Nuclear Astrophysics of neutron-deficient nuclei: experimental approaches at ISAC

Chris Ruiz - TRIUMF

Outline

- Reaction rates: reminder
- Direct measurements of radiative capture (DRAGON)
- Direct/indirect measurements of charged-particle reactions (TUDA)
- Mass measurements (TITAN)
- Beam production

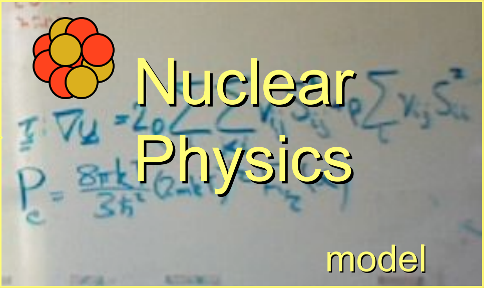
Nuclear Astrophysics Aims

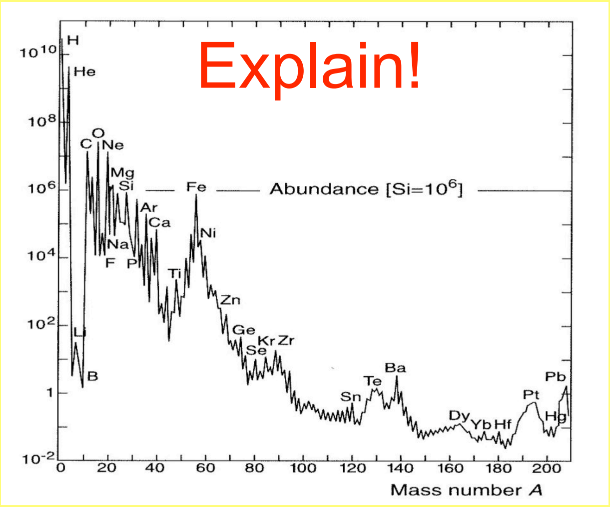
observation

compare

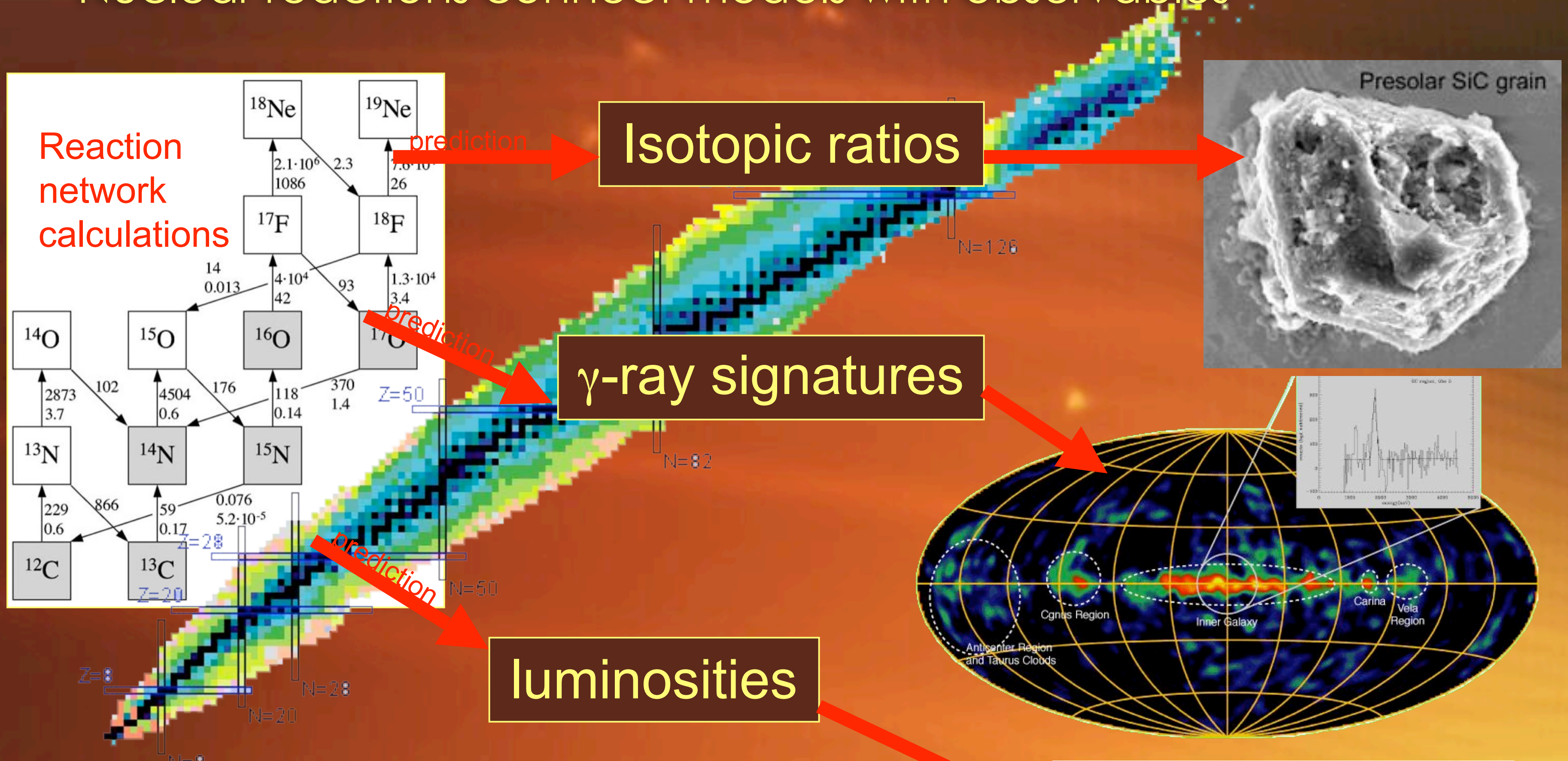
Understanding nucleosynthesis and how stars explode

