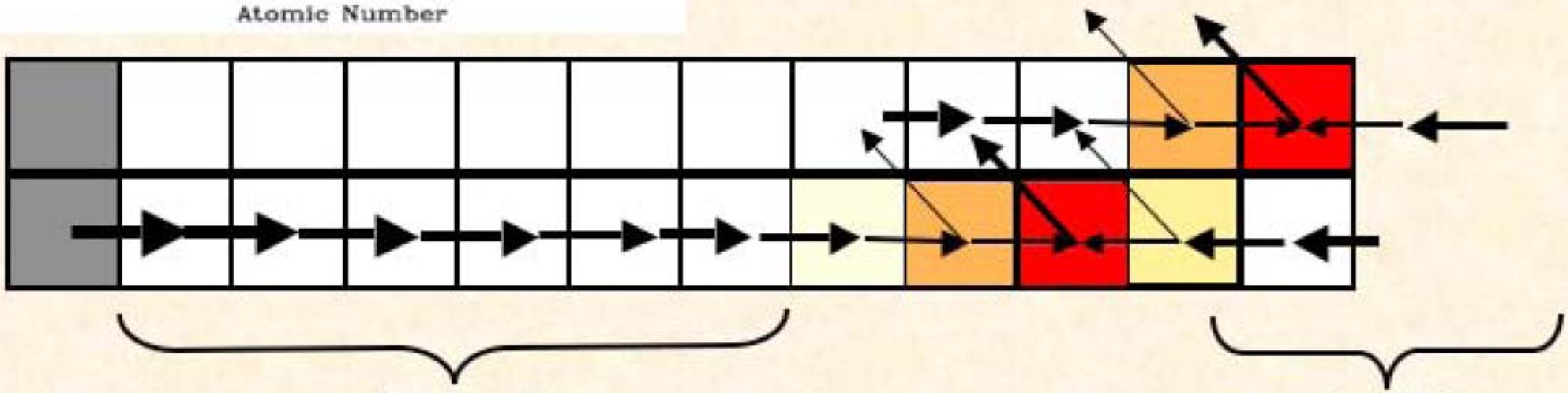


The eastern frontier

Tremendous new data from metal poor halo stars are helping us understand the r process

2 different r processes?

Need better data on neutron-rich nuclei



Large S_n

$(n,\gamma) >> (\gamma,n) >> t_{1/2}$

Small S_n

$(\gamma,n) >> (n,\gamma) >> t_{1/2}$

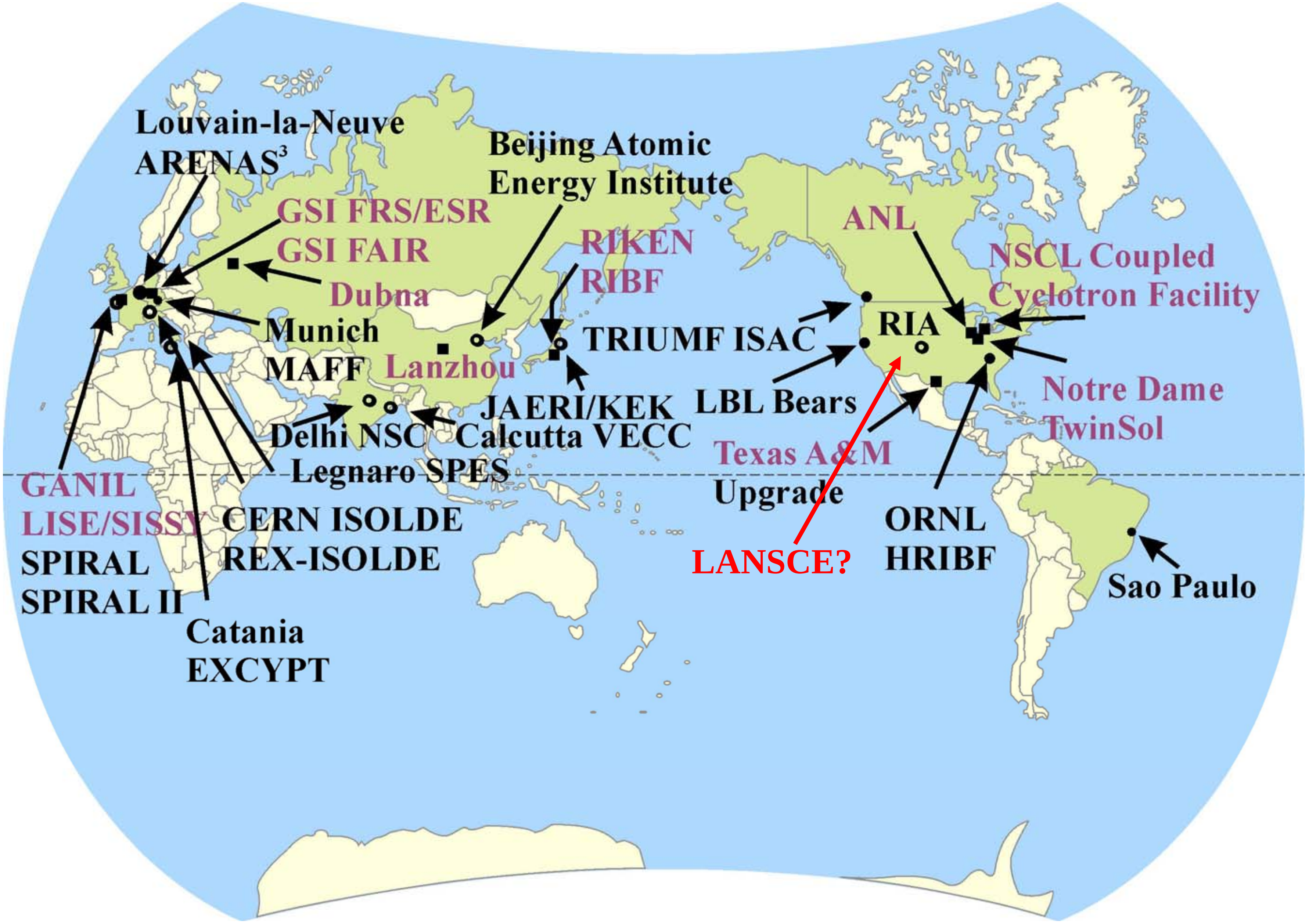
Masses, half-lives and decay properties (P_n) are crucial

However, only a few dozen r process nuclei have been created so far → 1000's left

Basic nuclear structure information is also crucial: E(2+), B(E2), Single-particle levels

Neutron Capture Cross Sections also needed for s-process and p-process

Facilities Worldwide



What is needed to do these studies ?

The most important requirement is the production of the RB.

ISOL (like) Approach (e.g. ISOLDE, ISAC, LLN, HRIBF, SPIRAL)

Projectile Fragmentation (e.g. GANIL, MSU, RIKEN, GSI)

In-flight Technique (e.g. TAMU, UND, RIKEN, ANL)

Alternate batch method (e.g. ANL, BEARS at LBL, ISAC?)

For masses, decay studies can use stopped RB (ISOL) of reasonable intensities, high purity, and appropriate detection systems , e.g. gamma arrays, traps, etc. or PF approach (masses in storage rings, decay of energetic fission fragments.

For Reaction Rates, **need**

- Radiative Capture - Direct Studies
  - Wide spectrum of **intense** (>10^8 p/s) radioactive beams (on target)
  - Low velocity (~0.2 – 1.5 MeV/u) accelerator
  - Appropriate detection systems (inverse kinematics)
    - e.g. DRAGON at ISAC, ARES at Louvain, DRS at HRIBF

- Particle Reactions (Direct) and Radiative Capture Reactions (Indirect)
  - Wide spectrum of reasonably intense (~10^{4-6} p/s) radioactive beams
  - Higher velocity accelerator for indirect studies
  - Appropriate detection/separator systems
  - e.g. TUDA with EMMA at ISAC, CRIB at RIKEN, RMS at HRIBF
    REX-ISOLDE systems, VAMOS at GANIL, FMA at ANL

What is happening at some facilities?

<u>INDIRECT STUDIES</u>

Louvain

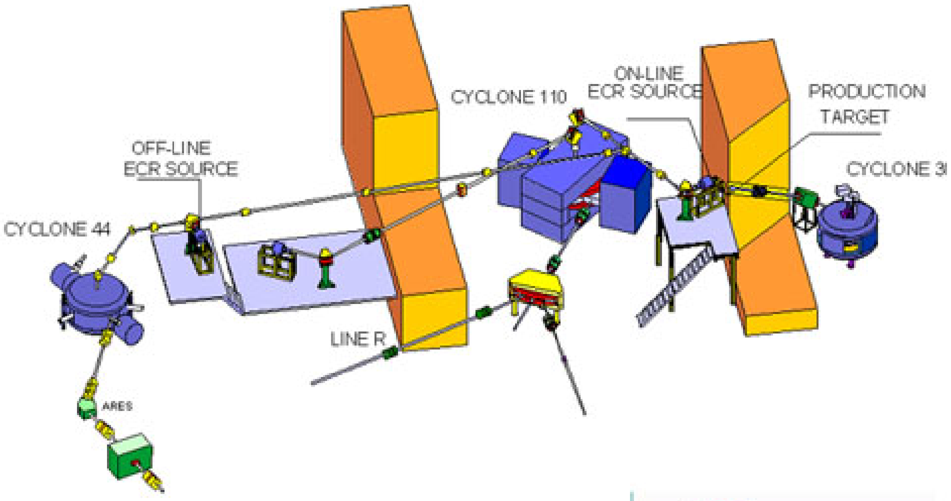
HRIBF/ORNL

GANIL/SPIRAL

RIKEN

ANL

Louvain-la Neuve



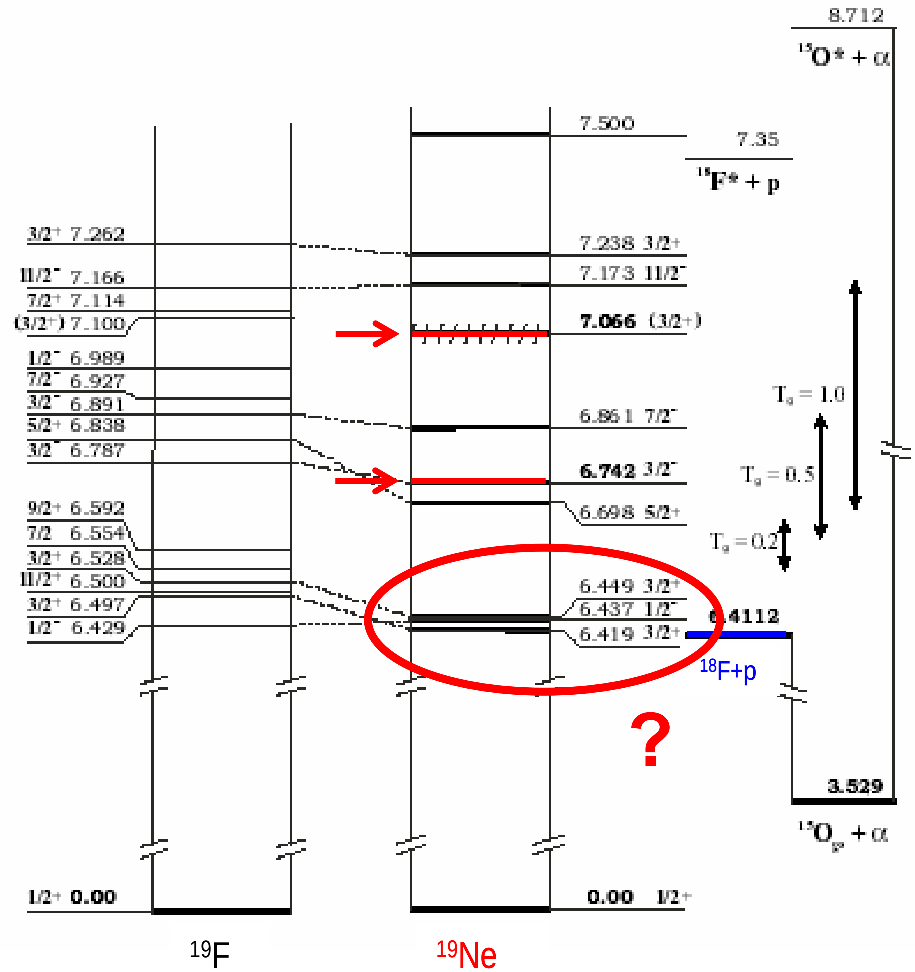
Element	$T_{1/2}$	*q*	*Intensity [pps]*	*Energy range [MeV]*
^{6}Helium	0.8 s	1+ 2+	$9\cdot10^{6}$ $3\cdot10^{5}$	5.3 - 18 30 – 73
^{7}Beryllium	53 days	1+ 2+	$2\cdot10^{7}$ $4\cdot10^{6}$	5.3 - 12.9 25 – 62
^{10}Carbon	*19.3 s*	1+ 2+	$2\cdot10^{5}$ $1\cdot10^{4}$	*5.6 - 11* *24 - 44*
^{11}Carbon	20 min	1+	$1\cdot10^{7}$	6.2 - 10
^{13}Nitrogen	10 min	1+ 2+ 3+	$4\cdot10^{8}$ $3\cdot10^{8}$ $1\cdot10^{8}$	7.3 - 8.5 11 - 34 45 - 70
^{15}Oxygen	2 min	2+	$6\cdot10^{7}$ $1\cdot10^{8}$	10 - 29 6 - 10.5 *
^{18}Fluorine	110 min	2+	$5\cdot10^{6}$	11 - 24
^{18}Neon	1.7 s	2+ 3+	$6\cdot10^{6}$ $4\cdot10^{6}$	11 - 24 24 - 33,45 - 55
^{19}Neon	17 s	2+ *2+* 3+ 4+	$2\cdot10^{9}$ *$5\cdot10^{9}$* $1.5\cdot10^{9}$ $8\cdot10^{8}$	11 - 23 *7.5 - 9.5 ** 23 - 35,45 - 50 60 - 93
^{35}Argon	1.8 s	3+ 5+	$2\cdot10^{6}$ $1\cdot10^{5}$	20 - 28 50 - 79

The role of $^{18}F(p,\alpha)^{15}O$ in the nova nucleosynthesis

- The $^{18}F(p,\alpha)^{15}O$ rate is largely uncertain: up to 300 on the γ-ray flux due to the unknown low-energy resonance strengths (A. Coc et al. A&A 2000)

- Most important reaction for understanding positron annihilation radiation from Novae
  - Previous studies at Louvain-la-Neuve, Oak Ridge and Argonne concentrated mainly on two ^{19}Ne states:
    - 7.066 MeV (3/2+)
    - 6.742 MeV (3/2-)
  - Influence of the low-energy levels? Interferences ?
    - 6.449 MeV (3/2+)
    - 6.437 MeV (1/2-)
    - 6.419 MeV (3/2+)
- Possible missing states ~6.5 - 7 MeV

- Present studies at ORNL and Louvain



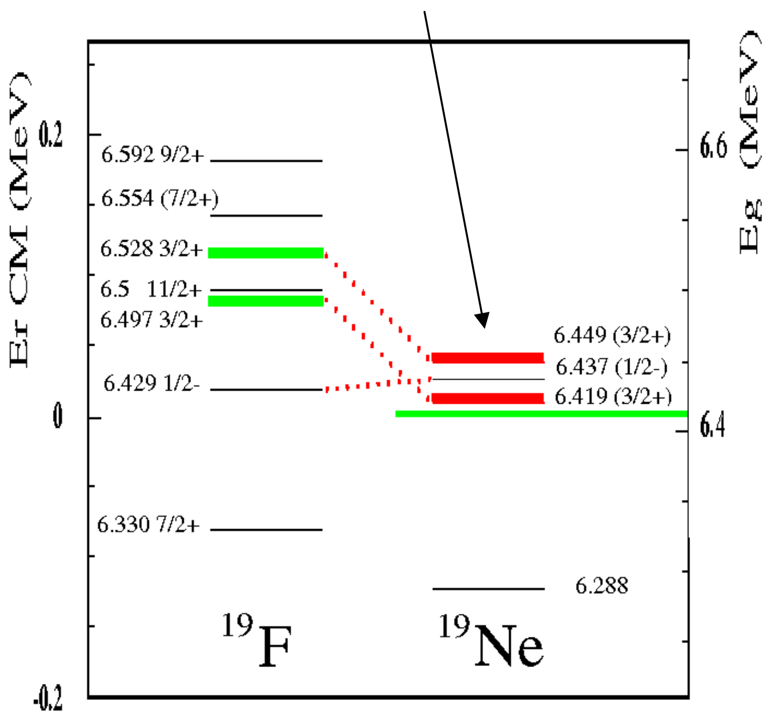
[J.S. Graulich et al. Phys. Rev. C63, 011302(R) (2001), and references therein.]

LLN

$^{18}F(d,p\alpha)^{15}N$: *an indirect way to investigate $^{18}F(p,\alpha)^{15}O$*

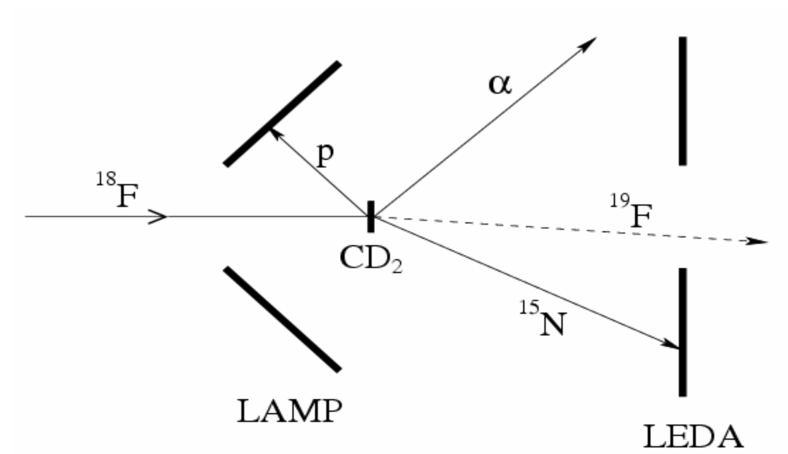
Study the analog levels in ^{19}F by the transfer reaction $d(^{18}F,p)^{19}F(\alpha)^{15}N$

^{19}Ne levels of interest



Experimental set up:

- A **14 MeV ^{18}F beam** (2×10^6 pps) on a CD_2 target
- Coincidences p (LAMP) and ^{15}N or α (LEDA)

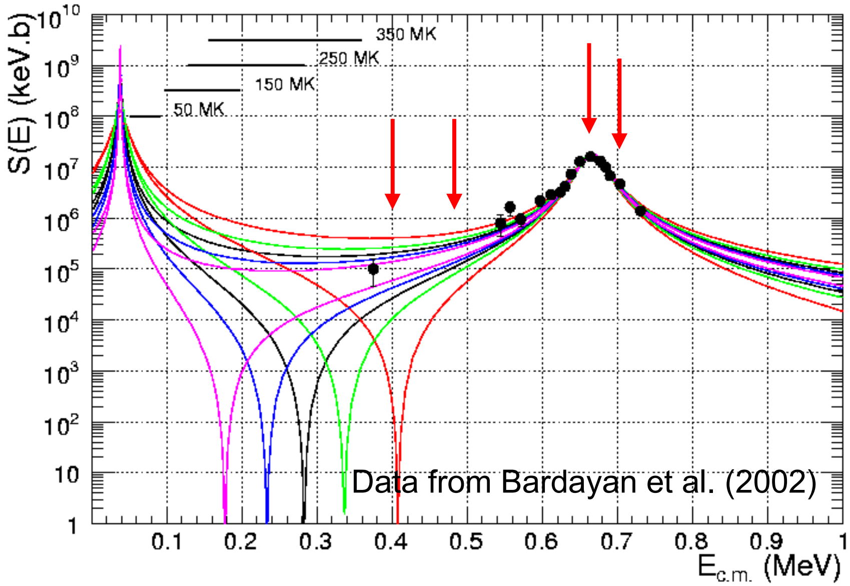


Carmen Argulo

A new $^{18}F(p,\alpha)$ direct measurement

May 17 – 25, 2005 @ Louvain-la-Neuve

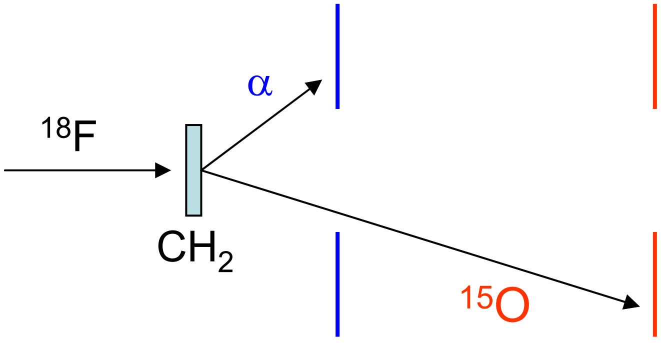
- **Remaining nuclear uncertainties**:
  - α-width for low energy resonances
  - interferences sign between $3/2^+$ resonances



Also: a proposal at TRIUMF on $^{18}F(p,\alpha)^{15}O$ (A. Laird, A. Murphy)

Experimental setup:

2 LEDA detectors in coincidence

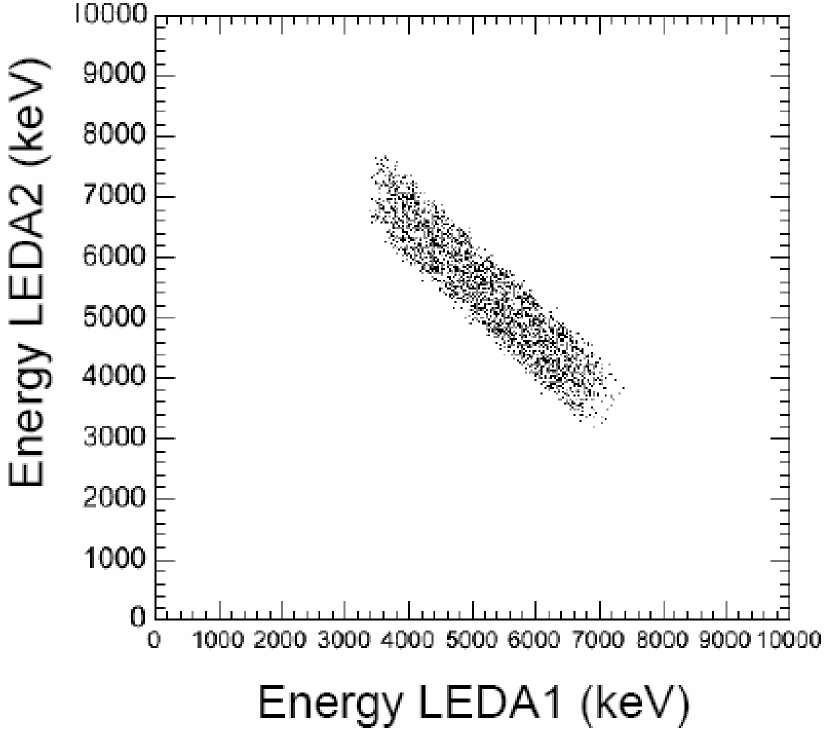


- nominal ^{18}F beam energy: 13.7 MeV
- beam current ~ $5 \times 10^5 – 3 \times 10^6$ pps
- a 70 $\mu g/cm^2$ CH2 target
- Al foil degraders: **measurement at 4 energies** (red arrows)
- total efficiency (incl α-15O coinc.) ≈ 27%

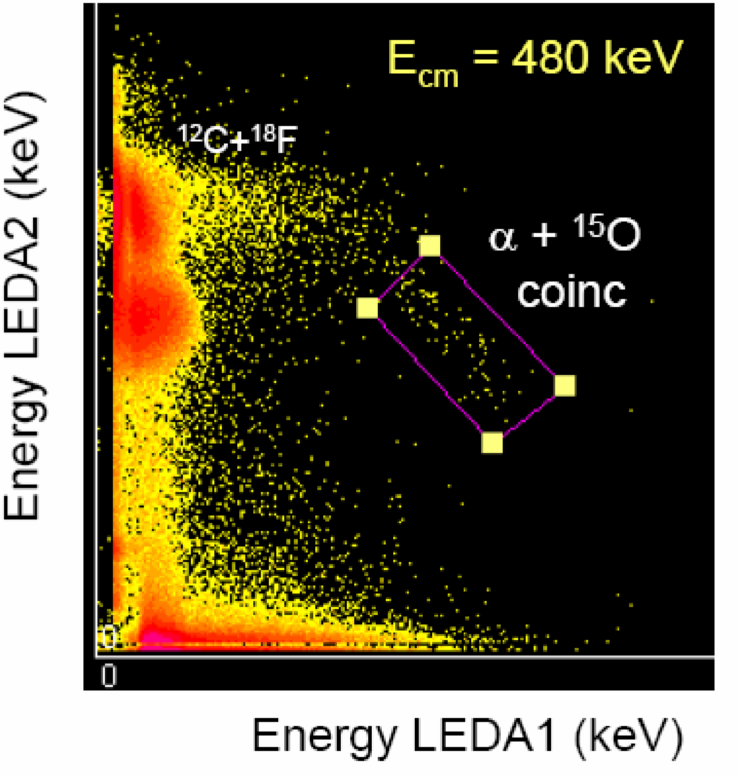
Carmen Argulo

On-line results

MC simulations



Typical spectrum



- Good agreement between data and simulations
- Statistics consistent with estimations

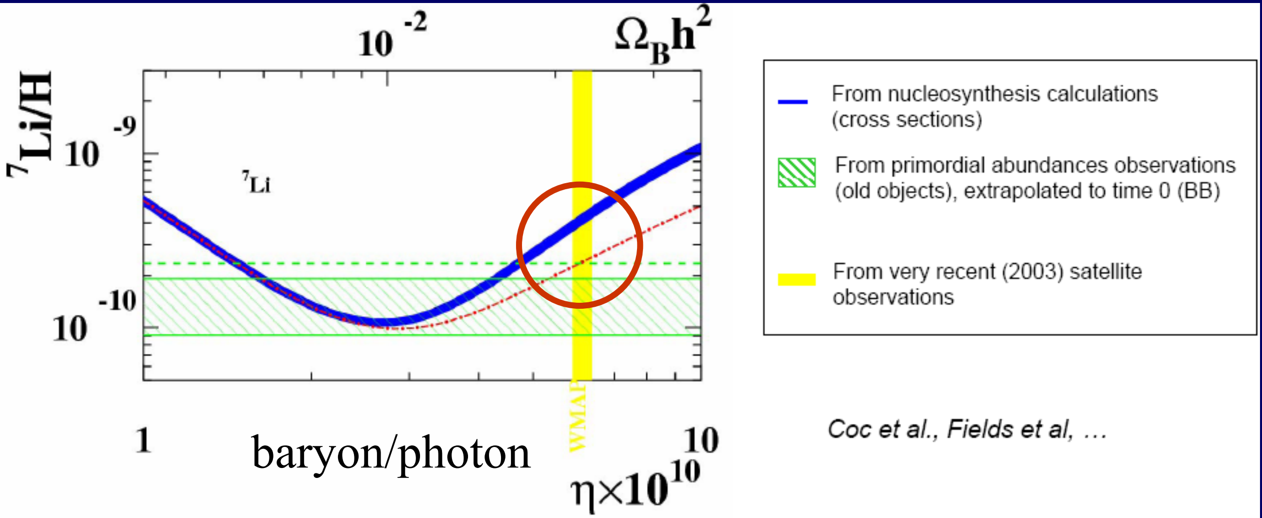
Still too early to conclude on the interference sign

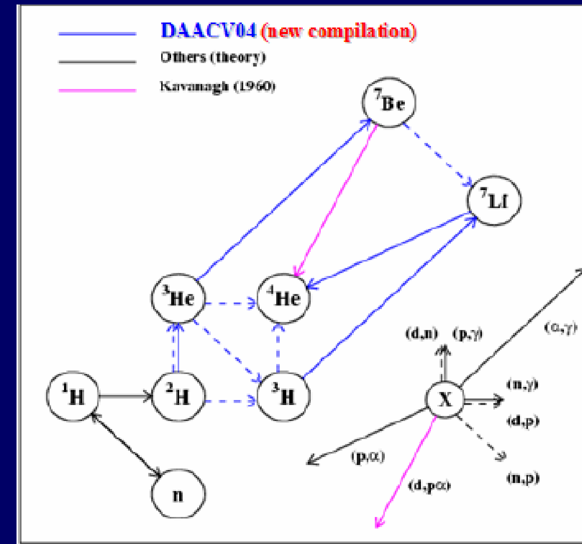
- E_{cm} = 480 keV ~150 events
- E_{cm} = 400 keV ~40 events

CRC

LLN

^{7}Be(d,p) and the 7Li primordial abundance





What about ^{7}Be(d,p)^{8}Be→2α ??