understand





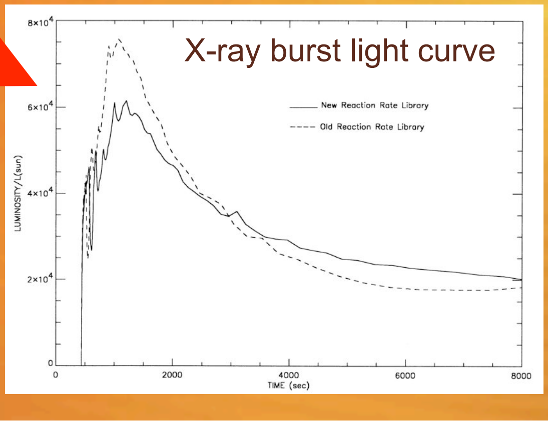
Nuclear reactions connect models with observables



Isotopic ratios

γ-ray signatures

luminosities



- Theory & simulation help identify which nuclear reactions are important
- Post-burst ash/envelope composition
- Reaction rate ≈ nuclear cross-section

Processing of neutron-deficient nuclei

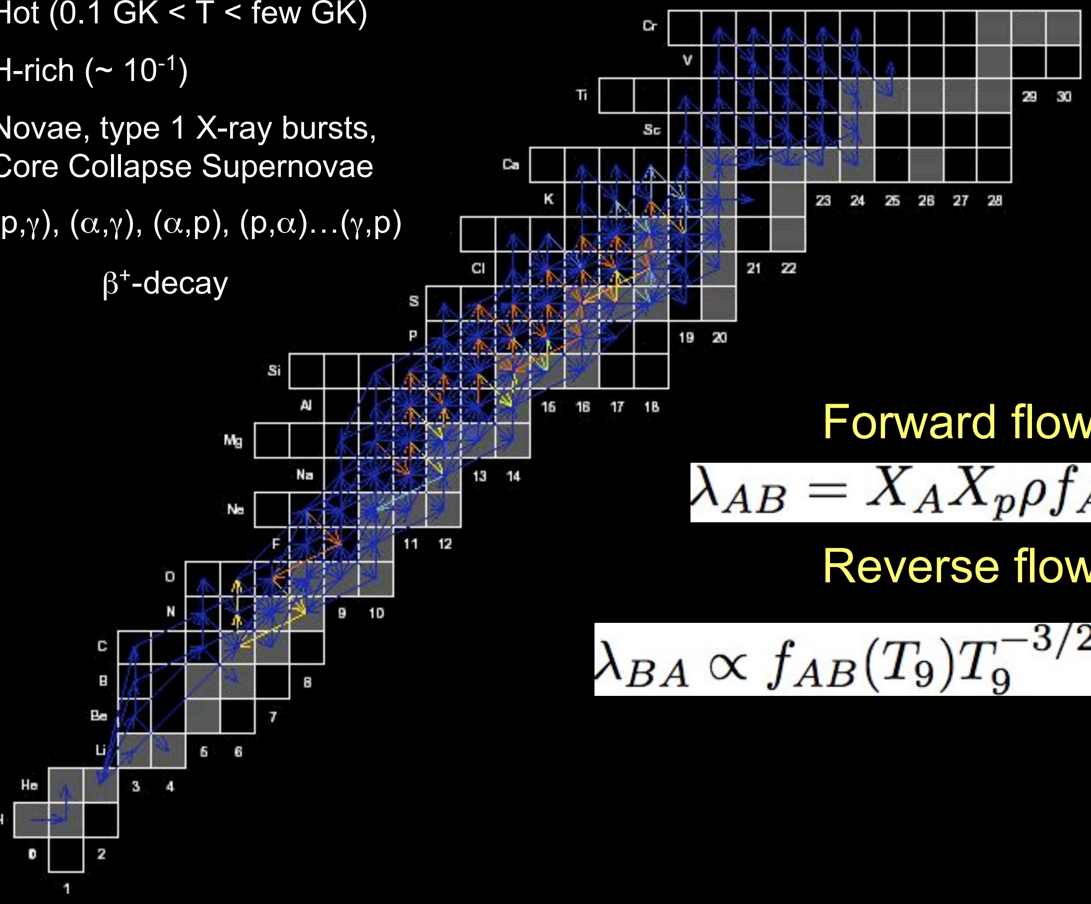
Hot (0.1 GK < T < few GK)

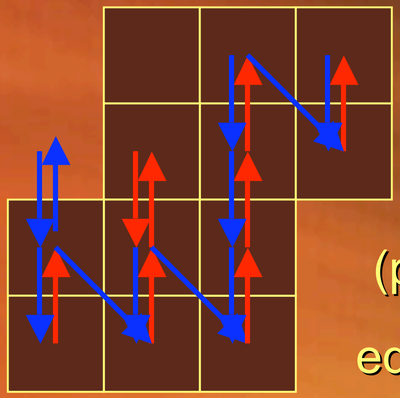
H-rich (~ 10^{-1})

Novae, type 1 X-ray bursts,
Core Collapse Supernovae

(p,γ), (α,γ), (α,p), (p,α)…(γ,p)

β^+-decay





(p,γ)/(γ,p)

equilibrium

Forward flow

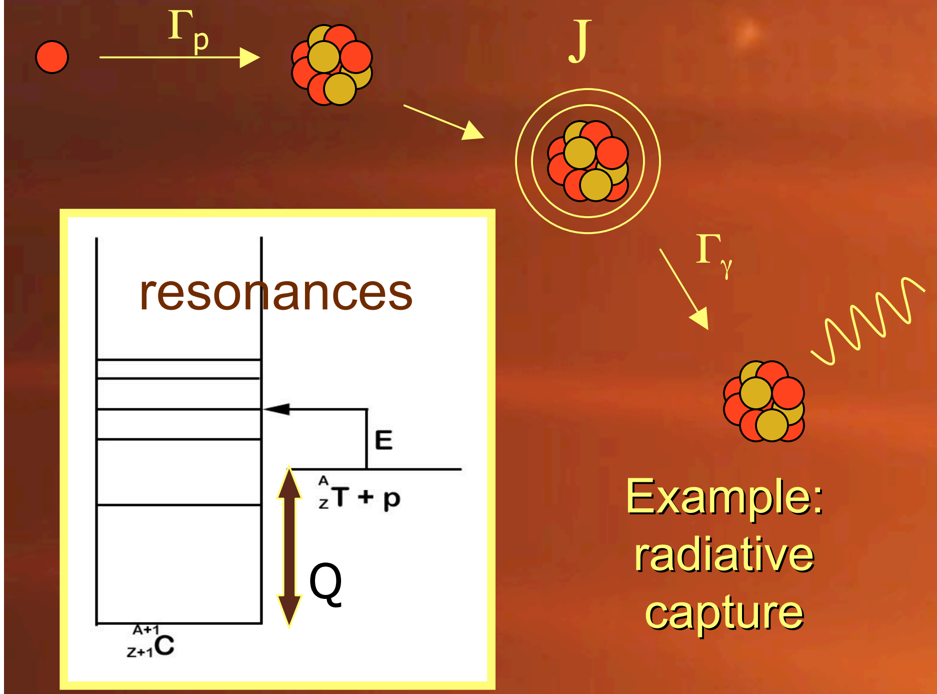
$$\lambda_{AB} = X_A X_p \rho f_{AB}(T_9)$$