Beam intensity: $(0.2\text{-}1)\times10^{7}$ pps of ^{7}Be (no ^{7}Li contamination observed)

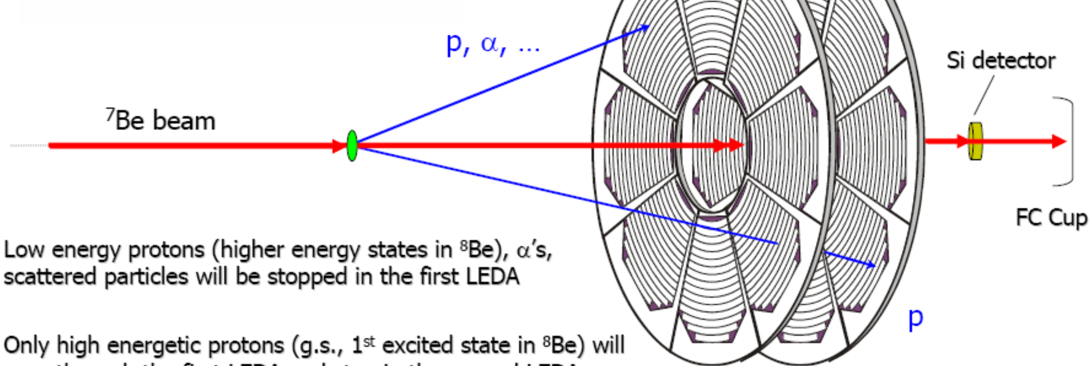
Beam energies: 5.545 and 1.710 MeV (c.m. range: 1.2-0.96 MeV and 0.38-0.15 MeV)

Target: 200 μg/cm² CD_2

Detectors: two (LEDA) multi-strips (8ϕ×16θ) Si detectors (thickness 300 and 500 μm):

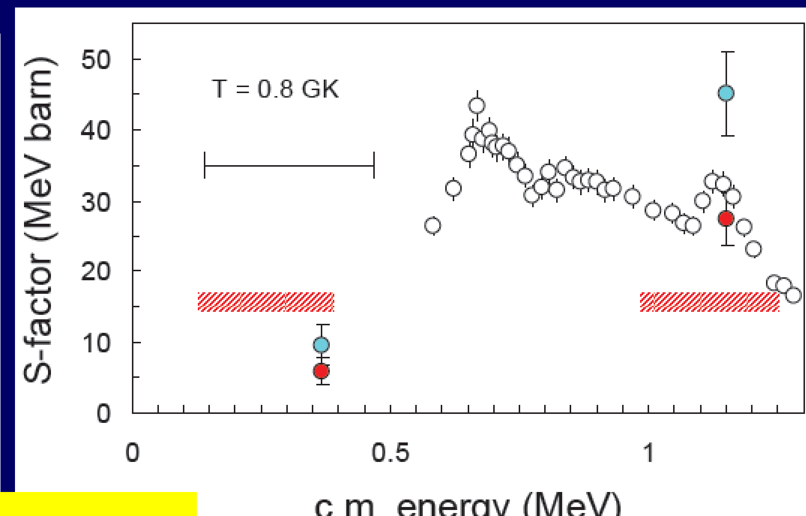
→ $\Delta E_1 - \Delta E_2$ system

→ angular covering : 7° - 17° (lab)



Low energy protons (higher energy states in ^{8}Be), α's, scattered particles will be stopped in the first LEDA

Only high energetic protons (g.s., 1st excited state in ^{8}Be) will pass through the first LEDA and stop in the second LEDA

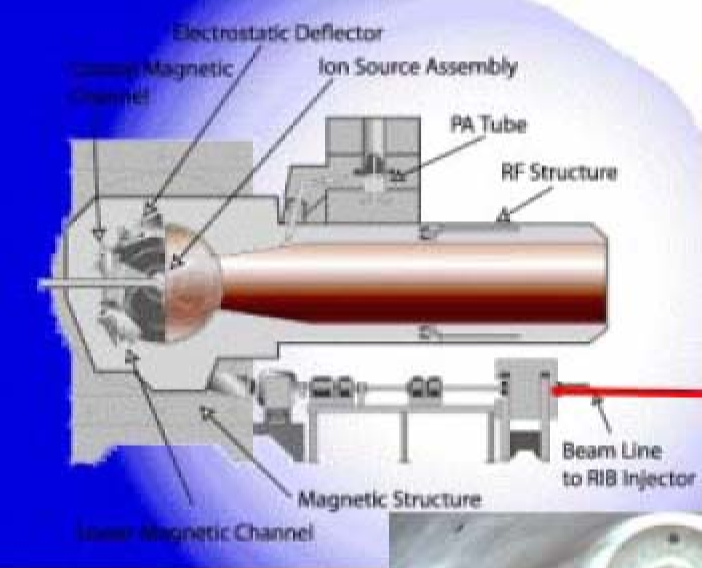


In press

Negligible effect in BBN:

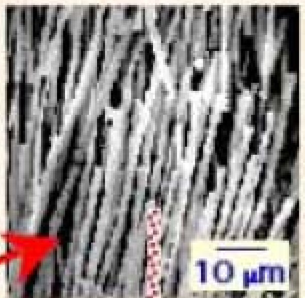
^{7}Li problem persists

ISOL
(e.g. Holifield RIBF)

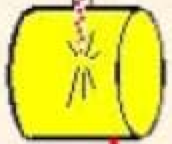


ORIC

p, d, or α



Hot, fibrous
production target



Ion source

RIB
(300 keV)

Mass analysis

25 MV tandem

Installing HPTL
2nd Production
Target system

To
experiments

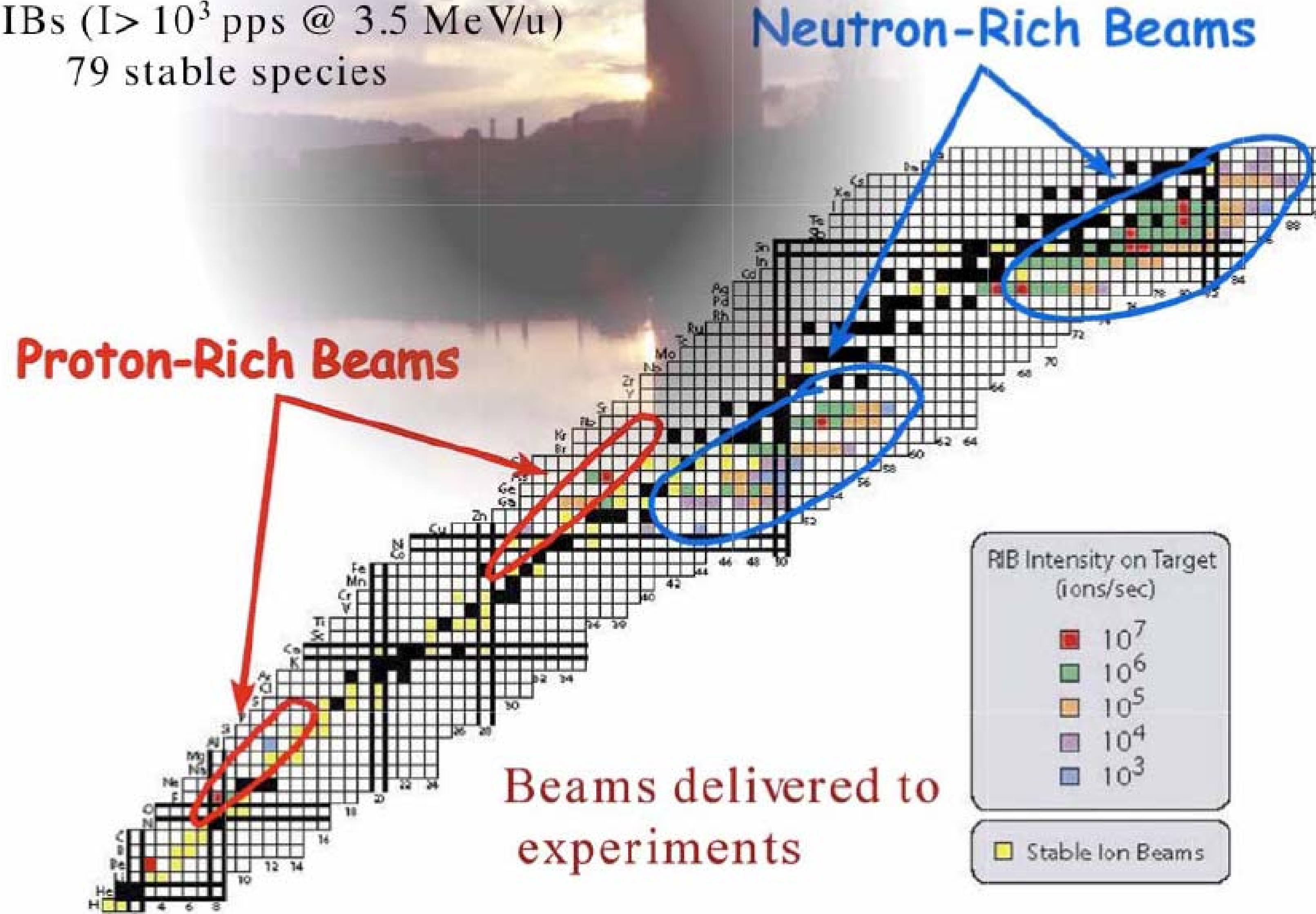
Jeff Blackmon

HRIBF Beams

Full suite of developed beams

120 RIBs (I> 10^3 pps @ 3.5 MeV/u)

79 stable species



Beams delivered to experiments

Michael Smith

HRIBF Measurements

Radioactive beams to understand Novae & X-ray bursts, Supernovae, & the Sun

- **$^{17}F(p,\gamma)^{18}Ne$** studied via
  - $^{17}F(p,p)^{17}F$ — INDIRECT TECHNIQUE — Scattering
  - $^{14}N(^{17}F, ^{18}Ne)^{13}C$ & $^{14}N(^{17}F, ^{17}F)^{14}N$ — INDIRECT — Asymptotic Normalization Coefficients

- **$^{14}O(\alpha,p)^{17}F$** via
  - $^{17}F(p,\alpha)^{14}O$ — INDIRECT — Inverse
  - $^{17}F(p,p)^{17}F$ — INDIRECT — Scattering
  - $^{17}F(p,p')^{17}F^{*}$ — INDIRECT — Scattering (Inelastic)

- **$^{18}F(p,\alpha)^{15}O$ and $^{18}F(p,\gamma)^{19}Ne$** via
  - $^{18}F(p,p)^{18}F$ thin — INDIRECT — Scattering
  - $^{18}F(p,p)^{18}F$ thick — INDIRECT — Scattering
  - $^{18}F(p,\alpha)^{15}O$ 660 keV level — **DIRECT** — Resonance Yield
  - $^{18}F(d,p)^{19}F$ — INDIRECT — Transfer
  - $^{18}F(p,\alpha)^{15}O$ 330 keV level — **DIRECT** — Resonance Yield
  - $^{18}F(d,n)^{19}Ne$ — INDIRECT — Transfer

- **$^{7}Be(p,\gamma)^{8}B$** via
  - $^{7}Be(p,\gamma)^{8}B$ — **DIRECT** — Non-Resonant Capture Yield
  - $^{7}Be(p,p)^{7}Be$, $^{7}Be(p,p^{*})^{7}Be$ — INDIRECT — Scattering

- **$^{3}He(^{3}He,2p)$** studied via
  - $^{7}Be(d,t)^{6}Be$ — INDIRECT — Transfer

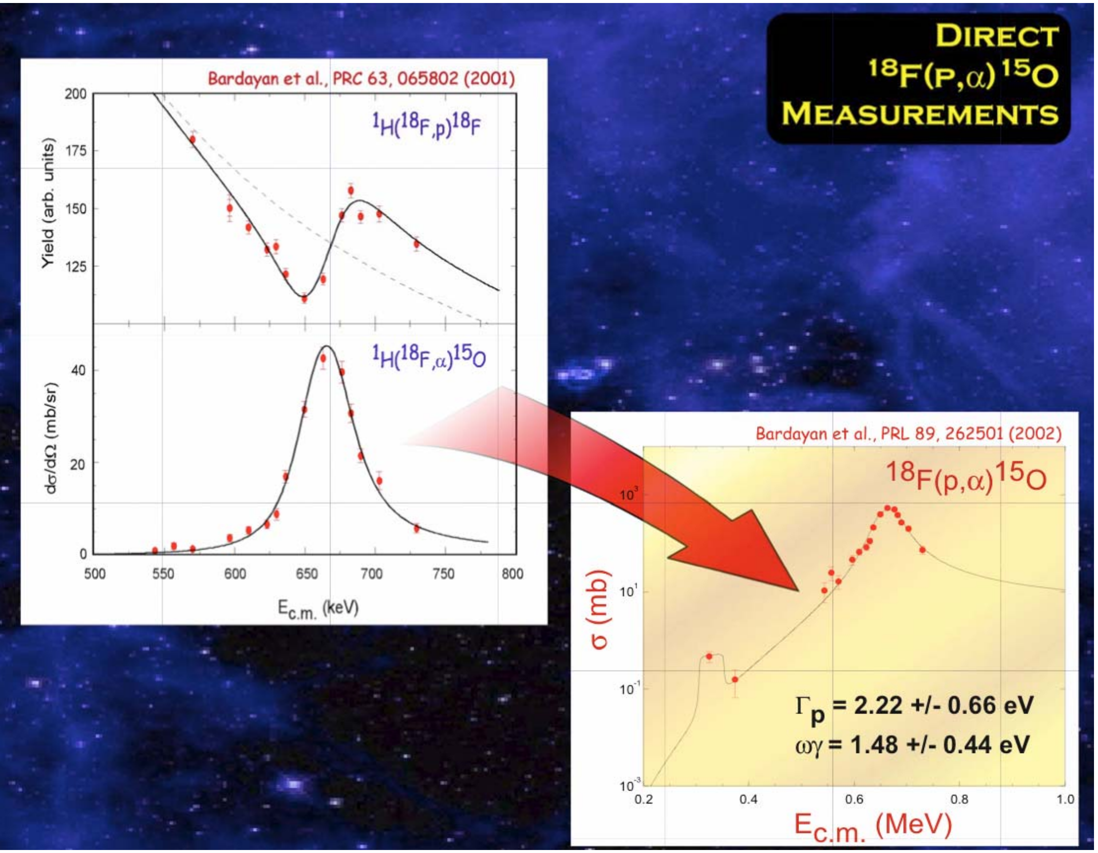
- **$^{82}Ge(n,\gamma)^{83}Ge$** via
  - $^{82}Ge(d,p)^{83}Ge$ — INDIRECT — Transfer

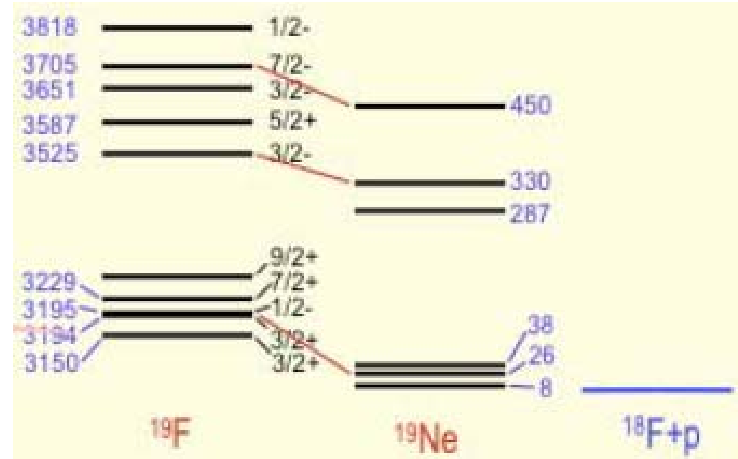
- **$^{84}Se(n,\gamma)^{85}Se$** via
  - $^{84}Se(d,p)^{85}Se$ — INDIRECT — Transfer

Michael Smith

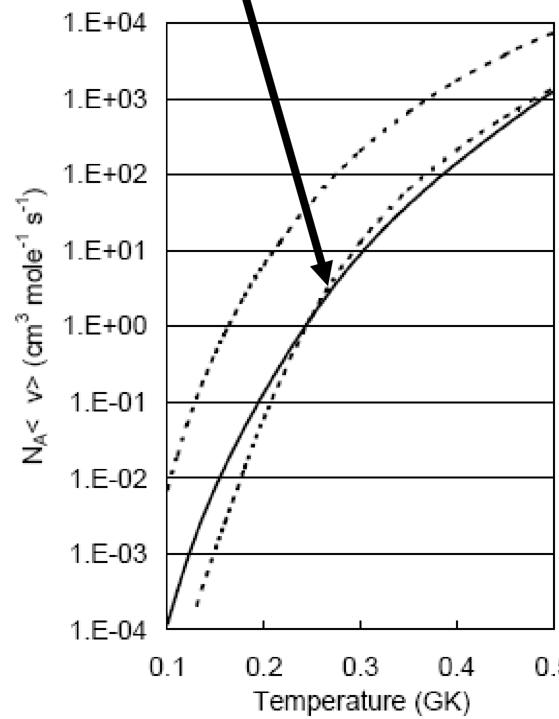
HRIBF

$^{18}F(p,\alpha)^{15}O$ Rate Using Direct and Indirect Studies

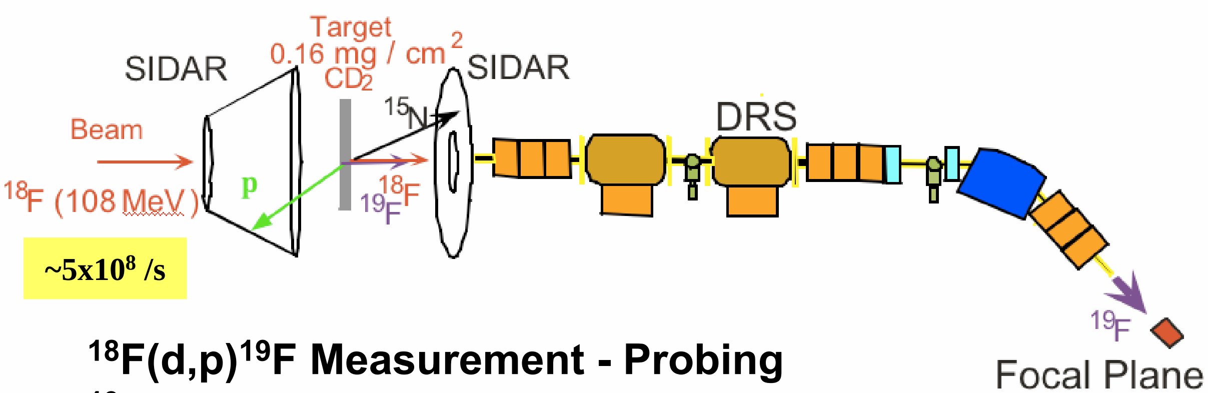




Using indirect info, deduced Γ_p of 8,38, 287 keV states; calculated new rate for reaction; factor 3-5 smaller.

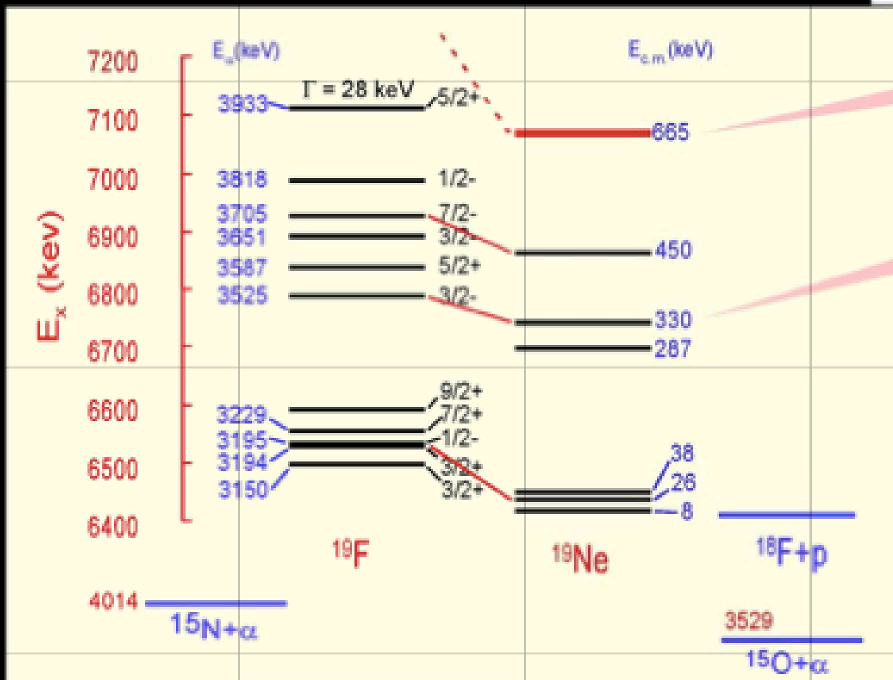


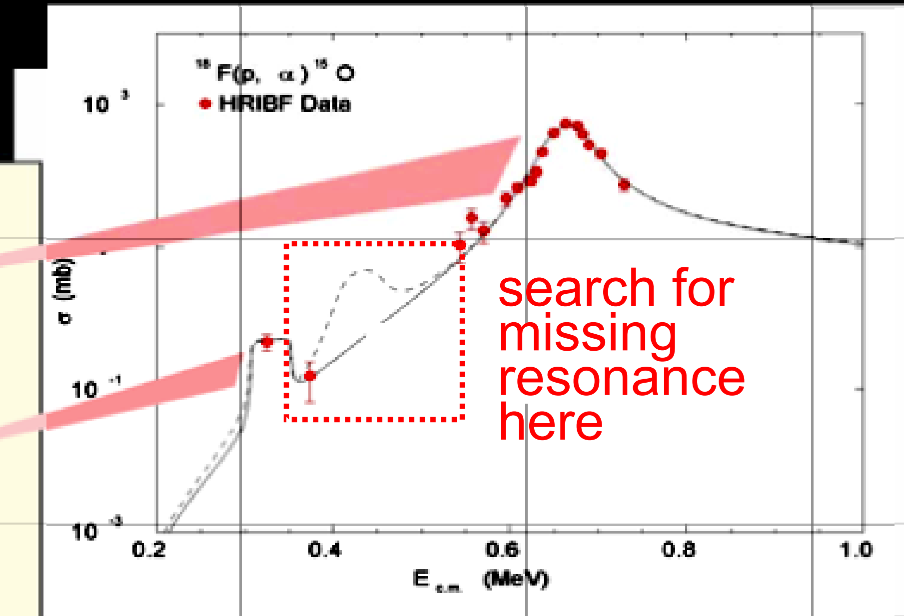
Kozub et al, NP A 758 (2005)

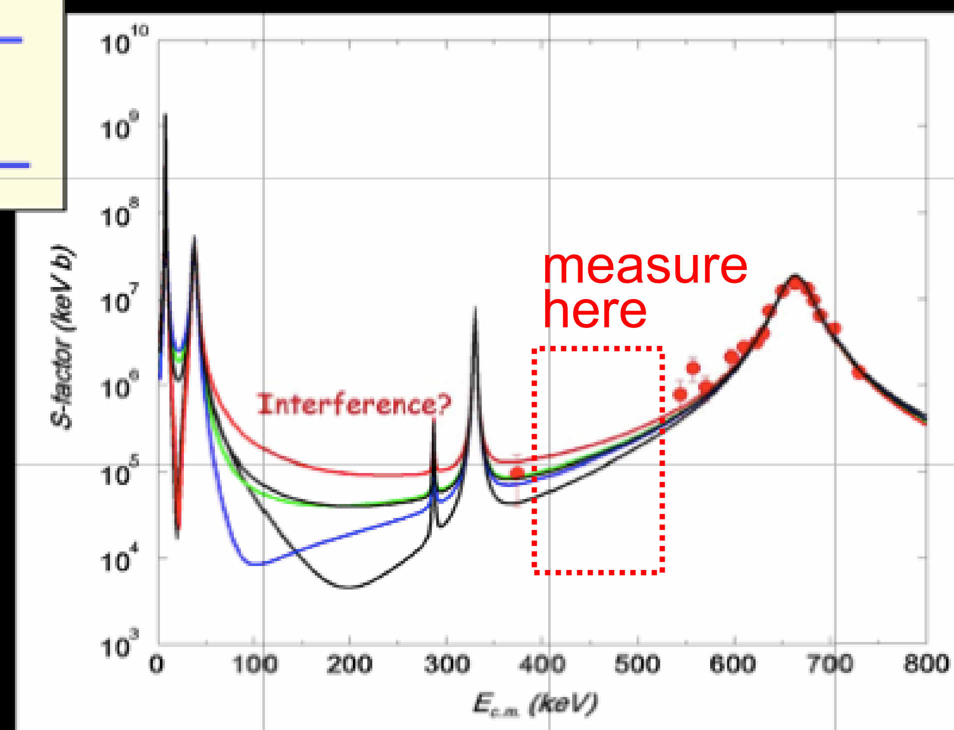


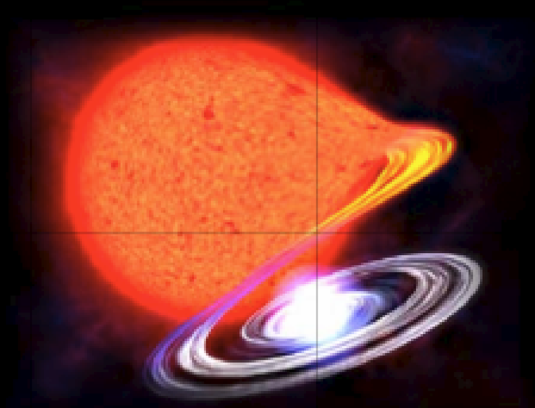
$^{18}F(d,p)^{19}F$ Measurement - Probing ^{19}Ne Analog States

August 2005: $^{18}F(p,\alpha)$ resonance search

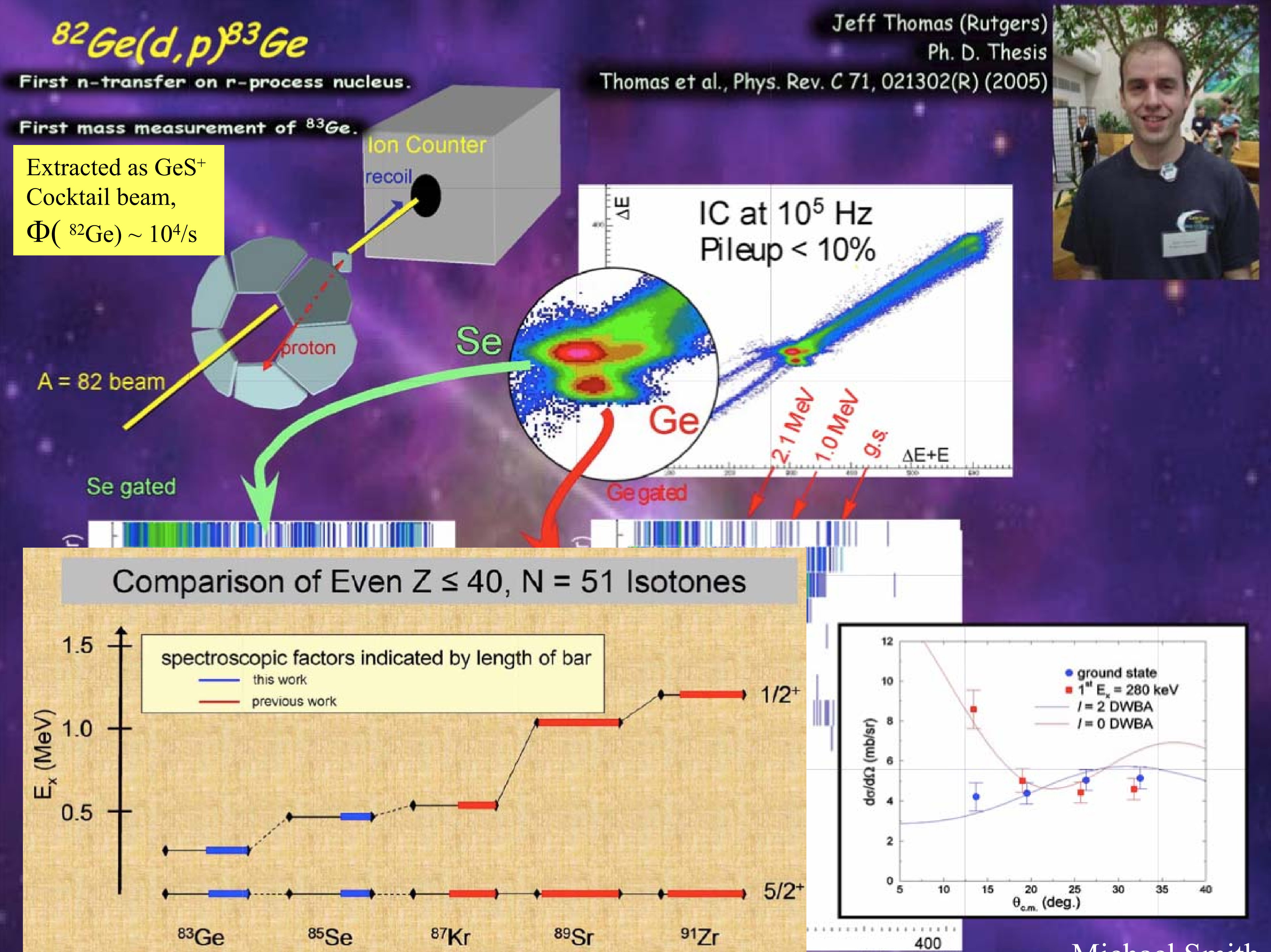








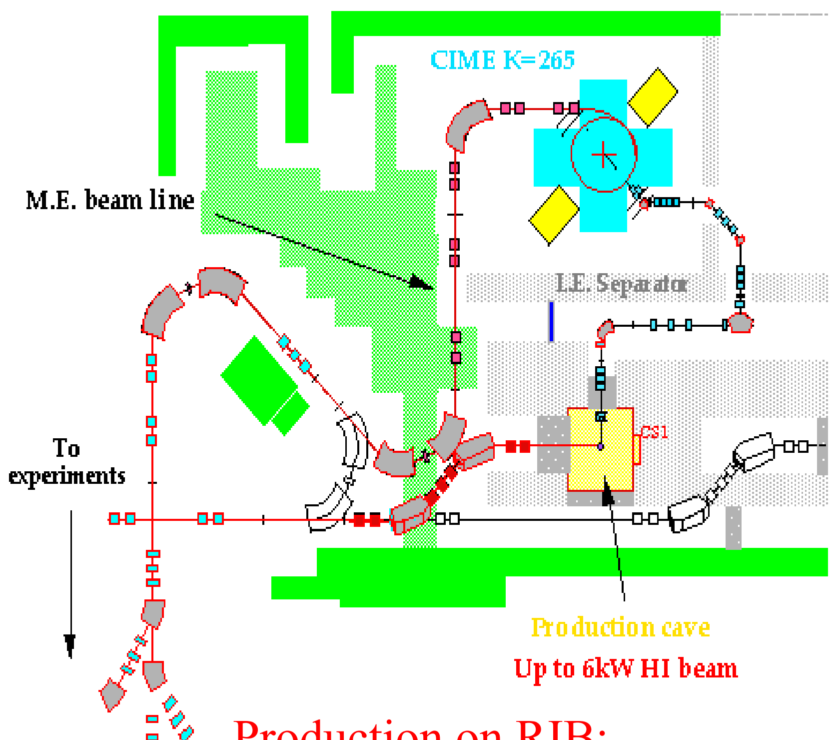
Michael Smith


$^{82}Ge(d,p)^{83}Ge$
First n-transfer on r-process nucleus.
First mass measurement of ^{83}Ge.
Jeff Thomas (Rutgers)
Ph. D. Thesis
Thomas et al., Phys. Rev. C 71, 021302(R) (2005)
Extracted as GeS^{+}
Cocktail beam,
$\Phi(^{82}Ge) \sim 10^{4}/s$
Ion Counter
recoil
proton
A = 82 beam
Se
Ge
IC at 10^5 Hz
Pileup < 10%
ΔE
ΔE+E
2.1 MeV
1.0 MeV
g.s.
Se gated
Ge gated
Comparison of Even Z ≤ 40, N = 51 Isotones
spectroscopic factors indicated by length of bar
this work
previous work
E_x (MeV)
1.5
1.0
0.5
1/2+
5/2+
^{83}Ge
^{85}Se
^{87}Kr
^{89}Sr
^{91}Zr
ground state
1st E_x = 280 keV
l = 2 DWBA
l = 0 DWBA
$d\sigma/d\Omega$ (mb/sr)
$\theta_{c.m.}$ (deg.)
400
Michael Smith

Examples of RIB at SPIRAL1/GANIL

Primary beam	secondary beam	Max Intensity pps	Emin-Emax A.MeV
^{16}O	^{15}O	3.10^7	4-25
^{20}Ne	^{18}Ne	10^7	3-20
^{36}Ar	^{34}Ar	10^6	4-12
^{36}Ar	^{35}Ar	3.10^7	4-12
^{48}Ca	^{44}Ar	2.10^5	4-11
^{48}Ca	^{46}Ar	2.10^4	4-11

SPIRAL



Production on RIB:

-in flight fragmentation (~60A.MeV)

-in target fragmentation SPIRAL acceleration up to 20A.MeV

Production of post-accelerated secondary beams :

-optical quality similar to primary beams

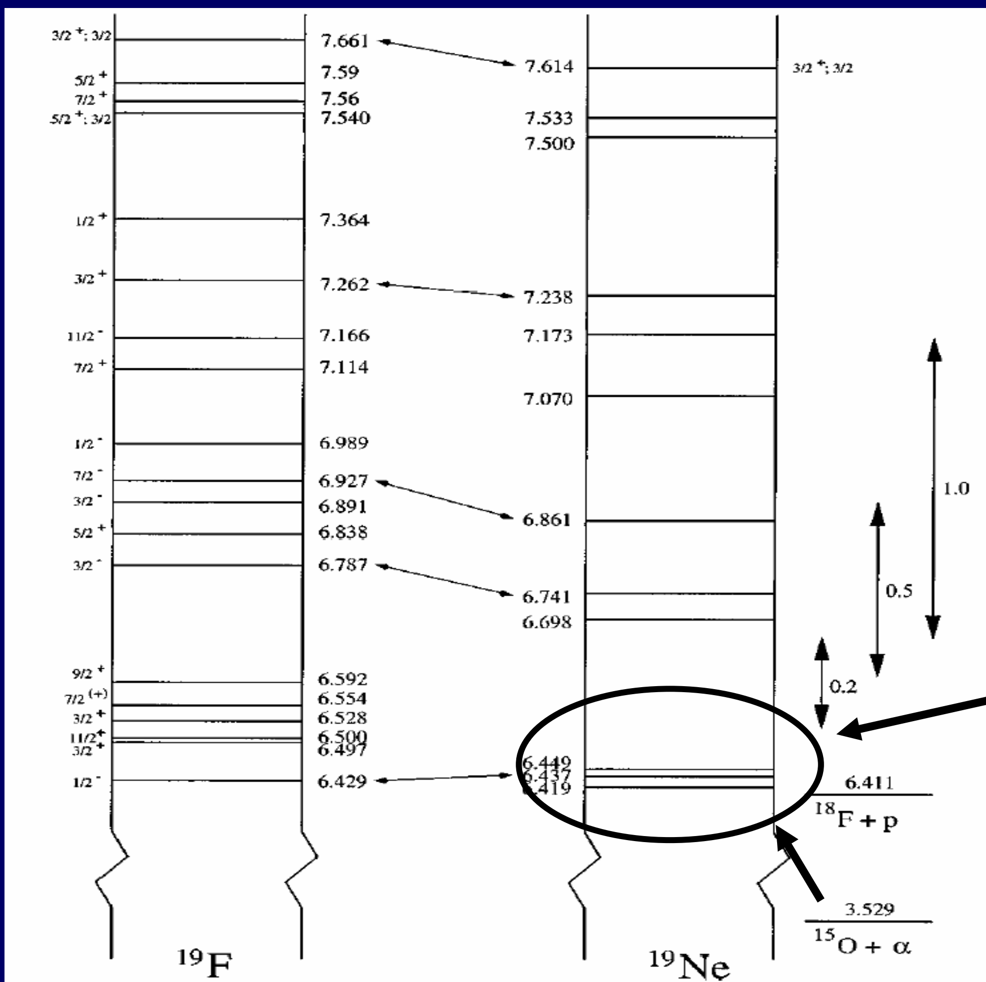
-used in existing experimental areas

O. Sorlin

GANIL

Proposal: $^{15}O(\alpha,\alpha)^{15}O$ to measure levels in ^{19}Ne

deOliveira, et al

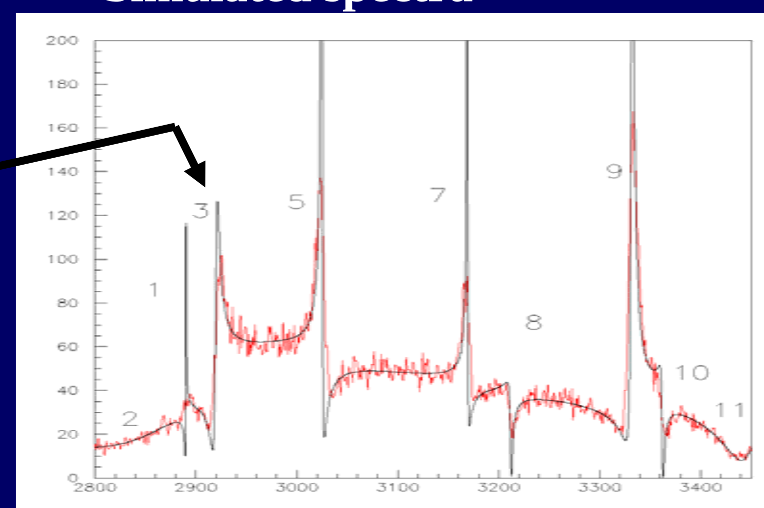


Rationale: Important for $^{18}F(p,\alpha)$

Background: Good cross section
1st excited state ^{15}O high
Could obtain desired info
Beam available

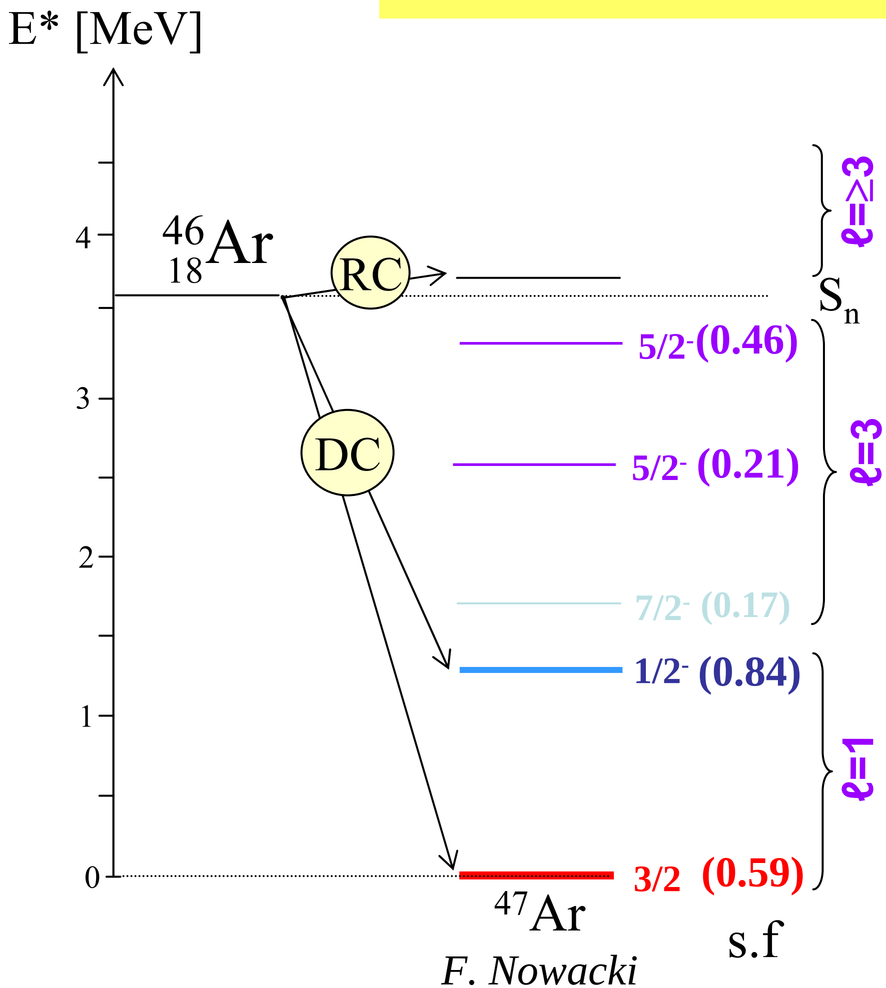
Requirements: ^{15}O - ~ 8 x 10^7 /s
1.74 MeV/u

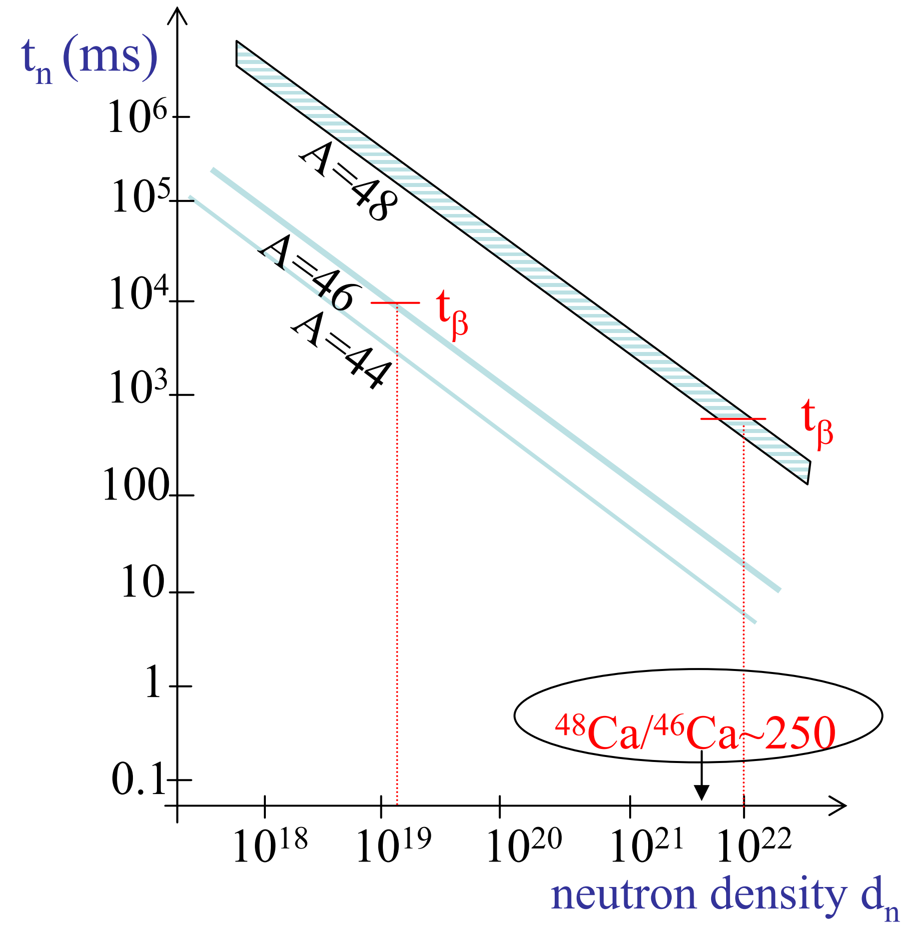
Simulated spectra



Study of the N=28 closed shell through $^{45,47}Ar(d,p)$ reaction

Neutron capture rates on $^{44,46,48}Ar$





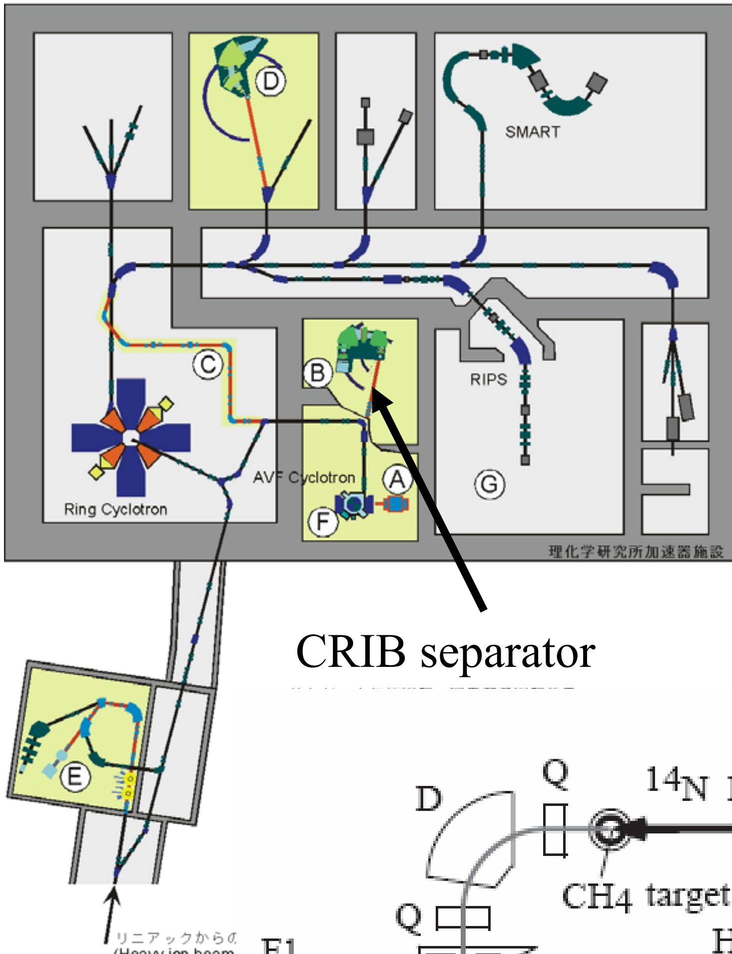
(d,p) access to E*, s.f., spins → derive (n,γ) stellar rates