Reverse flow

$$\lambda_{BA} \propto f_{AB}(T_9) T_9^{-3/2} \exp\left(-11.605 Q_{A+p\rightarrow B}/T_9\right)$$

Reaction rates, β^+-decay lifetimes, reaction Q-values (mass measurements)

Measuring fusion rates (cross-sections)



Example: radiative capture

$$< \sigma v >= \left(\frac{2\pi}{\mu kT}\right)^{3/2} \hbar f \sum_i (\omega\gamma)_i \exp\left(-\frac{E_i}{kT}\right)$$

$$\omega\gamma = \frac{2J+1}{(2I_1+1)(2I_2+1)}(1+\delta_{12})\frac{\Gamma_{en}\Gamma_{ex}}{\Gamma_{tot}}$$

- Cross-section depends on states above threshold in compound nucleus - level density low for light nuclei -> stat model not applicable
- Worse for unstable nuclei - low binding means few isolated narrow resonances and/or DC contribute
- Shell model not accurate enough, mirror correspondences not necessarily adequate
- Resonance strength, state energies, spin-parities needed experimentally

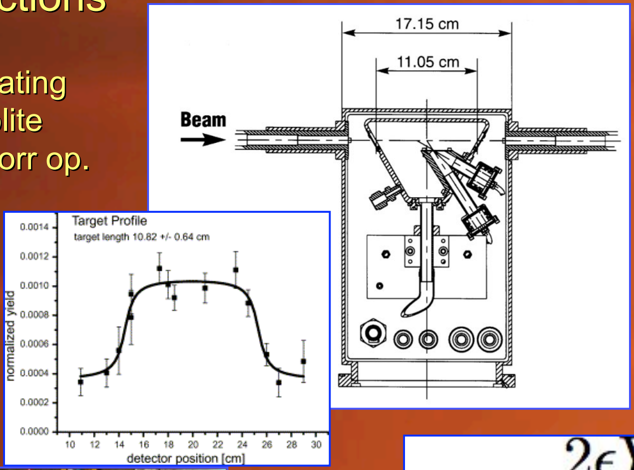
Radiative Capture Reactions: DRAGON

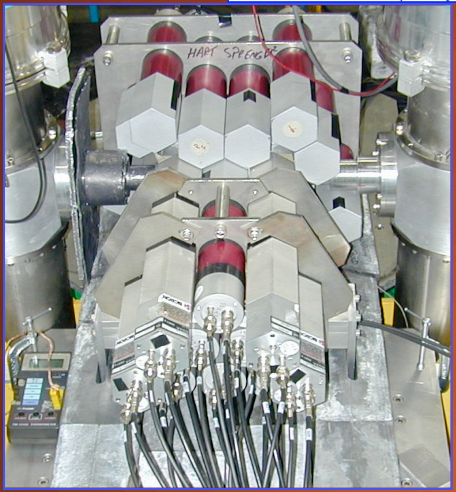
Detector of Recoils and Gammas of Nuclear Reactions