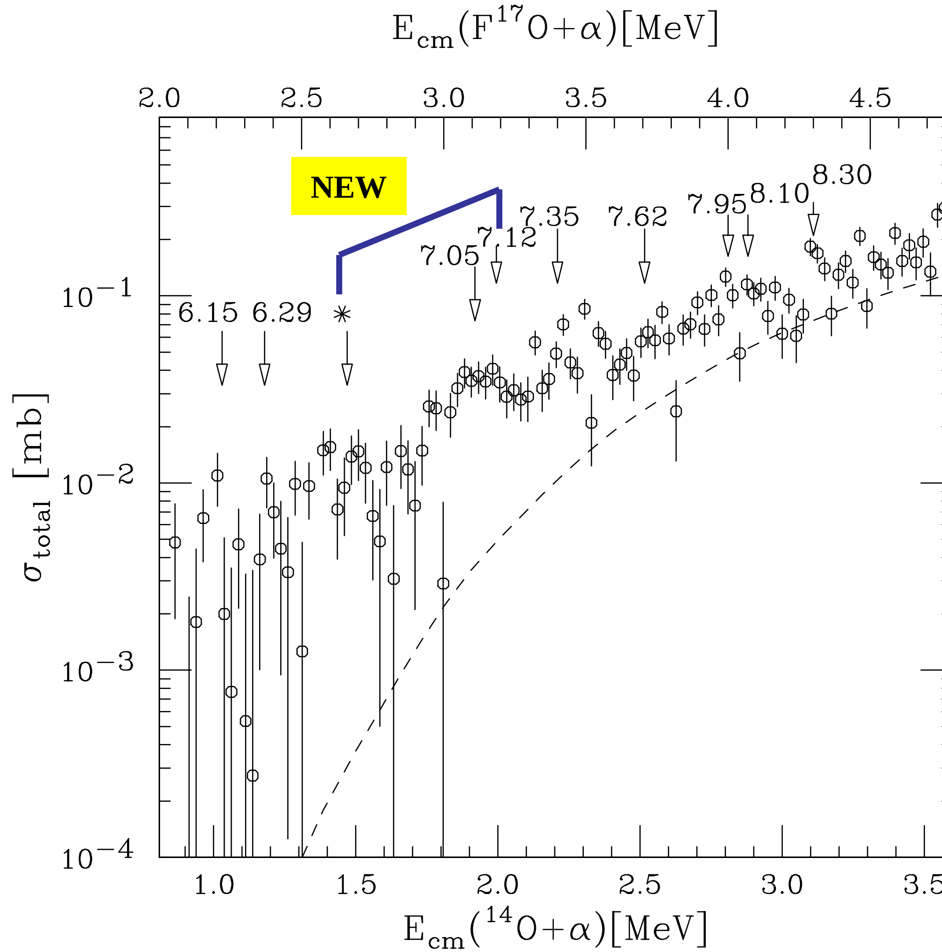
Direct capture (E1) with $\ell_n = 0$ on *p* states dominates

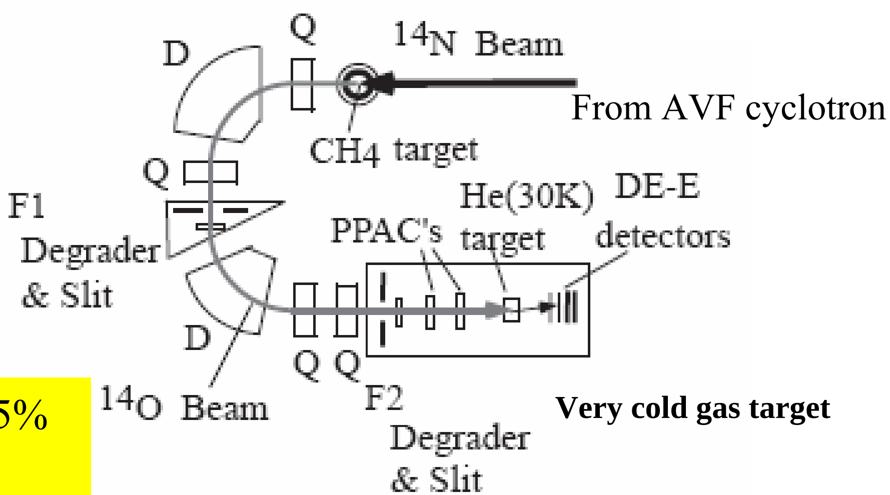
Speed up neutron-captures at the N=28 closed shell

O. Sorlin

$^{14}O(\alpha,p)^{17}F$
RIKEN (using CRIB)

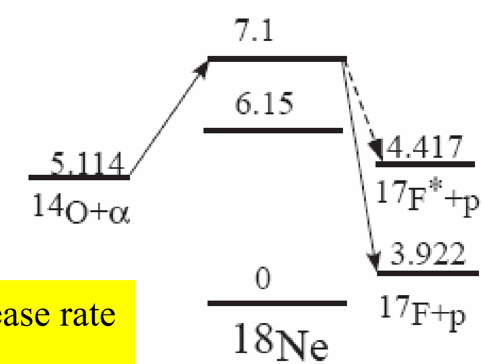






Very cold gas target

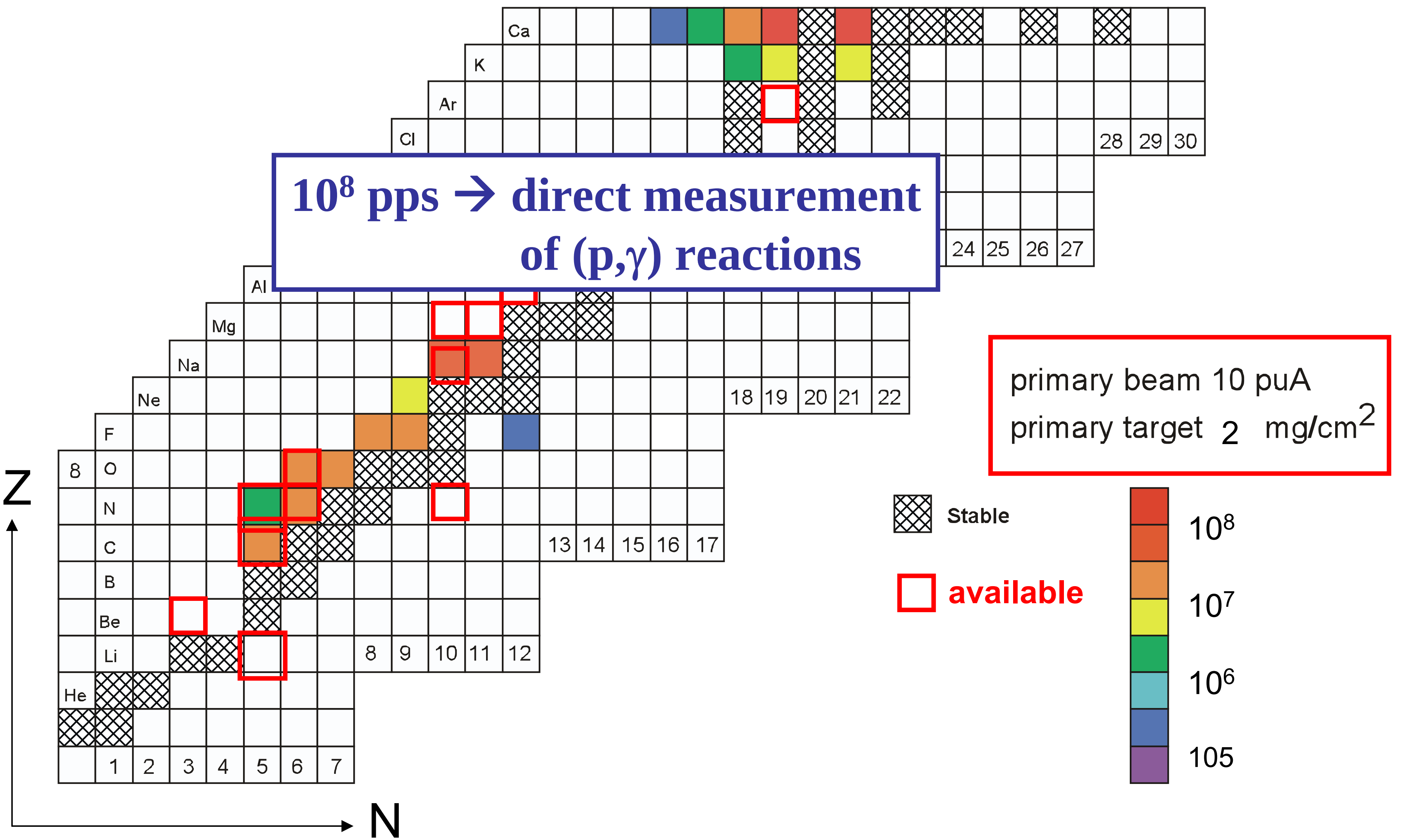
Notani, Kubono, et al NP A746(2004)



^{14}O ~10^6 p/s; 85% pure, 43 MeV

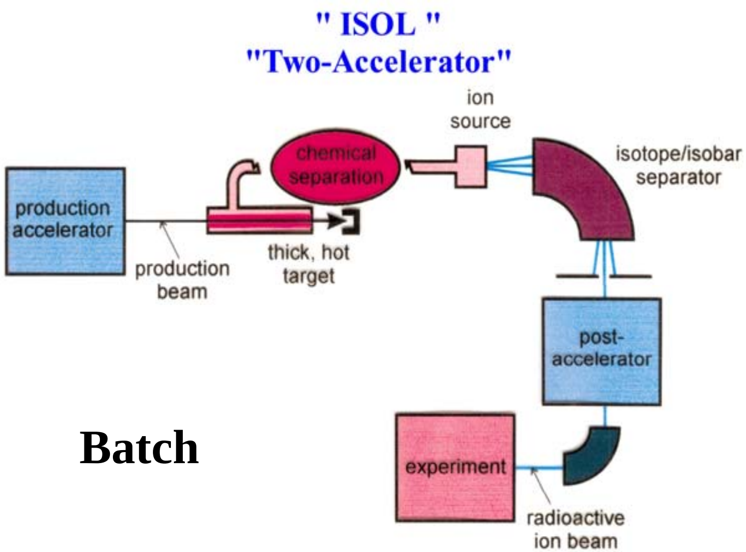
Could increase rate by 50%

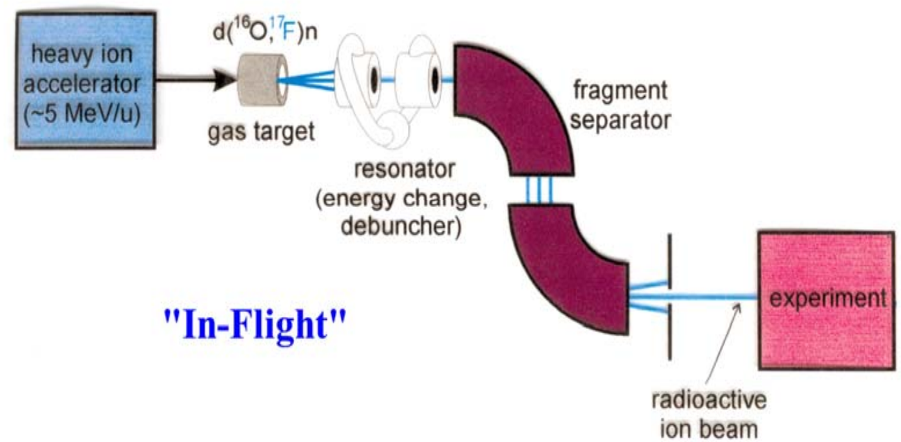
Goal of RIB Intensities to Be Reached at CRIB



ARGONNE

Beam Production Methods





+ “Atlas-quality” beams

(beam spot, divergence, timing)

- For long half-lives only

Examples: ^{56}Ni, ^{56}Co, ^{44}Ti, ^{18}F

+ for short half-lives

- Beam spot typically 5 mm
Energy resolution ~ 0.5-1%

Examples: ^{6}He, ^{8}Li, ^{8}B, … ^{37}K

Ernst Rehm

Nuclear astrophysics studies with radioactive beams:

PRL 82, 3964(1999)
PRC 55, R566(1997)
PRC 52, R460(1995)
PRC 53, 1950(1996)

^{21}Na(p,α)^{18}Ne

^{18}F(p,α)^{15}O

^{17}F(p,α)^{14}O

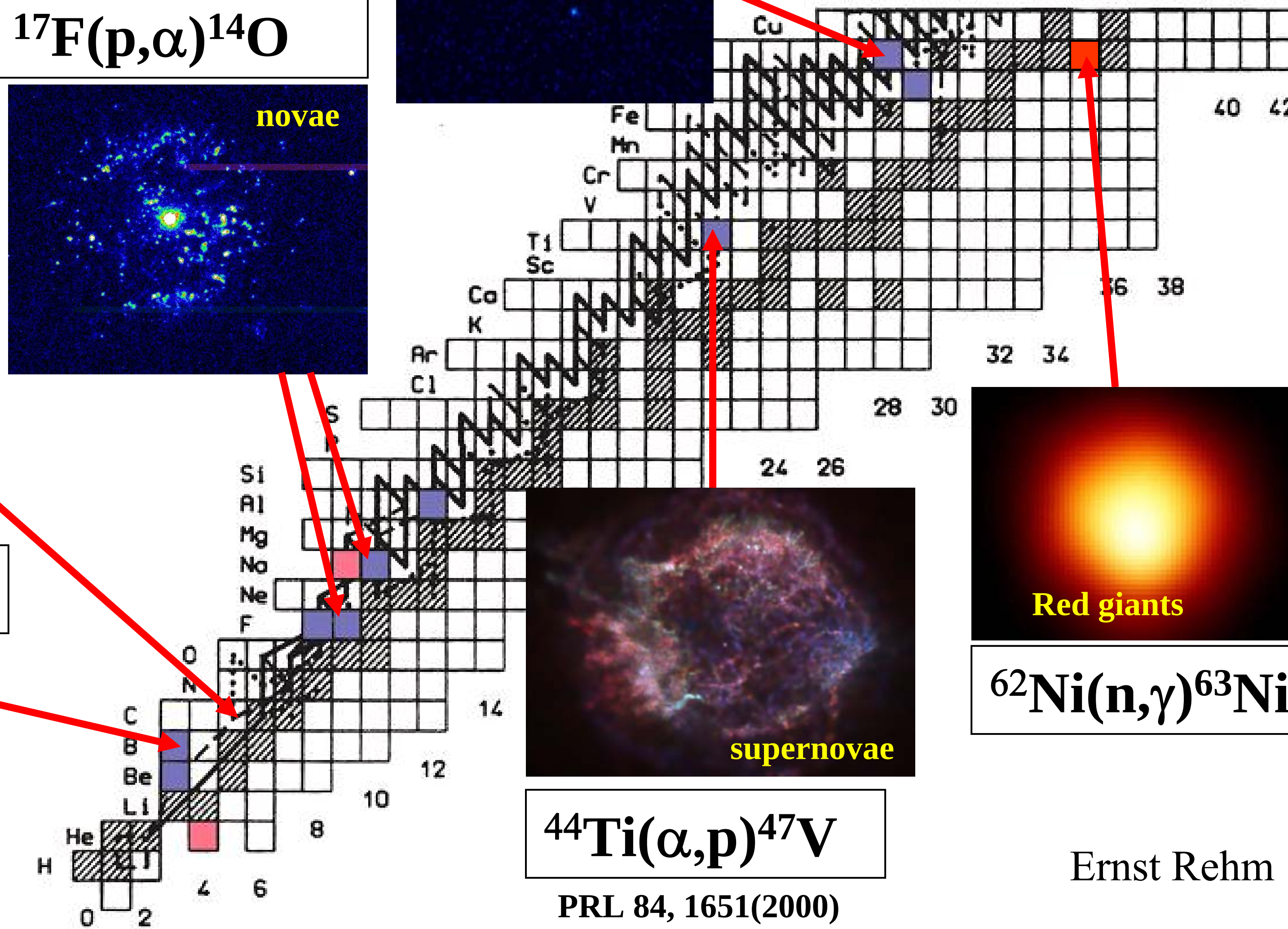
^{56}Ni(p,γ)^{57}Cu

PRL 80, 676(1998)

^{11}C(p,α)^{8}B

^{8}B(β^{+},ν) → 2α

PRL 91, 252501(2003)



^{44}Ti(α,p)^{47}V

PRL 84, 1651(2000)

^{62}Ni(n,γ)^{63}Ni

Ernst Rehm

DIRECT
Radiative Capture Studies

ARES @ Louvain
DRS @ HRIBF
DRAGON @ ISAC

Direct Studies of Radiative Capture

Experimental Challenges Using Radioactive Beams

- Inverse kinematic is optimal approach.
- Beam intensities much less than stable beams (if available at all).
- Cross sections are small (resonance strengths ~ 1 meV) .
- Beam is radioactive (background radiation, e.g., 511 keV γ, ~10^9/s)
- Radiative proton and helium capture may require gas target.

- What do you need to know before starting ?
  - Resonance energy (thickness of gas target ~ 14 keV)
  - Radioactive beam energy (different RB accelerators)
  - Accurate beam intensity (and reaction product yield)
  - Resonance width and gamma branching ratio useful
  - Angular spread of the recoils in inverse kinematics
  - Charge state distribution important

- What do you measure [Quantitative measurement to ± 20%]
  - Thick Target Yield = $\frac{1}{2} \lambda^2 \, \underline{\omega\gamma \;\; (1/} \, \varepsilon) \, (M_b + M_t)/(M_t)$ (for narrow resonance)
  - Need to do full scan for broad resonances

Louvain-la Neuve

$^{13}N(p,\gamma)^{14}O$

$\Phi(^{13}N) \sim 10^8/s$

VOLUME 67, NUMBER 7 PHYSICAL REVIEW LETTERS 12 AUGUST 1991

Determination of the $^{13}N(p,\gamma)^{14}O$ Reaction Cross Section Using a ^{13}N Radioactive Ion Beam

P. Decrock,[2] Th. Delbar,[1] P. Duhamel,[3] W. Galster,[1] M. Huyse,[2] P. Leleux,[1] I. Licot,[1] E. Liénard,[1] P. Lipnik,[1] M. Loiselet,[1] C. Michotte,[1] G. Ryckewaert,[1] P. Van Duppen,[2] J. Vanhorenbeeck,[3] and J. Vervier[1]

[1]*Institut de Physique Nucléaire and Centre de Recherches du Cyclotron, Université Catholique de Louvain, B-1348 Louvain-la-Neuve, Belgium*

[2]*Instituut voor Kern- en Stralingsfysika, Katholieke Universiteit Leuven, B-3001 Leuven, Belgium*

[3]*Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, B-1050 Bruxelles, Belgium*

(Received 2 May 1991)

The cross section for the astrophysically important $^{13}N(p,\gamma)^{14}O$ reaction has been measured directly with an intense (3×10^8 particles/s) and pure (> 99%) 8.2-MeV ^{13}N radioactive ion beam. The average value, for the 5.8–8.2-MeV ^{13}N energy range, is 106(30) μb. The partial γ width of the resonance which occurs in this reaction at a center-of-mass energy of 0.545 MeV has been deduced to be 3.8(1.2) eV. It is compared with theoretical predictions and indirect determinations.

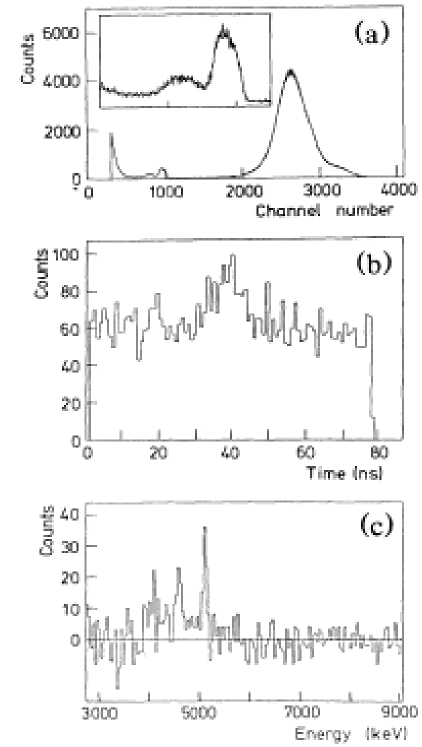


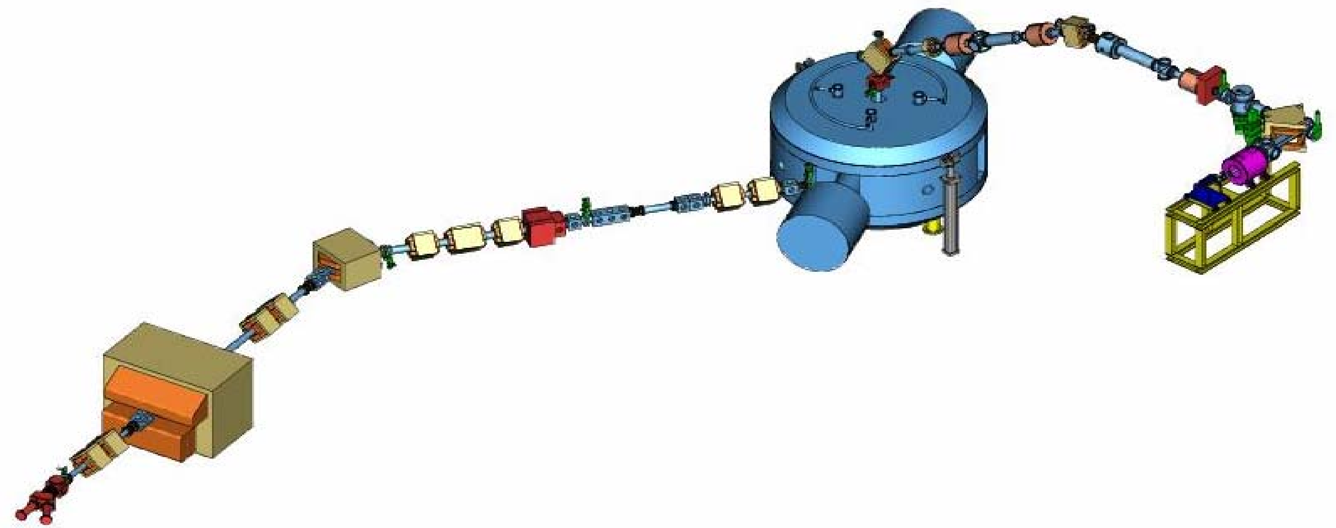
FIG. 1. (a) Charged-particle spectrum from the interaction between an 8.2-MeV ^{13}N beam and a $(CH_2)_n$ polyethylene target. The peak to the right corresponds to the scattered ^{13}N projectiles and ^{12}C recoils (right shoulder), the peak to the left and in the inset, to the proton recoils. (b) Spectrum of the time difference between the γ-ray pulses from the Ge diode and the cyclotron radio frequency, for a 3.8–5.2-MeV γ-ray energy window. (c) Spectrum of the prompt γ rays resulting from the $^{13}N(p,\gamma)^{14}O$ reaction, after subtraction of the random events. These spectra correspond to an effective running time of 33 h, with a ^{13}N beam intensity of 50 ± 10 particle pA as monitored with a shielded Faraday cup some 2 m downstream from the target.

Γ_γ (eV)	Reference
3.8(1.2)	Present
2.44	5
1.9	6
1.2	7
1–10	8
4.1	9
2.7(1.3)	10
$\leq$7.6(3.8)	11
1.4(7)$\sigma_{\theta_0}/\sigma_{\theta_1}$	12

E_r = 545 keV

Γ_γ = 3.81 eV ~ <u>ωγ</u>

The ARES recoil separator @ CRC/UCL



Reactions that can be investigated with ARES:

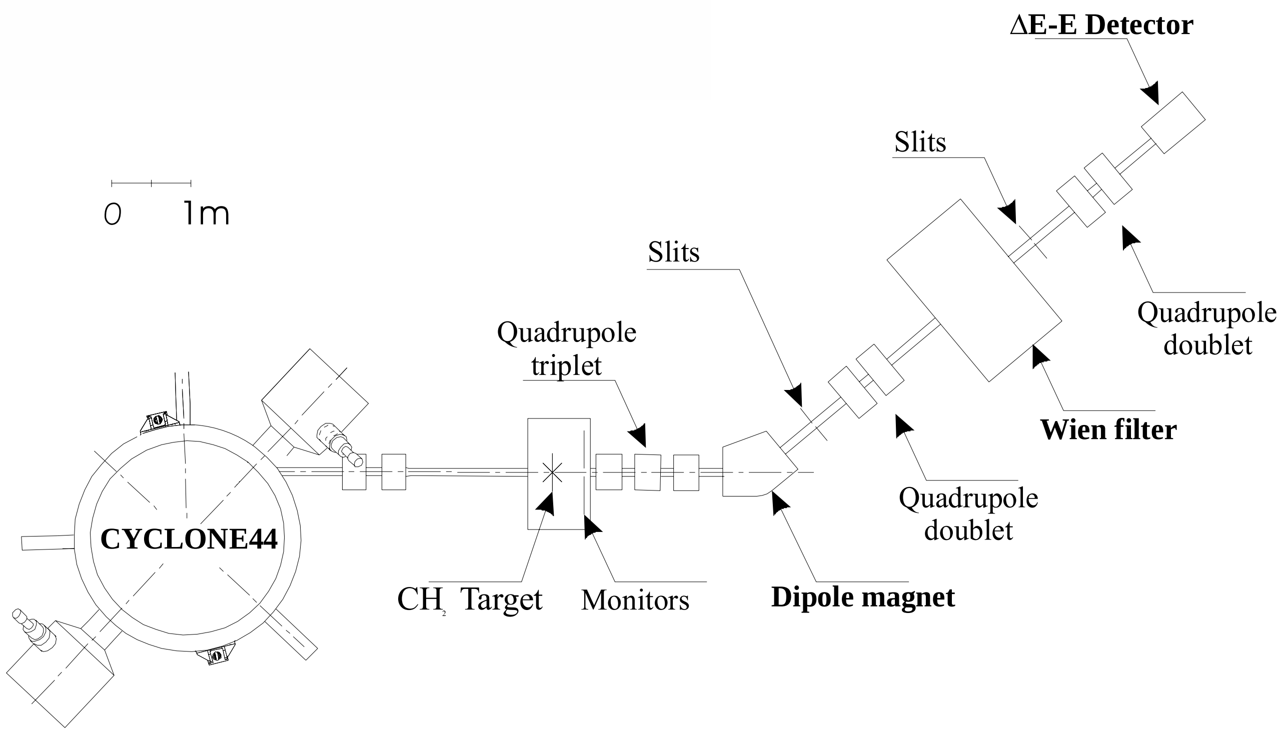
$^{19}Ne(p,\gamma)^{20}Na$

$^{13}N(p,\gamma)^{14}O$

$^{11}C(p,\gamma)^{12}N$

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

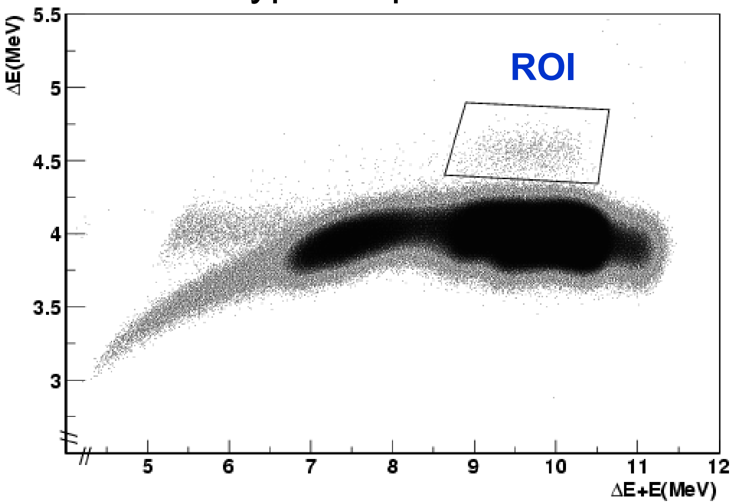
$^{7}Be(\alpha,\gamma)^{11}C$…



Characterization and Use of ARES for (p,γ) reactions

- ARES has been characterized with a ^{19}F stable beam
  - Study of the well-known state at 13.48 MeV in ^{20}Ne (635 keV above the ^{19}F+p threshold), reasonably narrow (Γ= 6.3 keV) and strong ($\omega\gamma$ = 1.6 eV).
- ^{19}F beam, intensity 6×10^8 pps during 20 hours:
  - 4% global efficiency, transmission of 11.5% for $^{20}Ne^{7+}$, well reproduced by simulations.

Typical spectrum

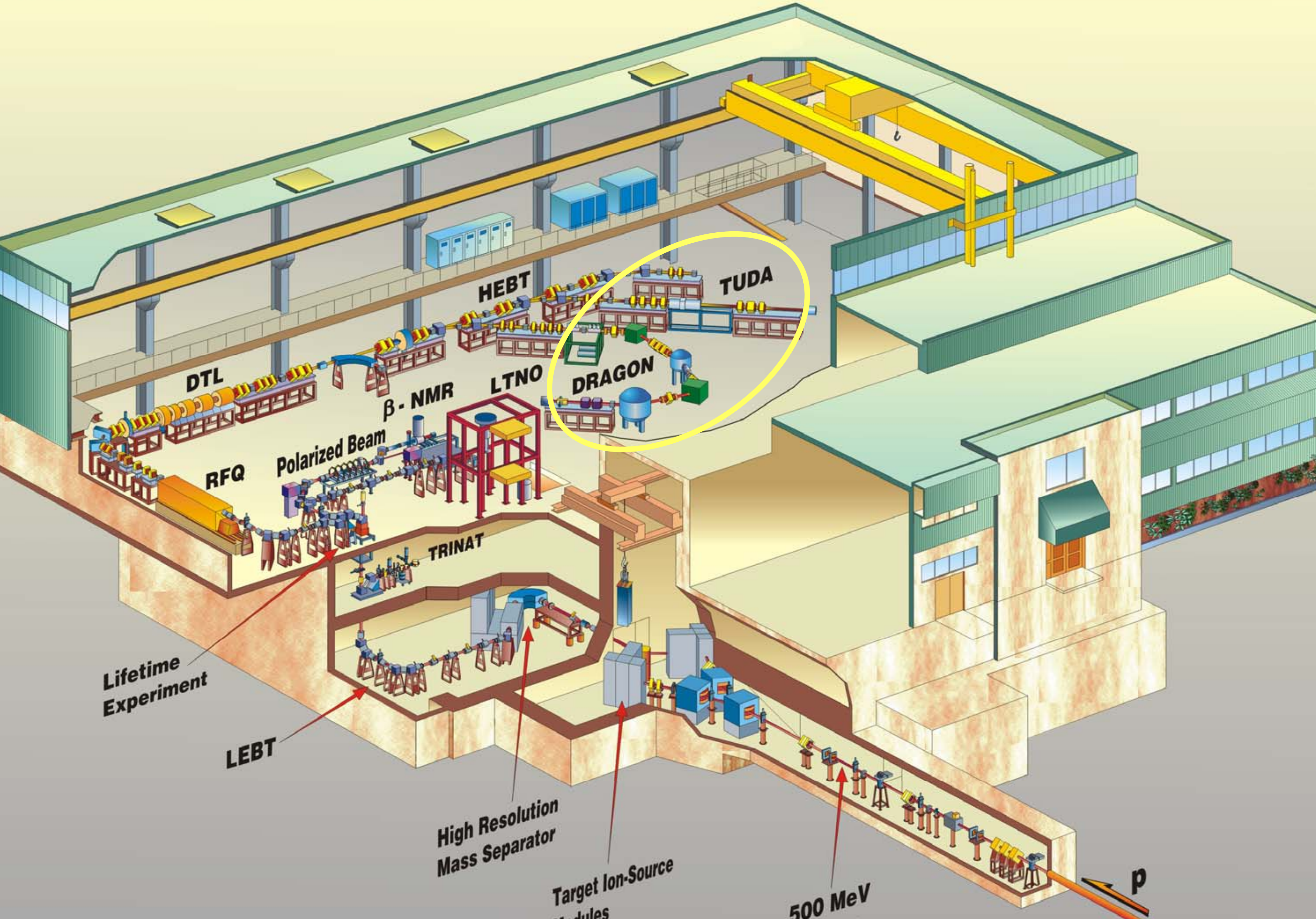


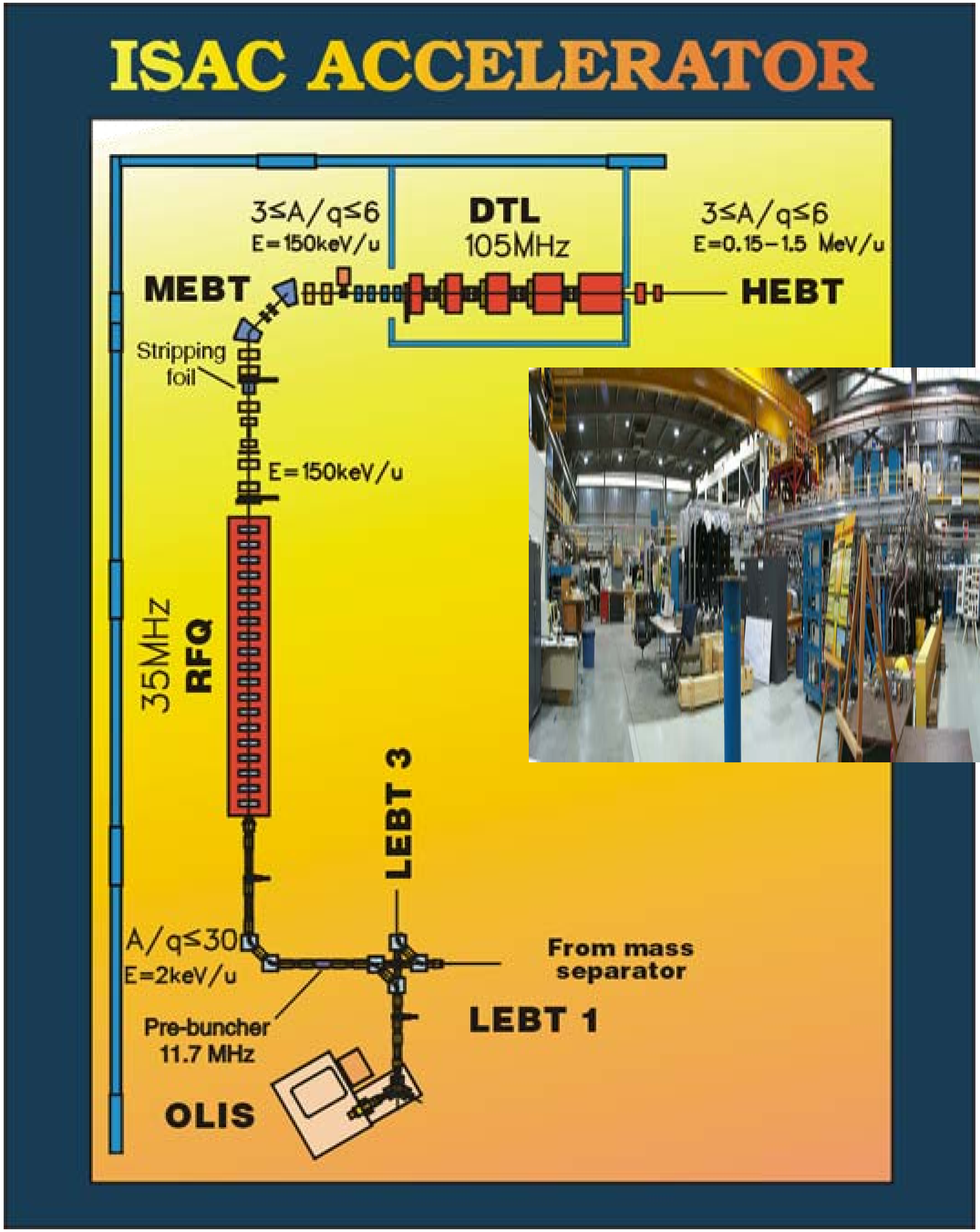
Performance of ARES for (p,γ) reactions: M. Couder et al., NIM A **506** (2003) 26

Direct Study of the **^{19}Ne(p, γ)^{20}Na** Reactions: M. Couder et al, PR C**69**, (2004) 022801R

- **First ^{19}Ne radioactive beam from CYCLONE44 : ~ 5 x 10^9 pps on target**
- **Study of the 2.643 MeV level in ^{20}Na: $\omega\gamma \leq$ 15.2 meV (90% c.l.)**

ISAC at TRIUMF

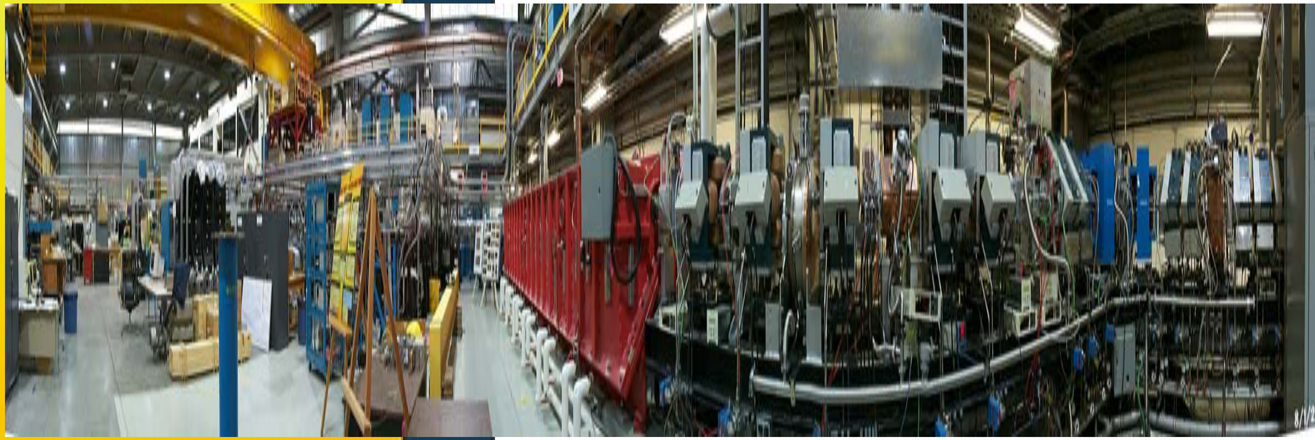




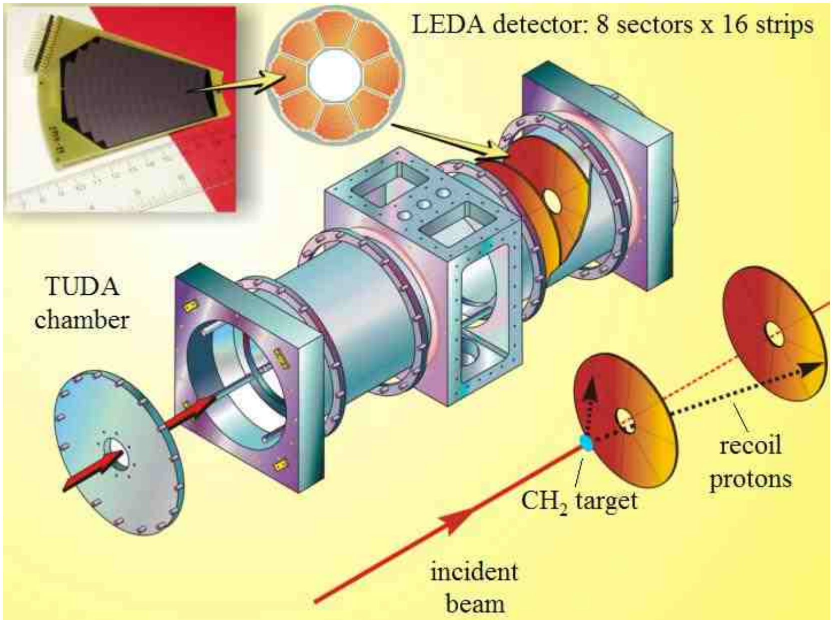
ISAC LINACS

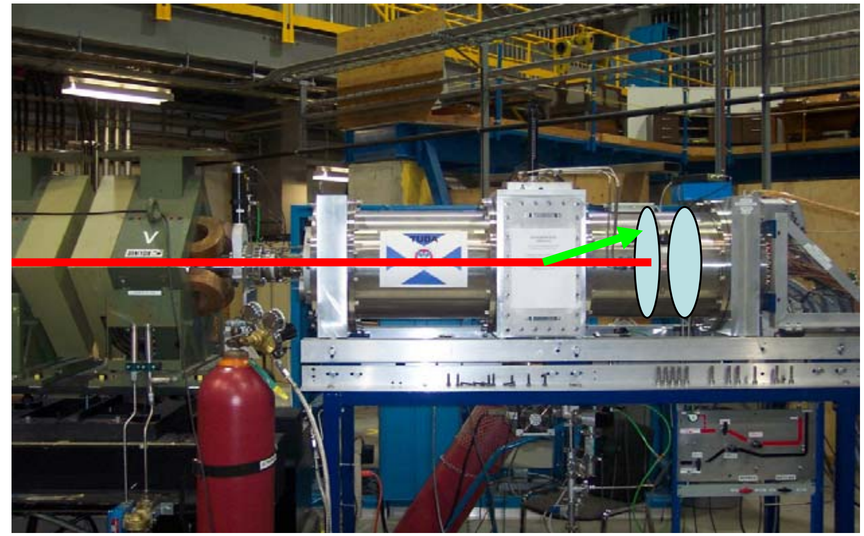
Energy: 0.15 – 1.5 MeV/u
Pulse Iteration: 86 ns
Masses: A < 30 amu

Built for Astrophysics program

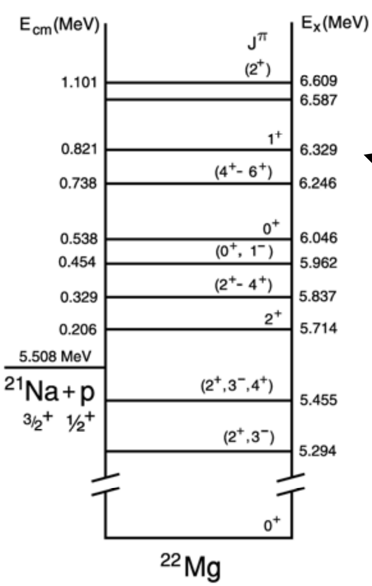


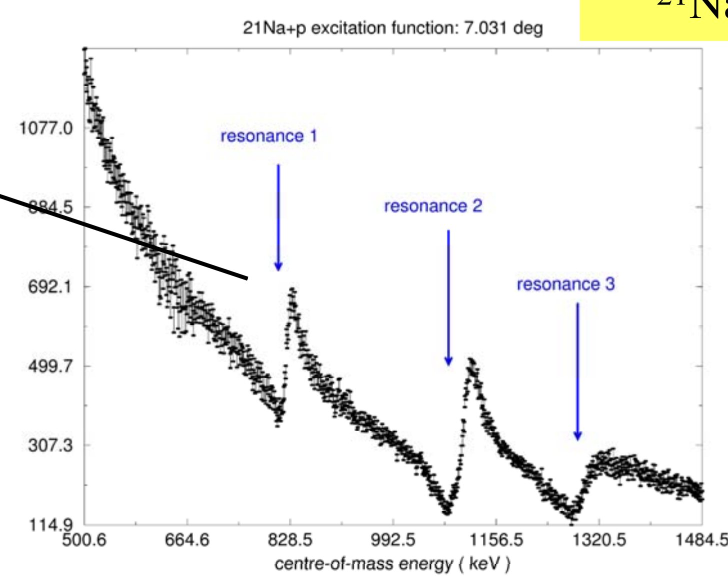
TUDA TRIUMF Univ. of Edinburgh Detector Array

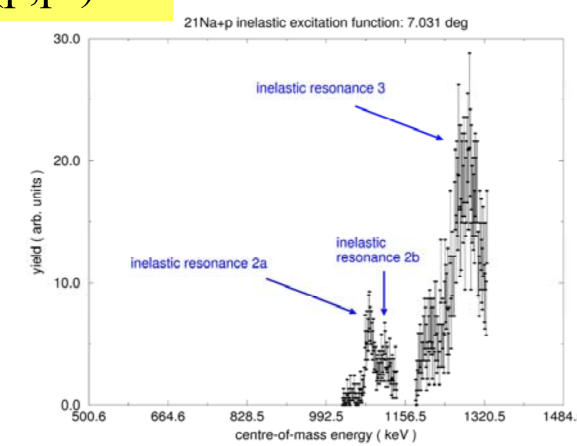




^{21}Na(p,p')

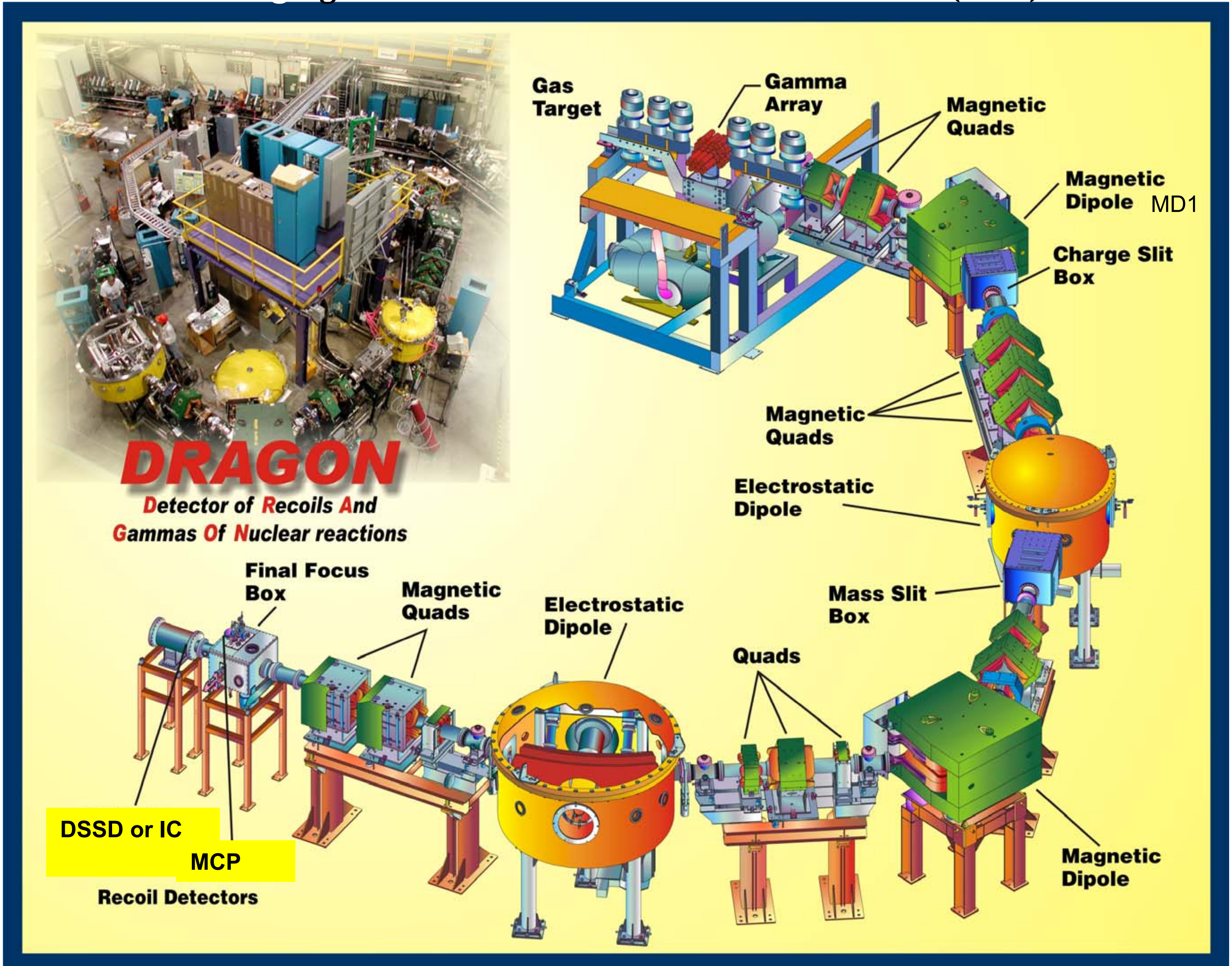






C.Ruiz *et al.*, Phys. Rev. C 65,(2002) www.triumf.ca/dragon

NIM A498(2003)190



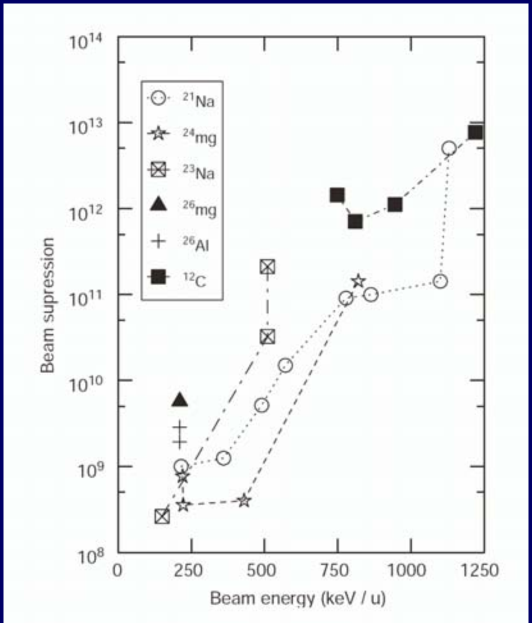
Features/Performance of DRAGON

- All operations are EPICS remotely controlled.
- DRAGON is ~20 m long; 1-4 μs in flight path depending..
- DRAGON acceptance is <~± 20 mrad; ± 4% in energy
- Gas target operates <~ 8 torr (H_2 and He).
- Special holder used for solid targets.
- CSB foil of SiN (50 nm) used to increase aver. Charge.
- BGO Gamma Array efficiency ~ 50% depending….
- MD1 used to measure beam energy to ~ 0.15%
- RMS limitations:

  electric rigidity = 8 MV (2E/q);

  magnetic rigidity = 0.5 T-m [m/q $(2E/m)^{1/2}$]
- RMS accepts only one charge state.
- Beam transmission/suppression depends on beam energy; up to 10^{-15} **with separator, t-o-f, and γ coin**
- Focal plane detectors
  - DSSSD (Double sided, Si strip detector)
  - Multi-anode Ionization chamber
  - Both detectors can be operated with a M system for fast signal
  - A second MCP/C system will be added f local T-O-F
- Upgrade of electronics funded and being inst
- Data acquisition by MIDAS; data analysis by
- DRAGON operates 24/7 for multi-week expe

NIM A in press

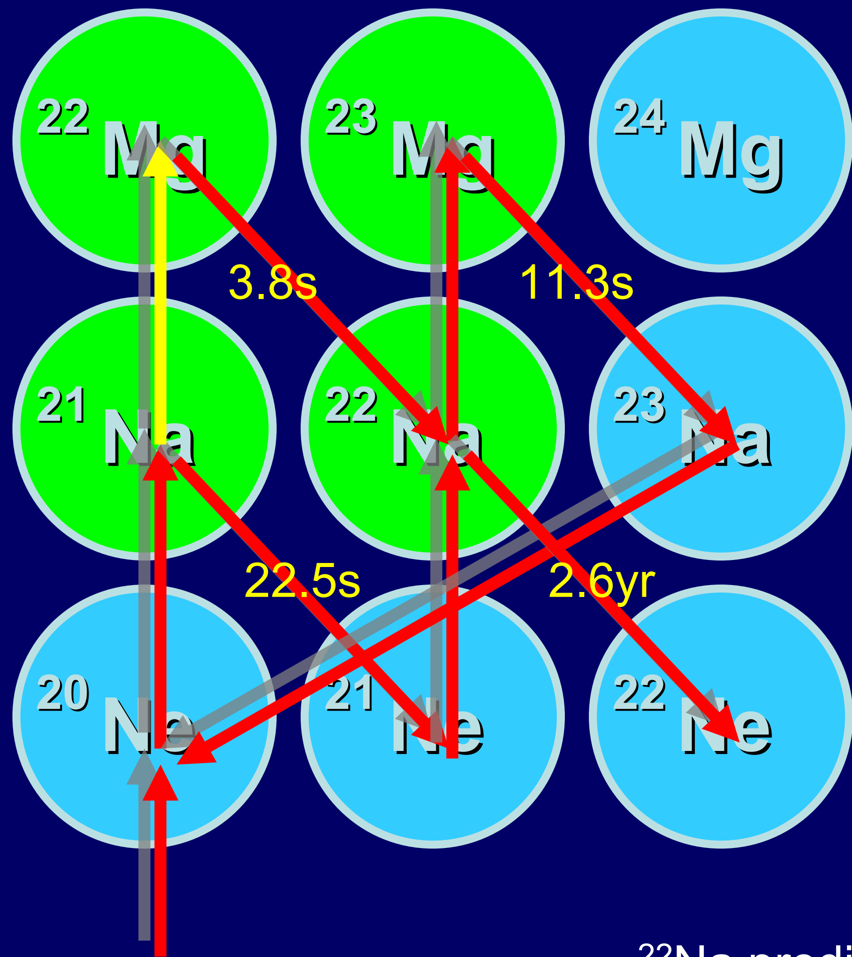


DRAGON Beam suppression; recoil mass separator only

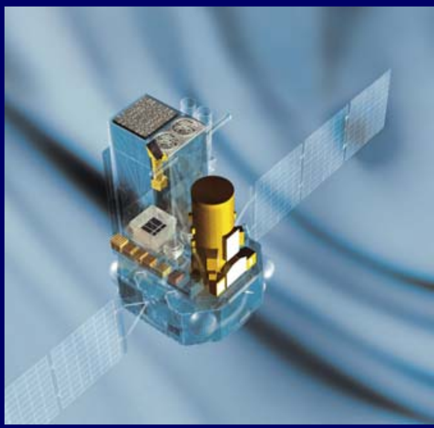
Reaction	$E_{c.m.}$(keV)	ωγ[DRA/Lit.]
$^{20}Ne(p,\gamma)^{21}Na$	1112.6	0.75±0.07 1.07±0.21
$^{21}Ne(p,\gamma)^{22}Na$	258.6	1.82±0.44
$^{21}Ne(p,\gamma)^{22}Na$	731.5	0.93±0.21
$^{24}Mg(p,\gamma)^{25}Al$	214.0	0.86±0.17
$^{24}Mg(p,\gamma)^{25}Al$	402.2	1.15±0.18
$^{24}Mg(p,\gamma)^{25}Al$	790.4	1.10±0.13

$^{21}Na(p,\gamma)^{22}Mg$
using
DRAGON at ISAC

^{22}Na formation: NeNaMg cycle



INTEGRAL



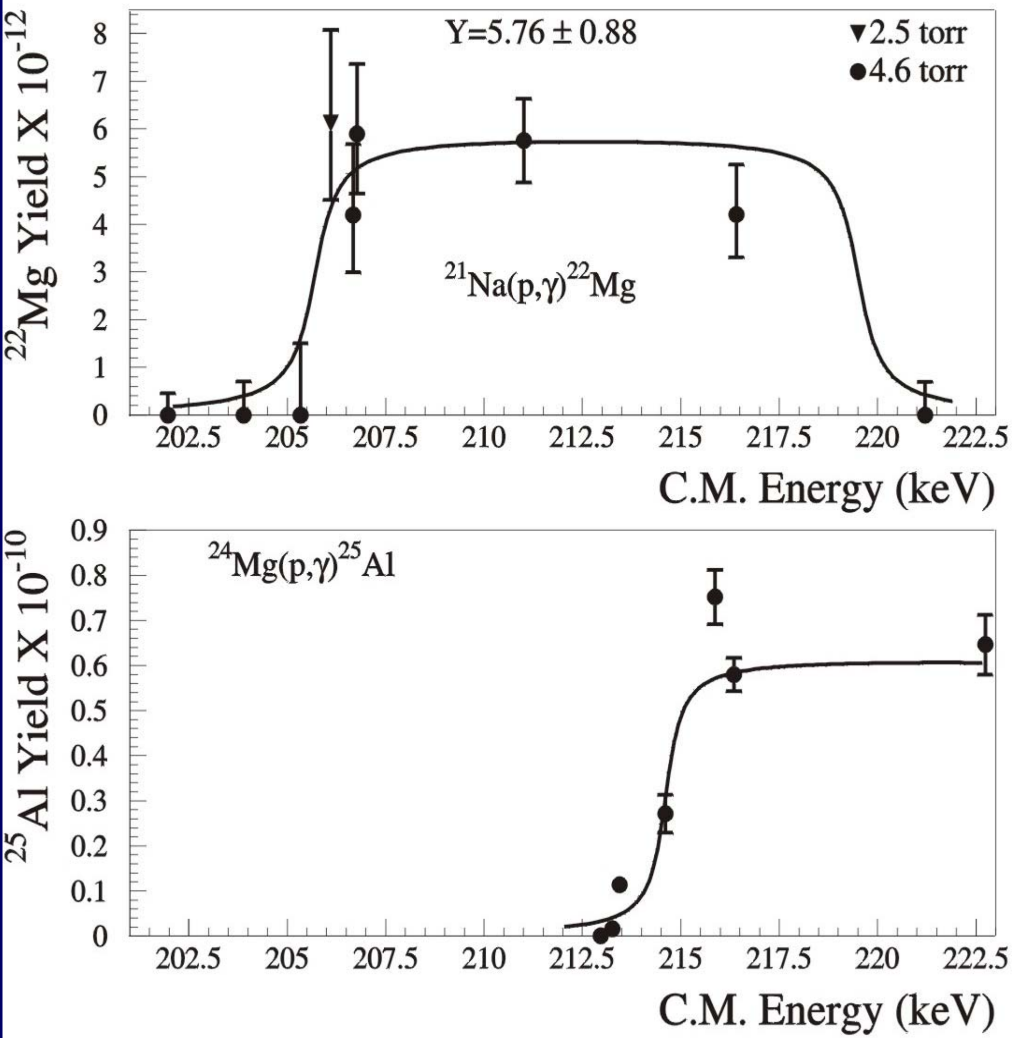
^{22}Na predicted to be seen but not observed by COMPTEL or INTEGRAL

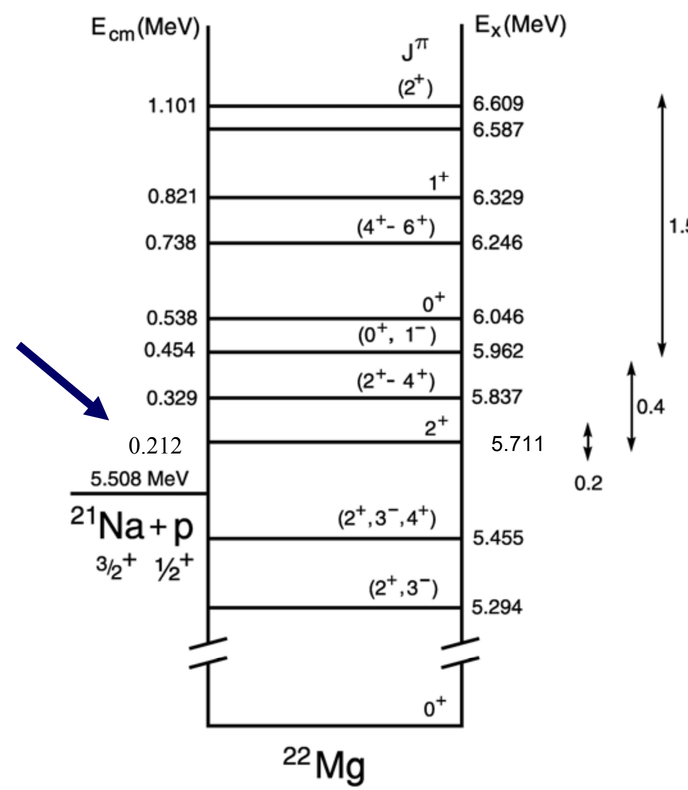
Results – resonance strengths

21Na(p,γ)22Mg

PRC 69 (2004) 065803
PRL 90 (2003) 162501

ωγ = 1.03 meV± 0.2; E =205.7 keV

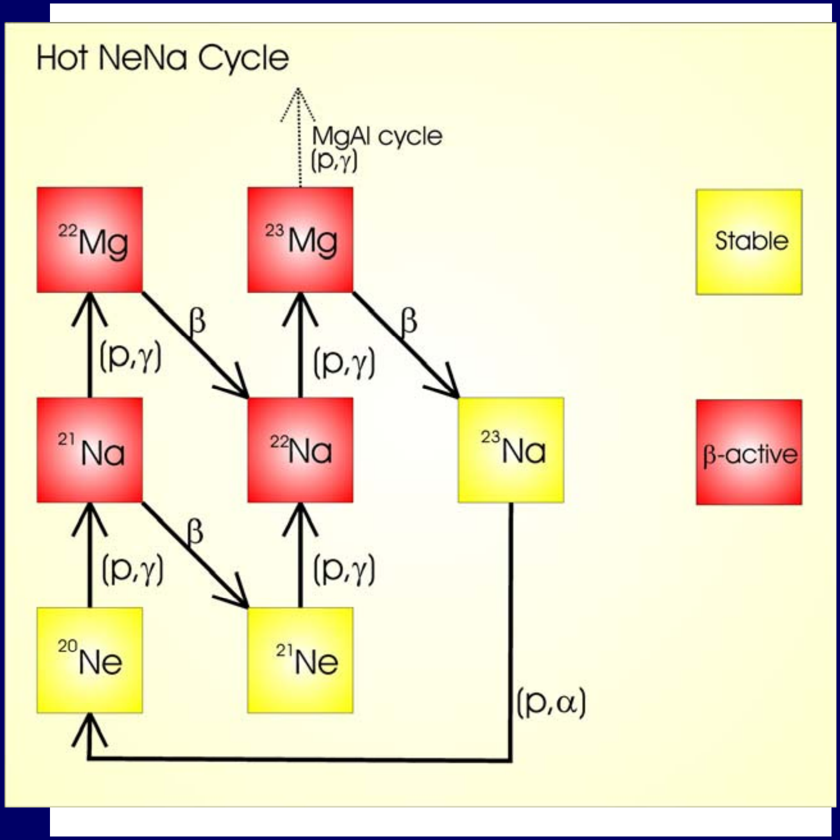




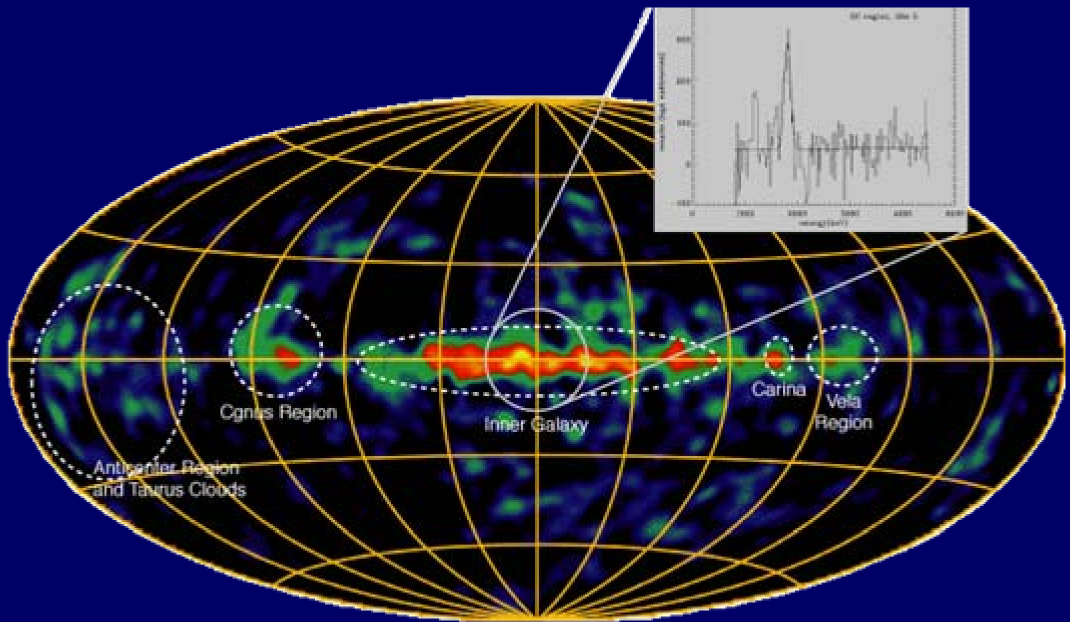
new^{22}Mg mass: -399.7 keV

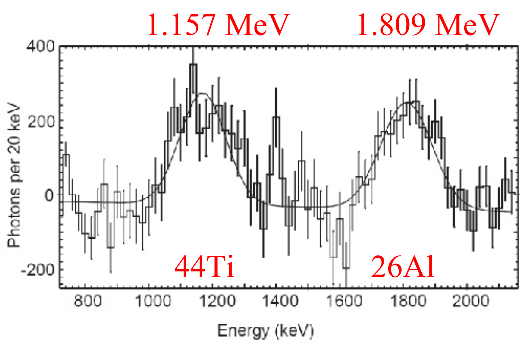
Reaction rate

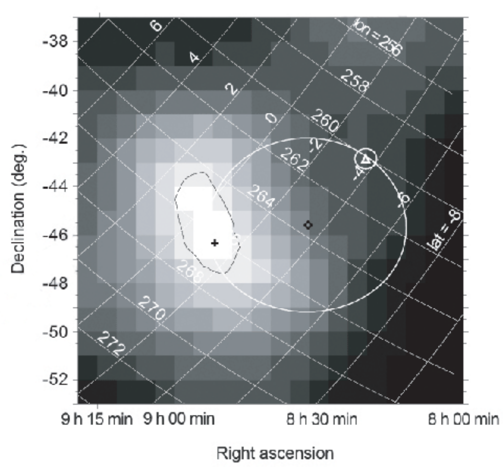
- The lowest measured state at 5.711 MeV (E_{cm} = 206 keV) dominates for all novae temperatures and up to about 1.1 GK
- Updated nova models showed that ^{22}Na production occurs earlier than previously thought while the envelope is still hot and dense enough for the ^{22}Na to be destroyed
  - ➢ This results in lower final abundance of ^{22}Na
  - ➢ Reaction not significant for XRB



$^{26}Al(p,\gamma)^{27}Si$
using
DRAGON at ISAC





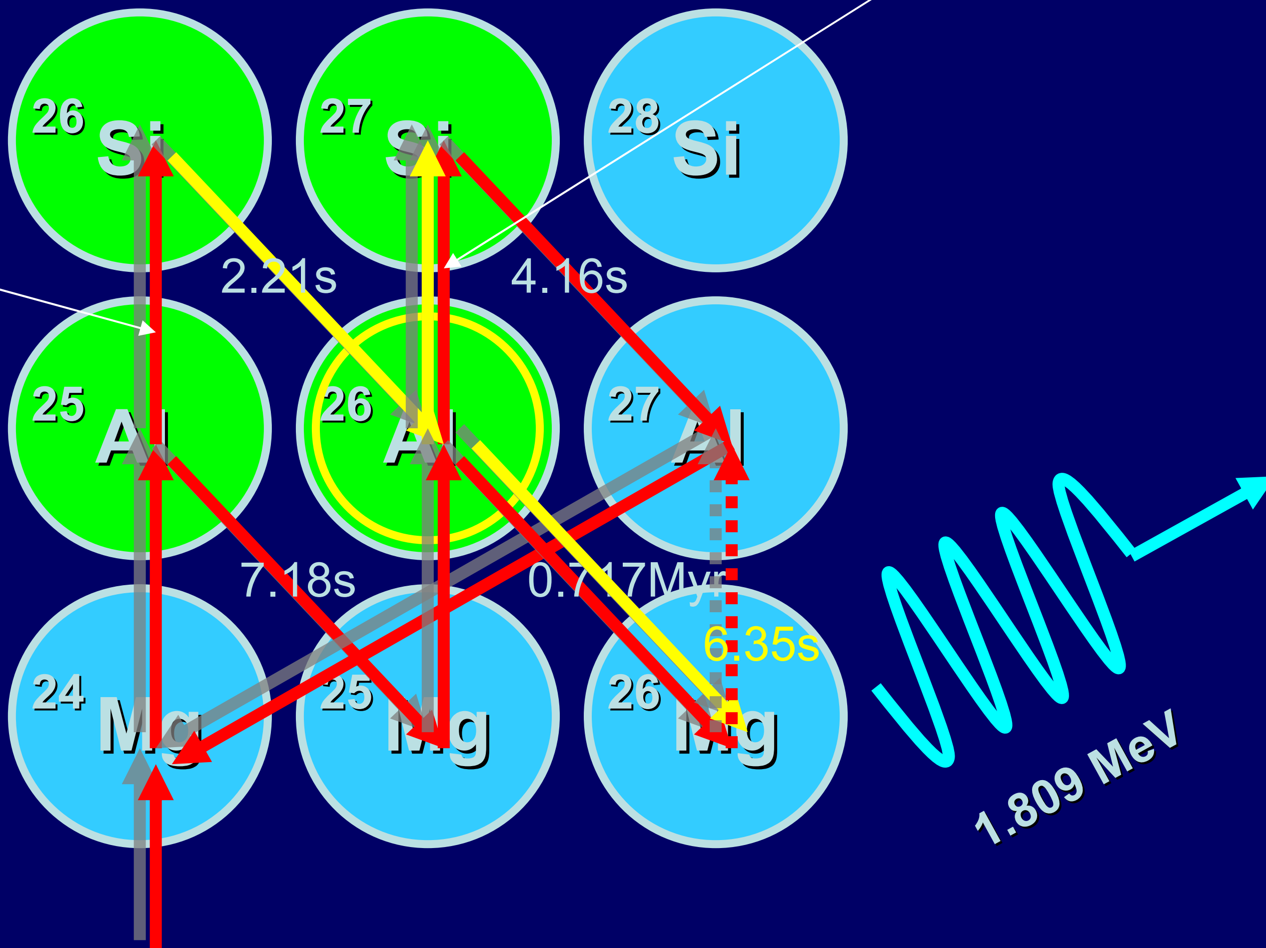


Detection of new supernova remnants
GRO J0852-4642 in VELA region

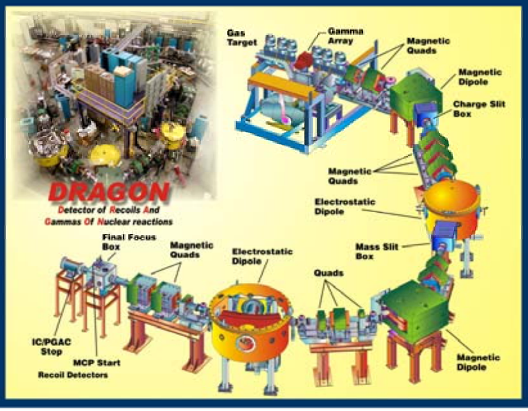
MgAl cycle

$^{26g}Al(p,\gamma)^{27}Si$, $^{26m}Al(p,\gamma)^{27}Si$:
E989,E990 (C. Ruiz and A. Murphy)
DRAGON and TUDA

$^{25}Al(p,\gamma)^{26}Si$:
E922 (A.Chen)
DRAGON

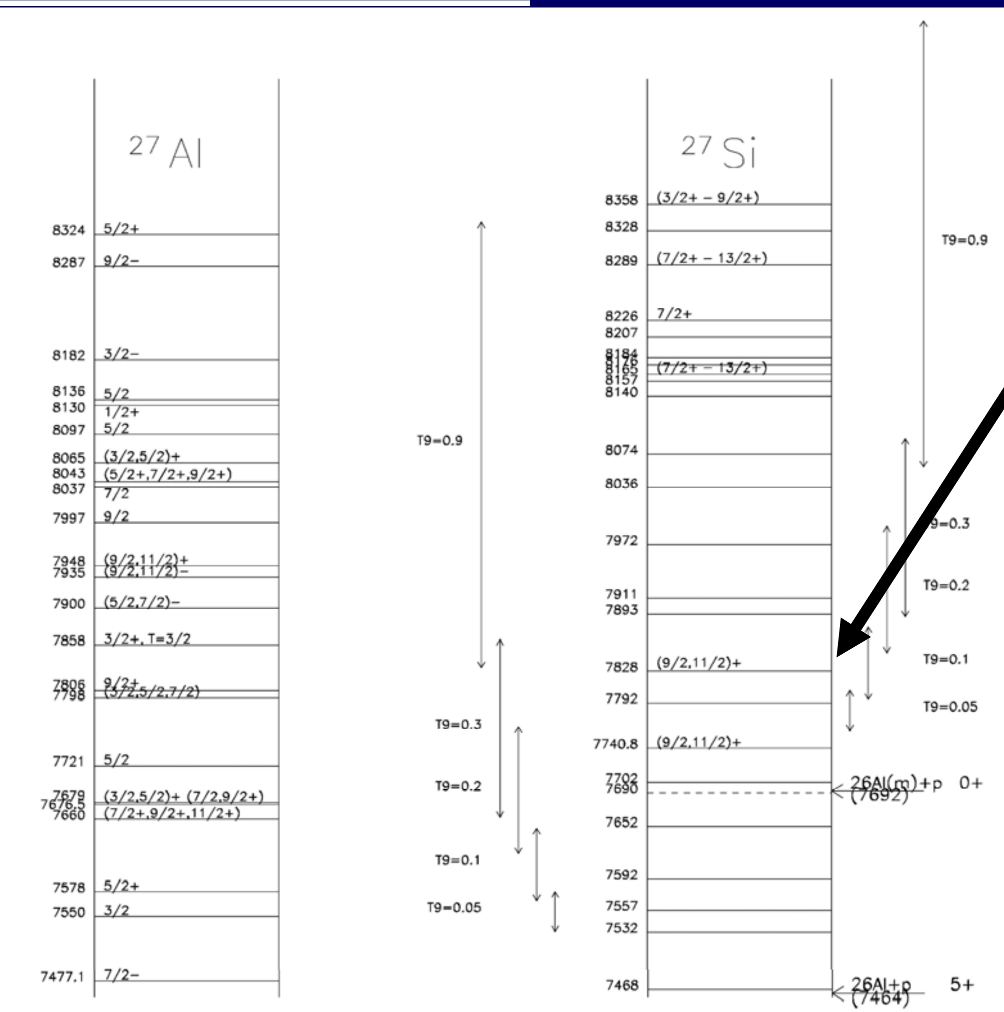


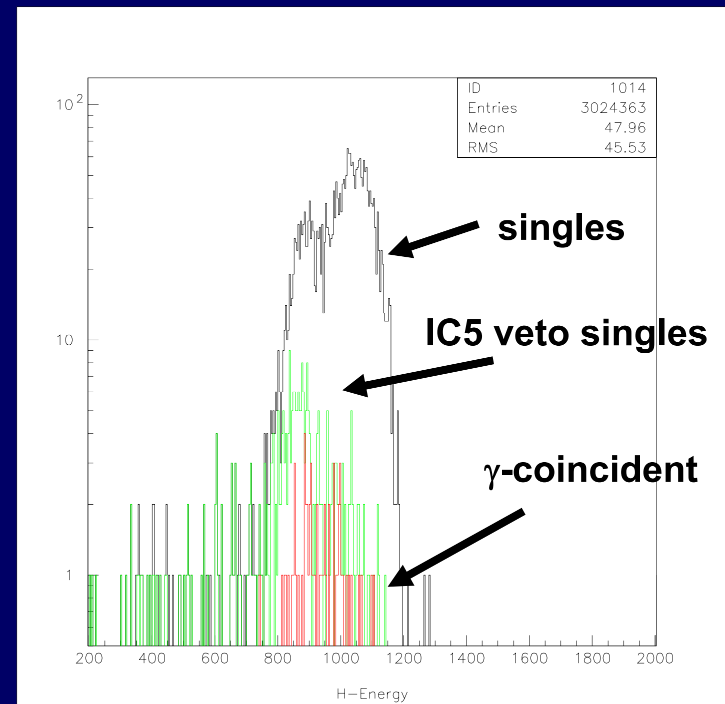
$^{26}Al(p,\gamma)^{27}Si$ Reaction Study
DRAGON Feasibility Run (2004)



E_b = 389 keV/u
E_R = 364 keV
$\Phi(^{26}Al) \sim 3 \times 10^8$/s
(with ~10% ^{26}Na)

Focal Plane Detector:
Ion Chamber (5 anodes)





SUMMARY of Feasibiity Studies, Summer **2004**

- 384 keV/u run: 51148 s (14.2 hrs), I(^{26g}Al) ~ 1 x 10^8 /sec, 117 coinc. recoil counts, 5 x 10^{12} ions on target,

- 205 keV/u run: 262407 s (72.9 hrs), I(^{26g}Al) ~ 7 x 10^7 /sec, 9 coinc. recoil counts, 1.95 x 10^{13} ions on target (wrong T-O-F)

- **resonance strength of 363 keV state**:

measured 56 ± 14 meV, literature 66 ± 18 meV

- **resonance strength of 188 keV state; (upper limit only based on non-obs.)**

$Y = cts/(It \times \varepsilon_{bgo} \times \varepsilon_q \times \varepsilon_{lt}) = 1/(1.95 \times 10^{13} \times 0.4 \times 0.35 \times 0.9)$

$= 4.1 \times 10^{-13}$; **$\omega\gamma < 65$ μeV**

Unpublished measured value is 55 μeV, previous adopted value is 65 μeV!

SUMMARY of RUNS, Summer 2005 (188 keV state)

Received 408 hours ^{26}Al (<8.3 x 10^8/s); 213 hours useful data

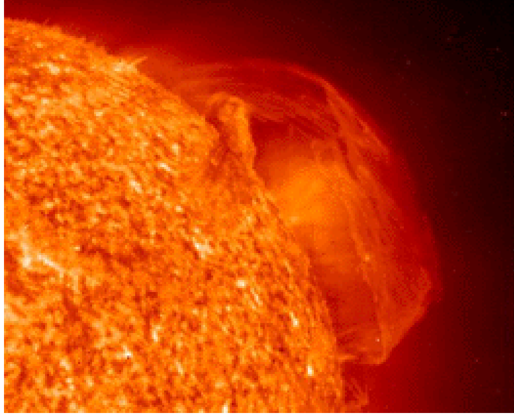
Coincident rate ~ 1 count/day; Laser IS increased beam by x4

Observed ~13 real events; Require ~ 30; data still under analysis

Run scheduled for Oct. 2005 (will use ~3-4 weeks)

$^{1}H(^{7}Be,\gamma)^{8}B$ using DRS at HRIBF

^{7}Be(p,γ)^{8}B Measurement at HRIBF



Neutrinos probe solar core

"Solar Neutrino Problem" - neutrino flux overprediction

Solution: neutrino oscillations (SNO)

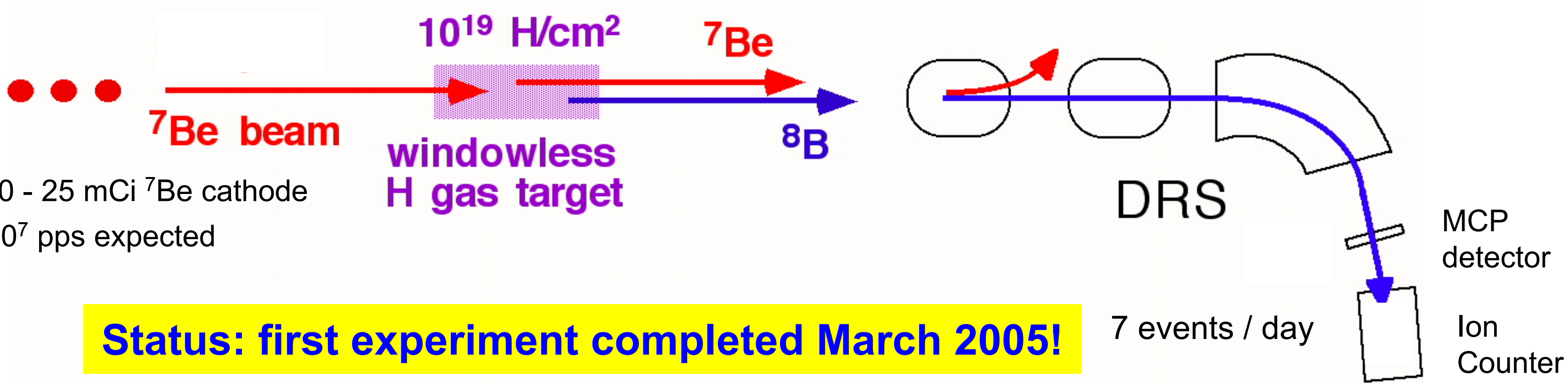
Dominant nuclear physics uncertainty in ν oscillation parameters:
normalization of ^{7}Be(p,γ)^{8}B cross section

Results of worldwide effort with ^{7}Be target discrepant with coulomb dissociation results

- Modern ^{7}Be target experiment: S_{17} = 21.4 ± 0.5 eV b
- Modern Coulomb dissociation experiments: S_{17} = 19.2 ± 0.7 eV b

Snover et al. PRC 70 (2004) 039801

HRIBF: Complementary Measurement with a 1 MeV ^{7}Be beam, H_2 gas target, and DRS will have **different** systematic uncertainties



Nov. 04: 20 - 25 mCi ^{7}Be cathode
10^7 pps expected

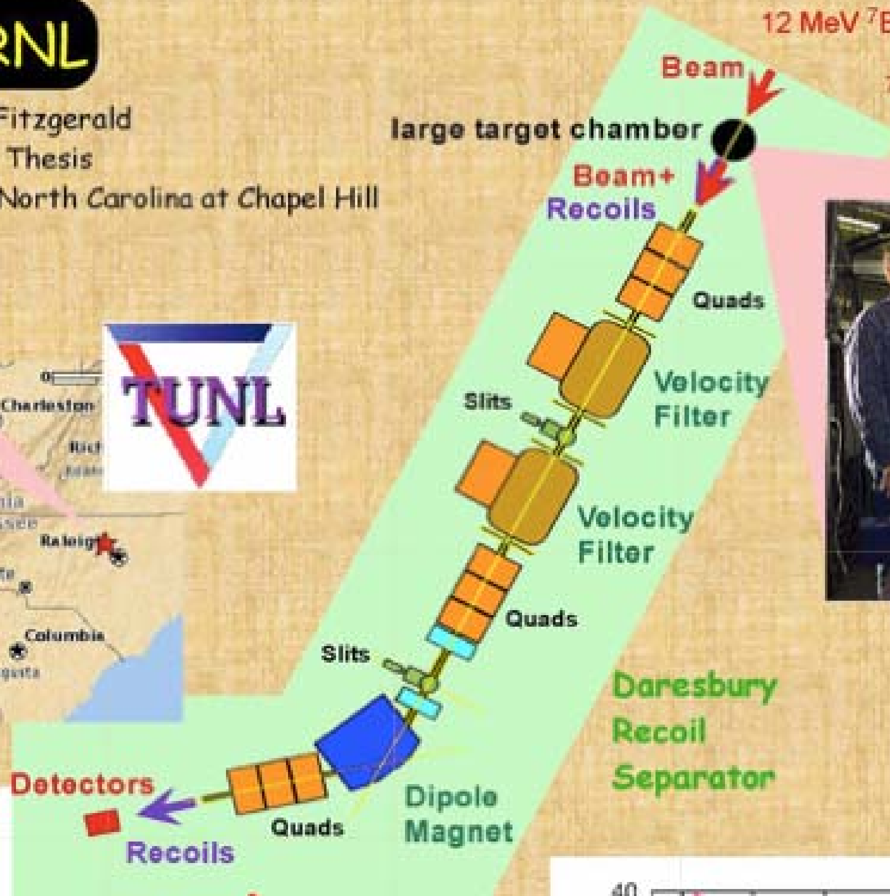
Status: first experiment completed March 2005!

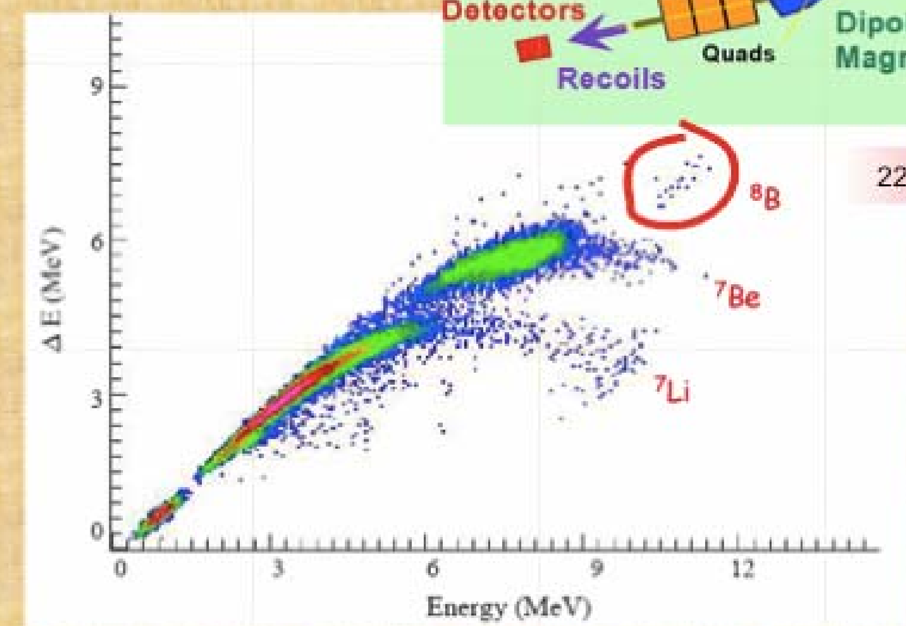
Michael Smith

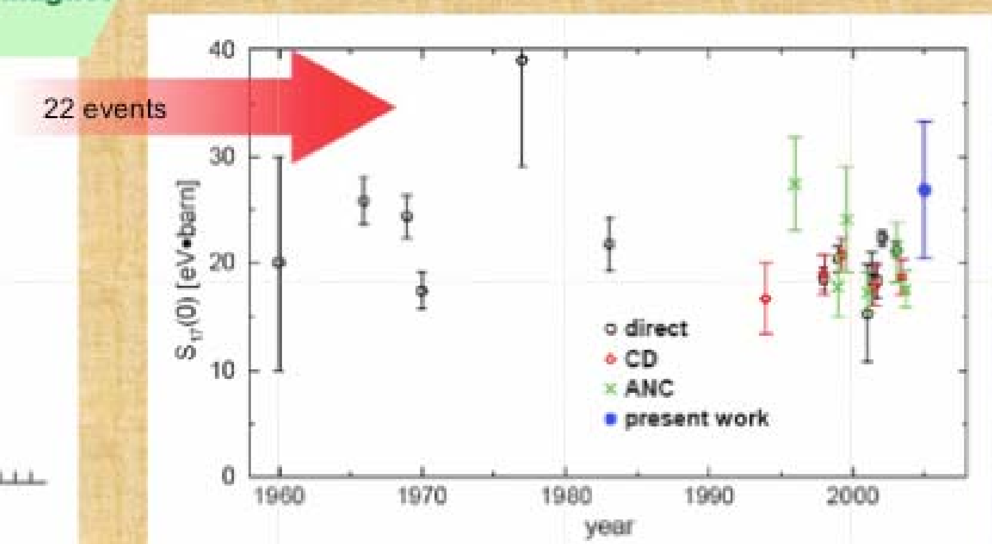
$^7Be(p,\gamma)^8B$ at ORNL

Michael Smith

yan Fitzgerald
h. D. Thesis
Iniv. North Carolina at Chapel Hill







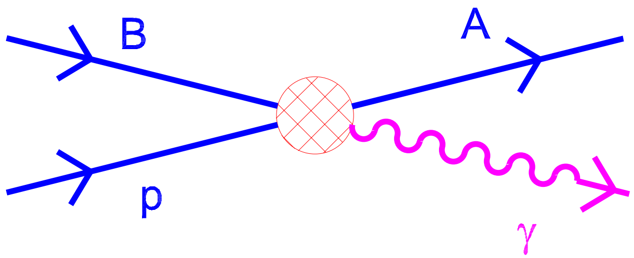
Other RIB Studies

ANC/Breakout

Indirect Techniques (mostly) with **RIBs** [focus on reaction rates]

- **Asymptotic Normalization Coefficients**

astrophysical energies $\Rightarrow$ p and α capture reactions are highly peripheral:



$$\sigma = |< I_{Bp}^{A}(r_{Bp}) \,|\, \hat{O} \,|\, \psi_i^{+}(r_{Bp}) >|^2$$

$$\mathrm{I} \approx \mathrm{C}_{\mathrm{Bp}}^{\mathrm{A}} \frac{\mathrm{W}(2\kappa_{Bp}\mathrm{r}_{\mathrm{Bp}})}{\mathrm{r}_{\mathrm{Bp}}}$$

$$\sigma \propto (\mathrm{C}_{\mathrm{Bp}}^{\mathrm{A}})^2$$ Direct Capture

Measure **ANCs**:
peripheral transfer reactions

ANCs at TAMU

from radioactive beams

- **$^{10}B(^{7}Be,^{8}B)^{9}Be$, $^{14}N(^{7}Be,^{8}B)^{13}C$** [$S_{17}(0)$] [$^{7}Be(p,\gamma)$]
  [^{7}Li beam ≈ 130 MeV, ^{7}Be beam ≈ 84 MeV]

- **$^{14}N(^{11}C,^{12}N)^{13}C$** ($^{11}C(p,\gamma)^{12}N$ – Pop III stars)
  [^{11}B beam ≈ 144 MeV, ^{11}C beam ≈ 110 MeV]

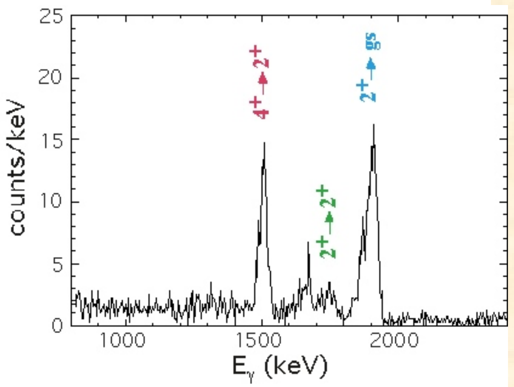
- **$^{14}N(^{13}N,^{14}O)^{13}C$** ($^{13}N(p,\gamma)^{14}O$ – HCNO cycle)
  [^{13}C beam ≈ 195 MeV, ^{13}N beam ≈ 154 MeV]

Proton transfer in inverse kinematics

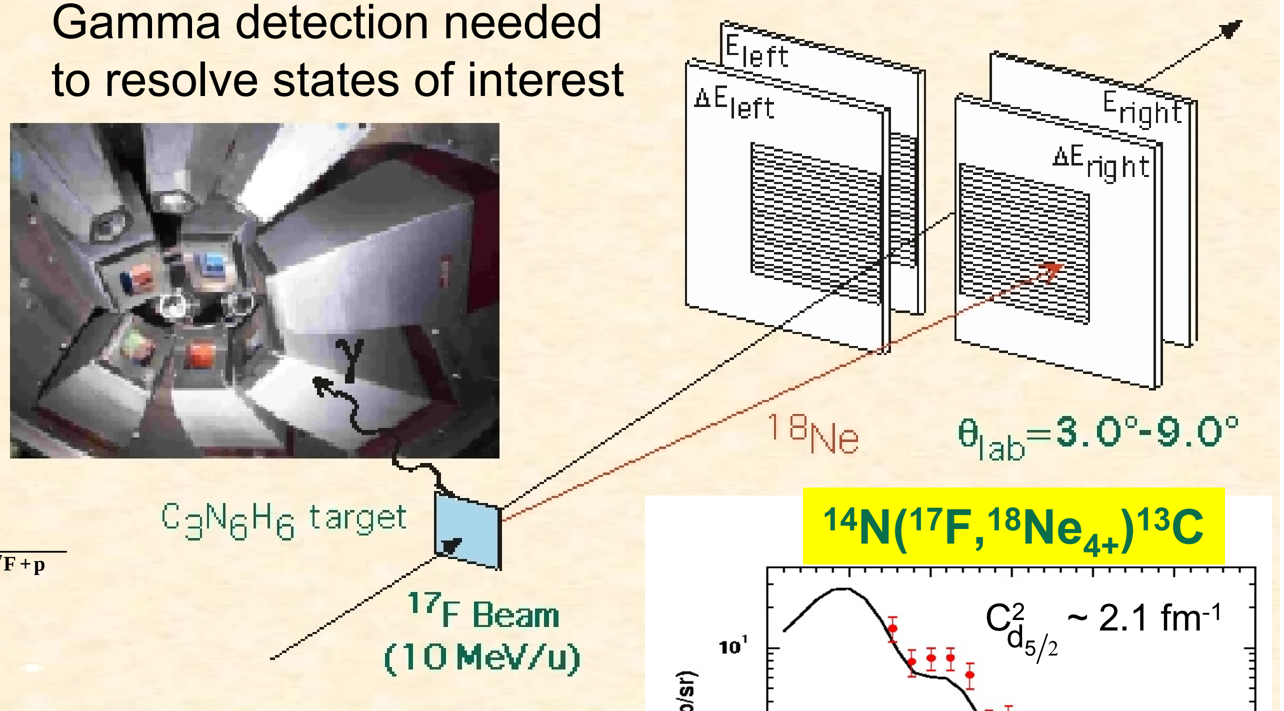
HRIBF

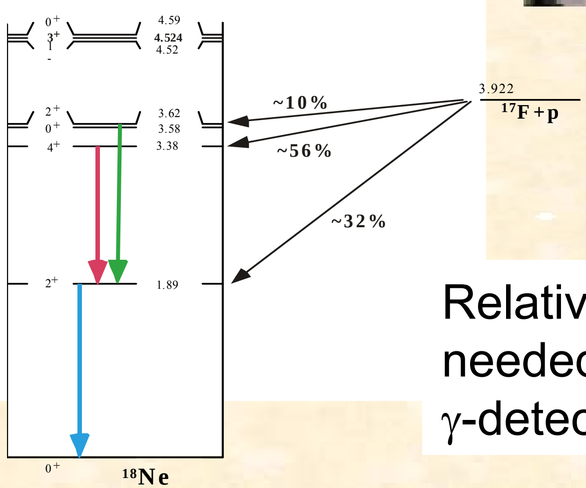
Heavy ion induced reactions

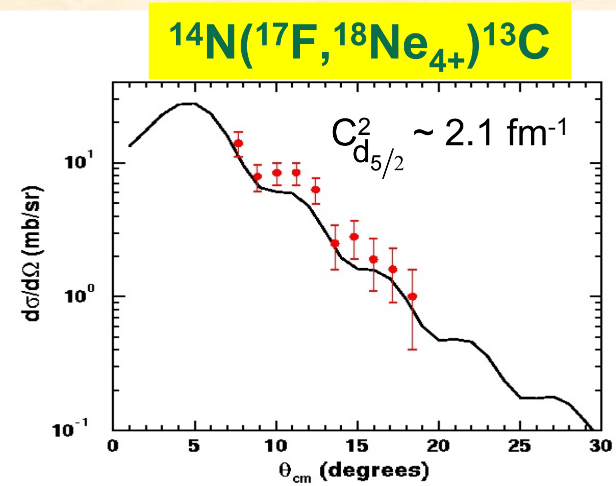
(^{14}N,^{13}C) - ANC's for ^{17}F+p measured for ^{17}F(p,γ)^{18}Ne direct capture



Gamma detection needed to resolve states of interest







Relative high beam intensity needed to compensate for poor γ-detection efficiency

Jeff Blackmon

Use of Radioactive Targets

$^{7}Be(p, \gamma)^{8}B)$

$^{22}Na(p,\gamma)^{23}Mg$

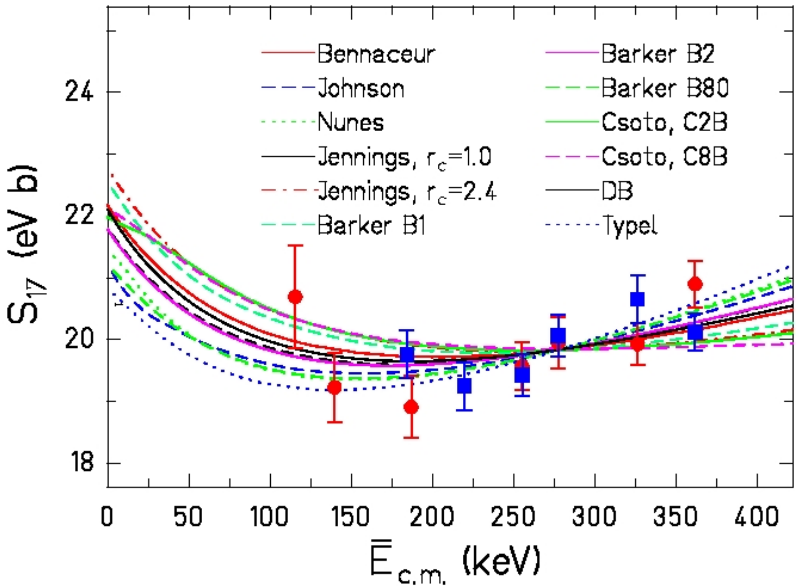
at

TRIUMF-ISAC and UWash.

n-T-O-F

$^{7}Be(p,\gamma)^{8}B$

Recent studies using implanted/deposited targets

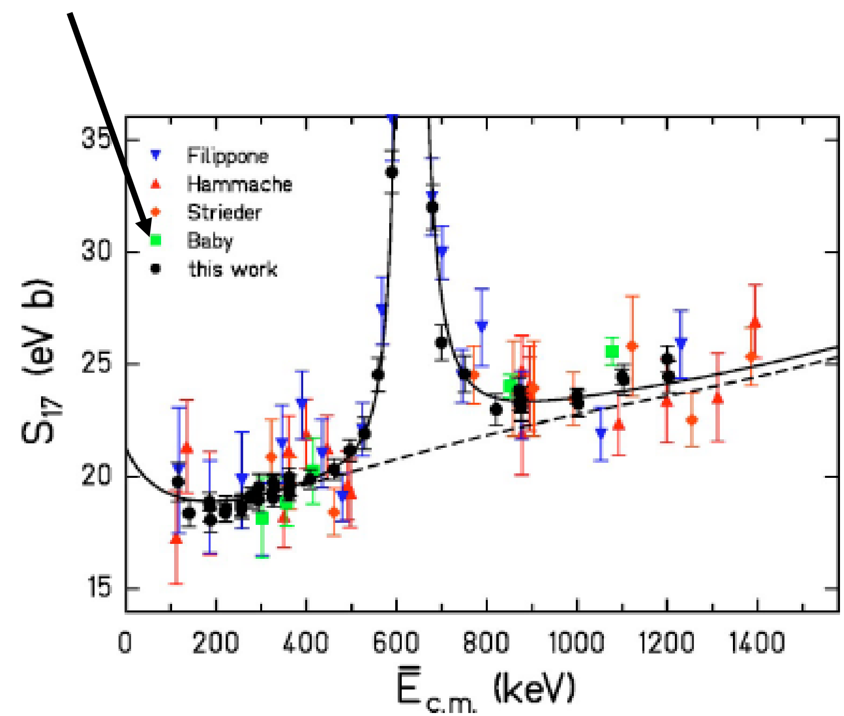


$S_{17}(0)$ = 22.1 ±0.6 eV b Seattle/TRIUMF

Junghans, et al., PR C 68, 065803 (2003)

$S_{17}(0)$ = 20.8 ± 0.8 eV b ISOLDE/Weizmann

Baby, et al., PR C 67 (2003) 065805
Baby, et al., PR C 69 (2204) 019902



$S_{17}(0)$ = 21.4 ± 0.6 eV b world

L. Buchmann

Understanding novae; $^{22}Na(p,\gamma)^{23}Mg$ revisited

E1027 Jac Caggiano

Motivation

- New excited state found in ^{23}Mg (2004)
- Could be dominant res. in $^{22}Na(p,\gamma)^{23}Mg$
- Most important reaction in determining abundance of cosmic gamma ray emitter ^{22}Na ($T_{1/2}$=2.6 years)
- Need to measure resonance strength
- ^{22}Na target required

Outline of Plan

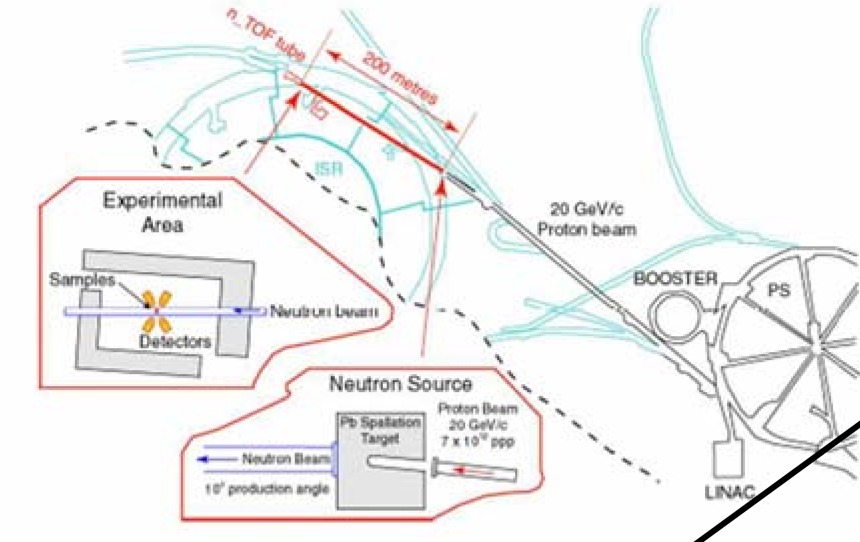
- Deposit in copper (rastering)
- Test implantation process/stability of deposit, etc.
- Prepare 1 ~10 μCi target
  - 81 seconds with 65μA protons (8.1x10^{11} ^{22}Na/s)
- Two <= 300 μCi targets
  - 45 minutes each with 65 μA protons
  - Double as strong sources and targets
  - Have up to 1 year before decay to 200 μCi
- TOTAL ISAC beamtime required 1.5 hours
- Expected Counting Rate for ^{22}Na(p,gamma)
  - Background: 1-10kHz in Ge
  - Measurement: $\omega\gamma$=1 meV -> Y=1.02x10^{-12};
  - With efficiency=0.001, 10μA => 0.64 cnts/sec

Status

- Deposition has been tested and it is understood.
- Initial attempt to prepare 300 μCi sample not successful as ISOL target died
- Another attempt planned for October, 2005.

Jac Caggiano

n-T-O-F facility



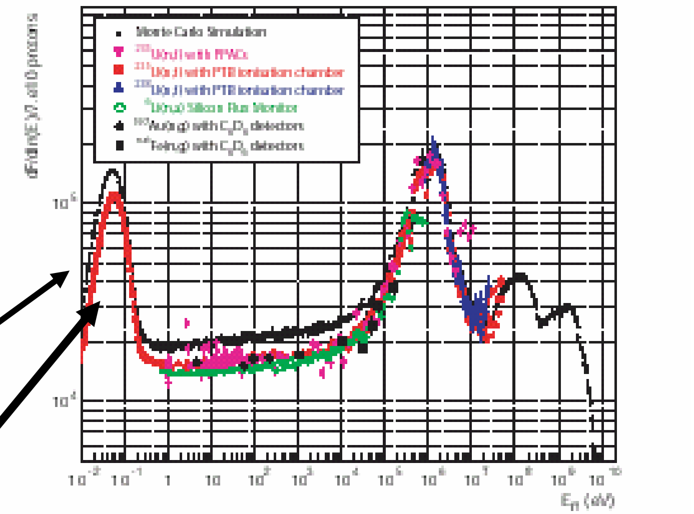


FIGURE 1. Neutron flux in EAR-1 as measured with different experimental techniques. A comparison is shown with the Monte Carlo simulations.

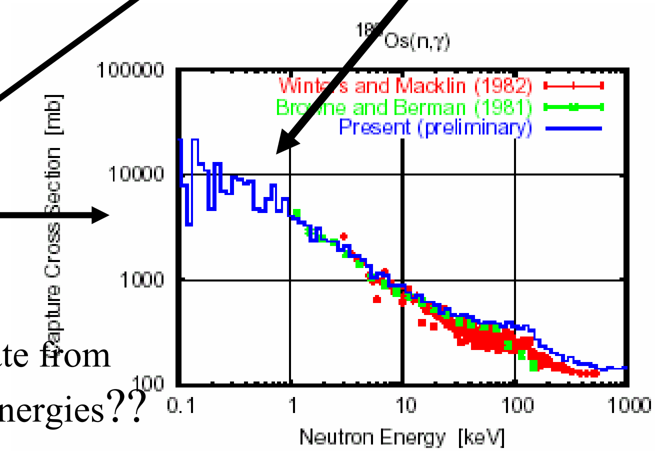
Parameters

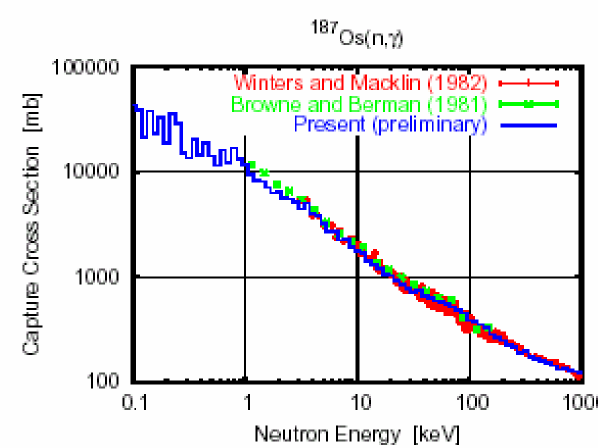
Target ~10^{21} atoms

Beam ~10^{6} n/pulse

Cross Section ~10^{-23}

N$\sigma\varphi$ ~ 10^{4} /pulse





Extrapolate from thermal energies??

U. Abbondanno et al., NP A 758 (2005)

What about?

Target ~10^{18}

Cross Section ~10^{-23}

Beam ~10^{6} n/pulse

N$\sigma\varphi$ ~ 10 /pulse

(Is it doable??)

Radioactive target

~10^{12} p/s x 8.6 x 10^{4} s/d x 10 d collection = ~10^{18} atoms

Future Plans

ISAC and DRAGON

RIA??

EUROISOL??

DRAGON Program (10 years)

Science Priority List

E952 $^{12}C(\alpha,\gamma)^{16}O$
E813 $^{15}O(\alpha,\gamma)^{19}Ne$
E922 $^{25}Al(p,\gamma)^{26}Si$
E989 $^{26g,m}Al(p,\gamma)^{27}Si$
E1024 $^{40}Ca(p,\gamma)^{44}Ti$
E1027 $^{22}Na(p,\gamma)^{23}Mg$
E811 $^{19}Ne(p,\gamma)^{20}Na$
E805 $^{13}N(p,\gamma)^{14}O$
E946 $^{17}F(p,\gamma)^{18}Ne$
E810 $^{23}Mg(p,\gamma)^{24}Al$
E983 $^{11}C(p,\gamma)^{12}N$
New: $^{17}O(p, \gamma)^{18}F$

Initial program based upon discussions at Parkville conference in 1985 with some upgrade following developments and beams availability

Science Priority List of DRAGON Collaboration

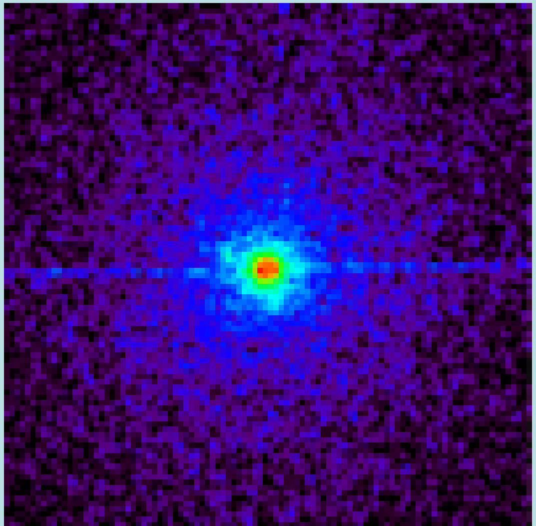
Radioactive Beams	Stable Heavy Ion Beams
E813 $^{15}O(\alpha,\gamma)$19Ne	E952 $^{12}C(\alpha,\gamma)^{16}O$
E922 $^{25}Al(p,\gamma)$26Si	E1024 $^{40}Ca(\alpha,\gamma)^{44}Ti$
E989 $^{26g,m}Al(p,\gamma)^{27}Si$	New: $^{17}O(p, \gamma)^{18}F$
E811 $^{19}Ne(p,\gamma)^{20}Na$	
E805 $^{13}N(p,\gamma)^{14}O$	
E946 $^{17}F(p,\gamma)^{18}Ne$	
E810 $^{23}Mg(p,\gamma)^{24}Al$	
E983 $^{11}C(p,\gamma)^{12}N$	

Feasibility Priority List of All Experiments

E989 $^{26g,m}Al(p,\gamma)^{27}Si$ [in progress]
E1027 $^{22}Na(p,\gamma)^{23}Mg$ [Seattle; p beam; in progress]
E1024 $^{40}Ca(\alpha,\gamma)^{44}Ti$ [in progress]
New: $^{17}O(p, \gamma)^{18}F$ [needs EEC approval]
E811 $^{19}Ne(p,\gamma)^{20}Na$ [needs beam; FEBIAD]
E922 $^{25}Al(p,\gamma)^{26}Si$ [needs beam; target]
E989 $^{26m}Al(p,\gamma)^{27}Si$ [needs beam; target]
E805 $^{13}N(p,\gamma)^{14}O$ [needs beam; ECR,alternate]
E983 $^{11}C(p,\gamma)^{12}N$ [needs beam; ECR,alternate]
E813 $^{15}O(\alpha,\gamma)^{19}Ne$ [needs beam; very difficult]
E946 $^{17}F(p,\gamma)^{18}Ne$ [needs beam;ECR]
E810 $^{23}Mg(p,\gamma)^{24}Al$ [needs beam;laser]
E952 $^{12}C(\alpha,\gamma)^{16}O$ [in progress]

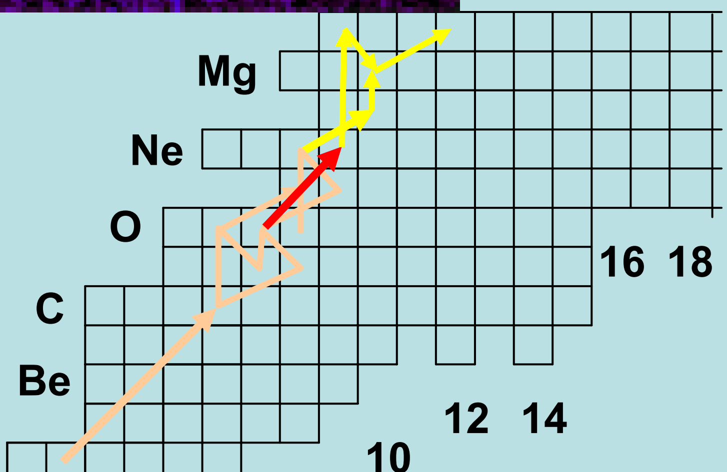
New: $^{26g}Al(^{3}He,t)^{26}Si(p)^{25}Al$ [rad. target;Yale study; needs EEC]

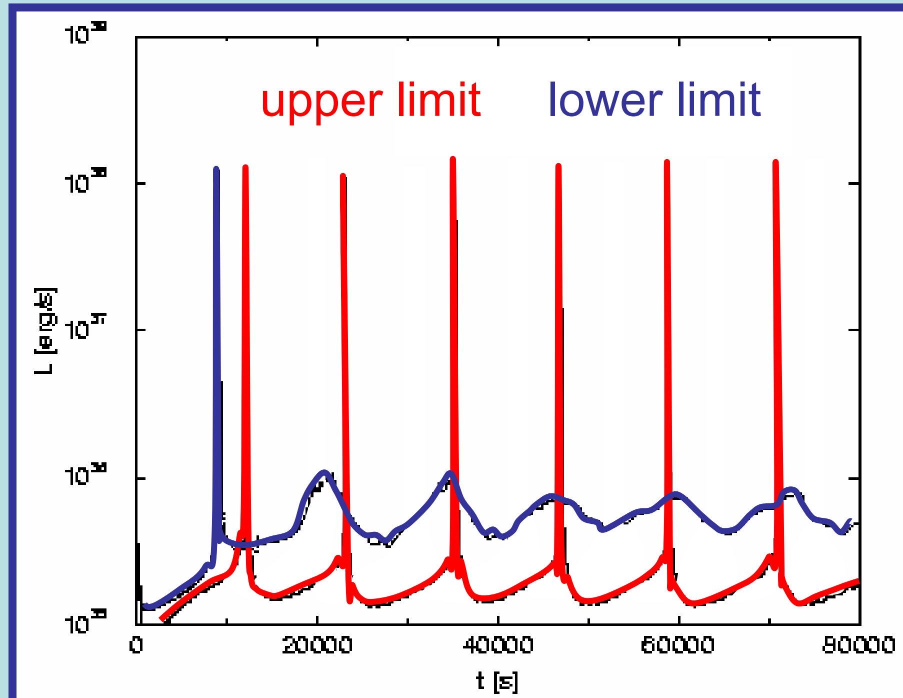
The nuclear trigger of X-ray bursts



$^{15}O(\alpha,\gamma)^{19}Ne$, $^{18}Ne(\alpha,p)^{21}Na$

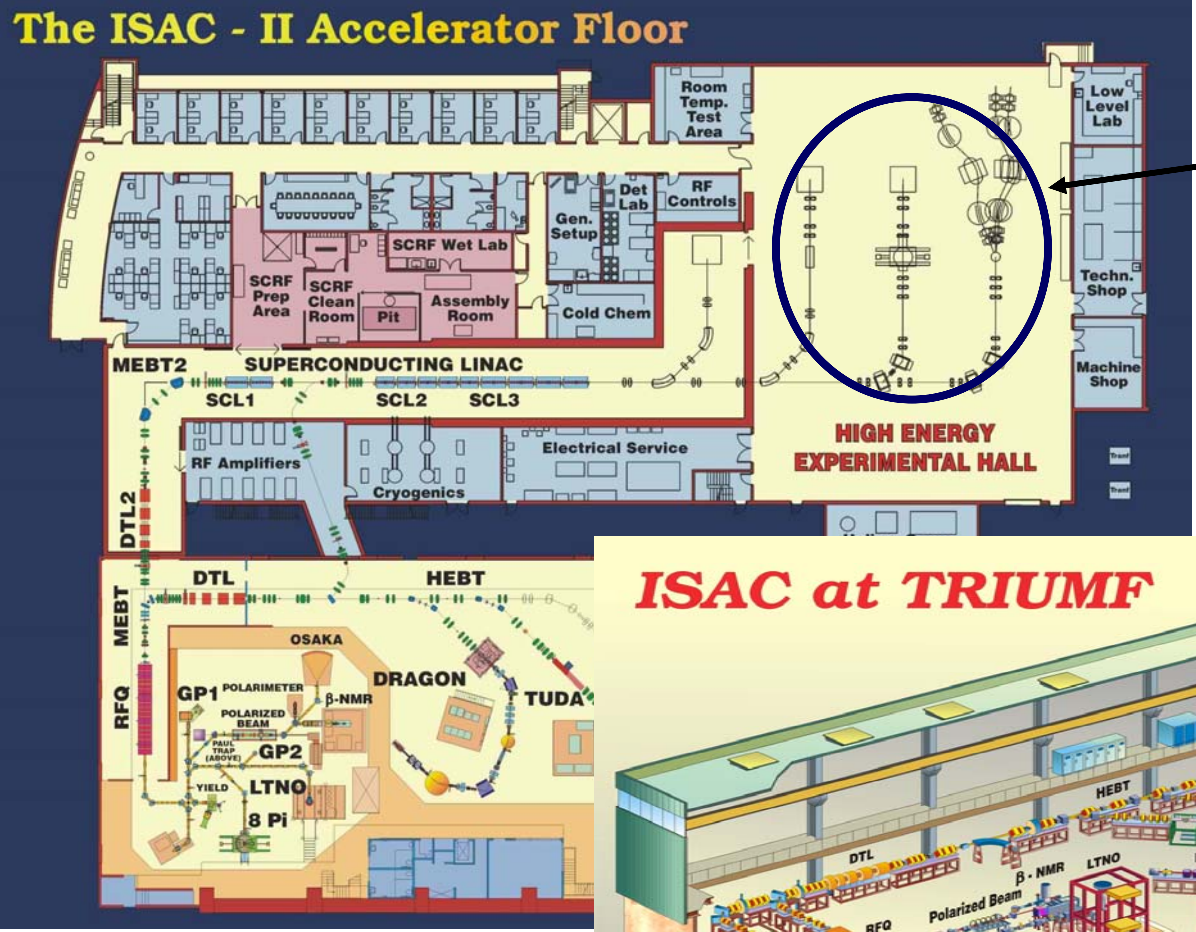
Reaction rate determined by single resonance





$^{15}O(\alpha,\gamma)^{19}Ne$ as switch for XRB pattern

MW



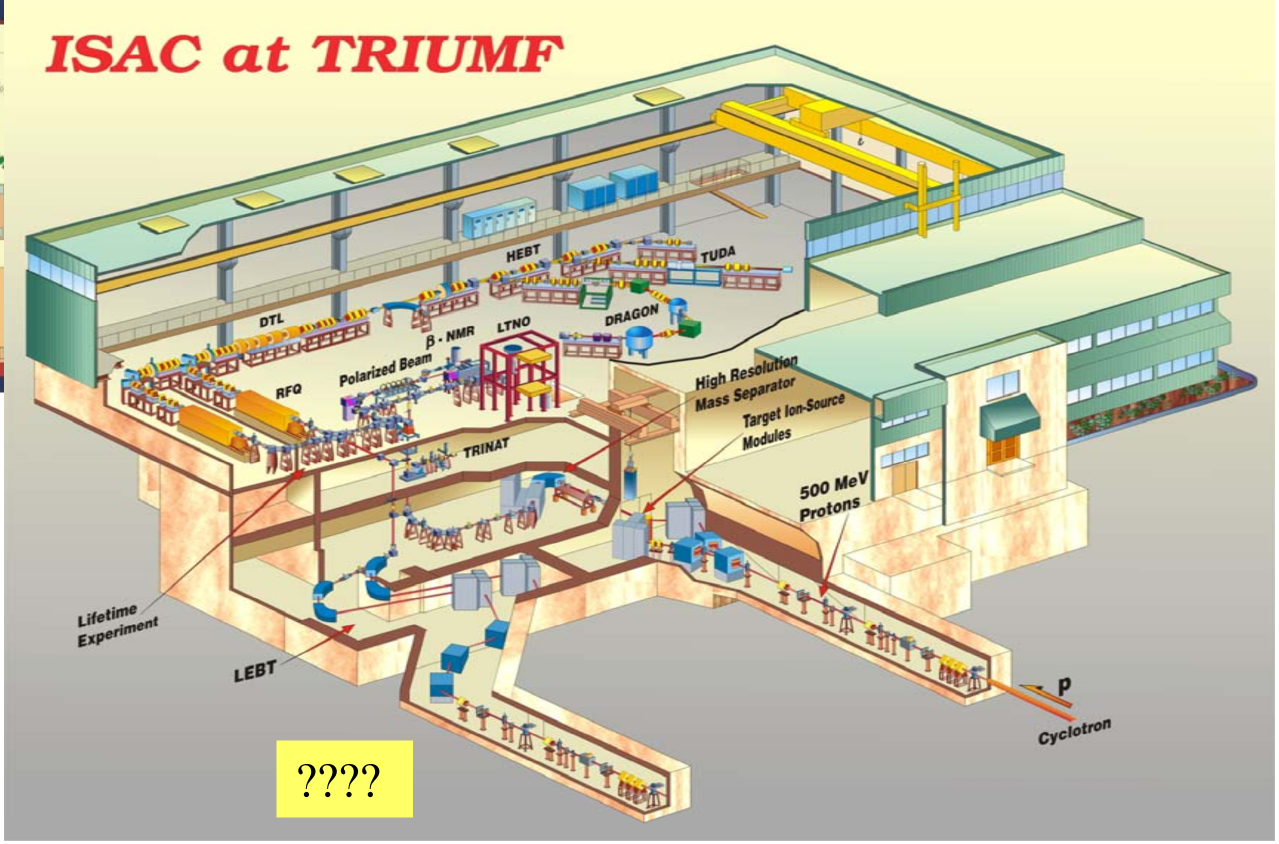
Not finalized

Facilities

Tigress

Emma

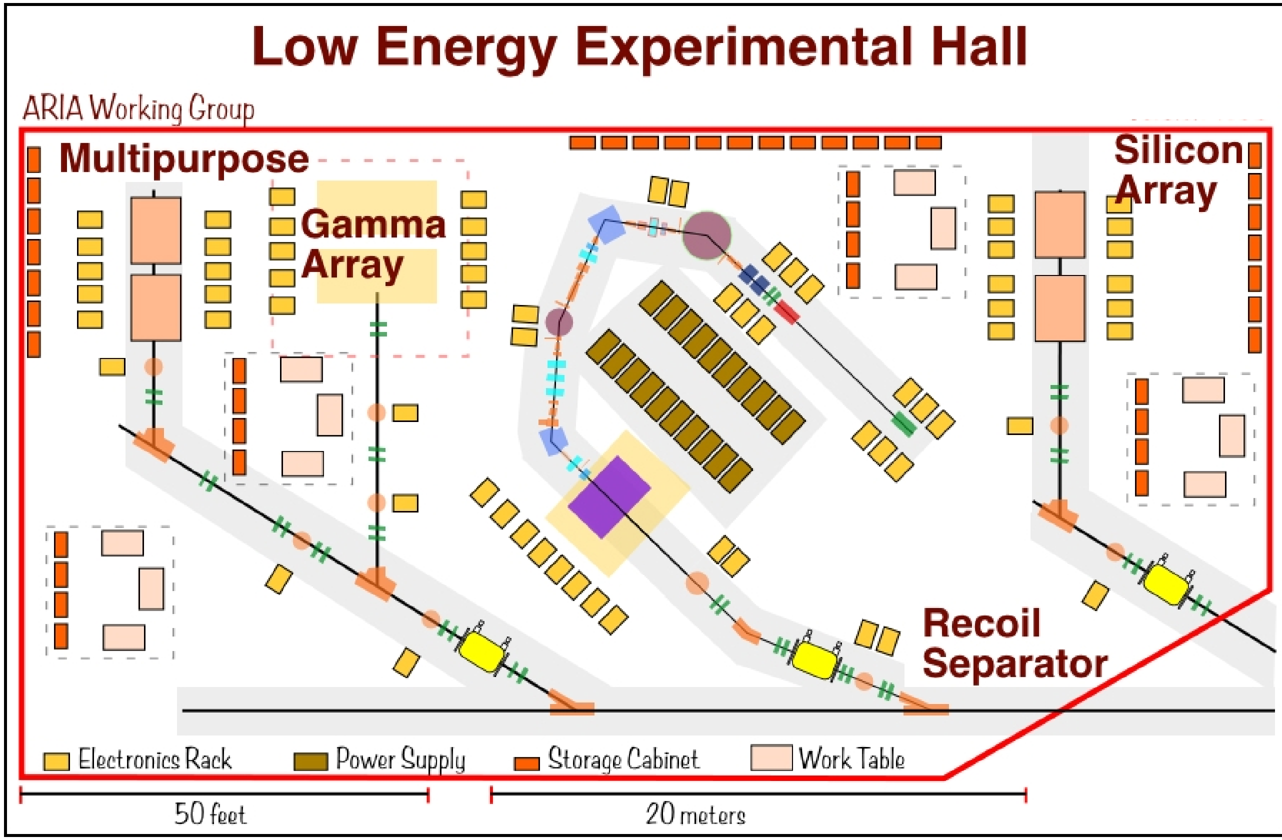
Tuda



RIA in astrophysics

ARIA working group design of nuclear astrophysics hall and equipment at RIA

28 members from 15 institutions!



Recoil separator and several generic multi-array detector stations for inverse kinematics experiments with radioactive beams.

MW

Summary

- Thanks to all…
- Many studies now in progress around the world using RB in nuclear astrophysics (and more to do!!!).
- These range from radiative capture to wide spectrum of particle reactions.
- ISOLDE had been benchmark of RB studies in the past with great successes.
- Most studies shown could be done at ISOLDE.
- Needs upgrade of facilities to be part of this new area of science (or to lead in this field !!!).
- RT coupled with n-TOF is optimal for s process studies.
- What about a second Production System???