High suppression recoil separator for inverse kinematics reactions

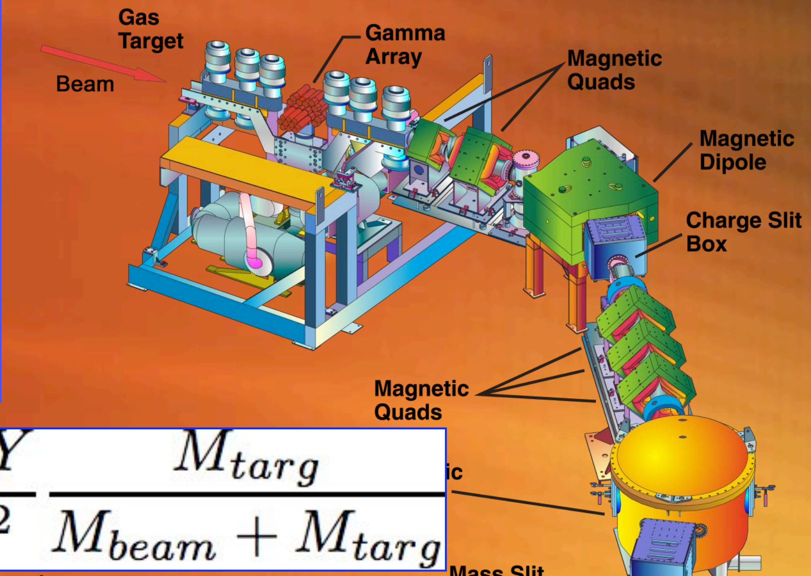
Windowless re-circulating H/He gas target. Zeolite cleaning trap. 0.5-8Torr op. range

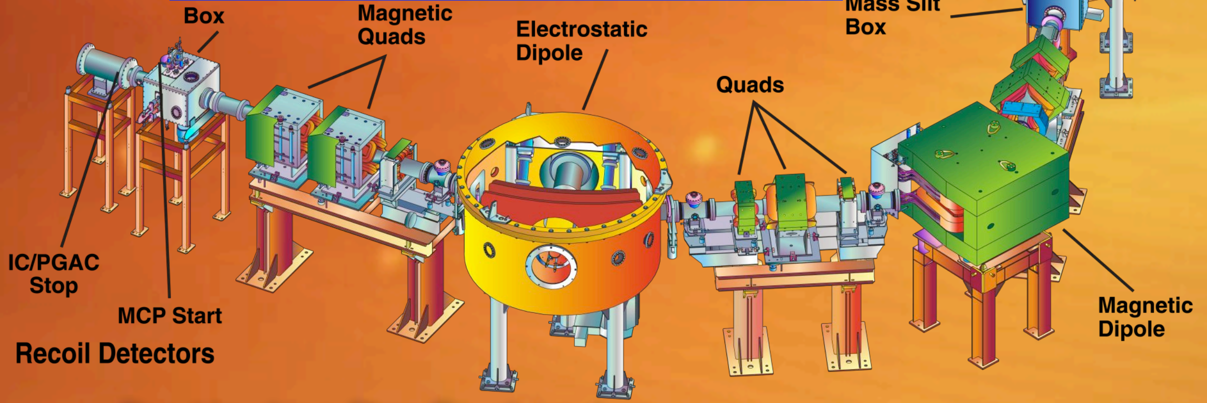
30 BGO detector array, ~50% efficiency for single gamma ray





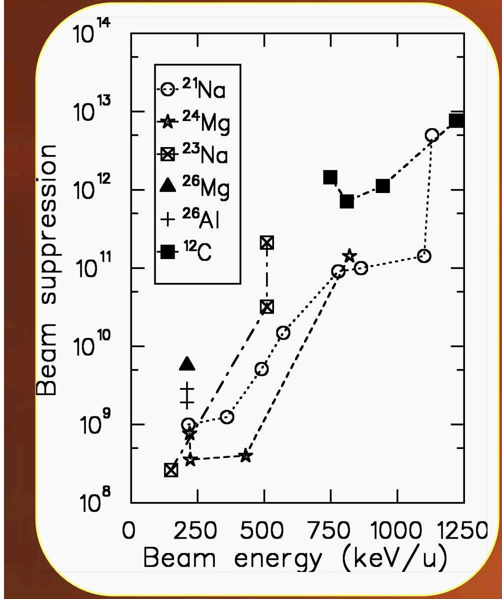
$$\omega\gamma = \frac{2\epsilon Y}{\lambda^2}\,\frac{M_{targ}}{M_{beam}+M_{targ}}$$



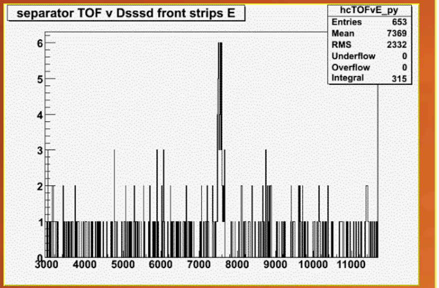


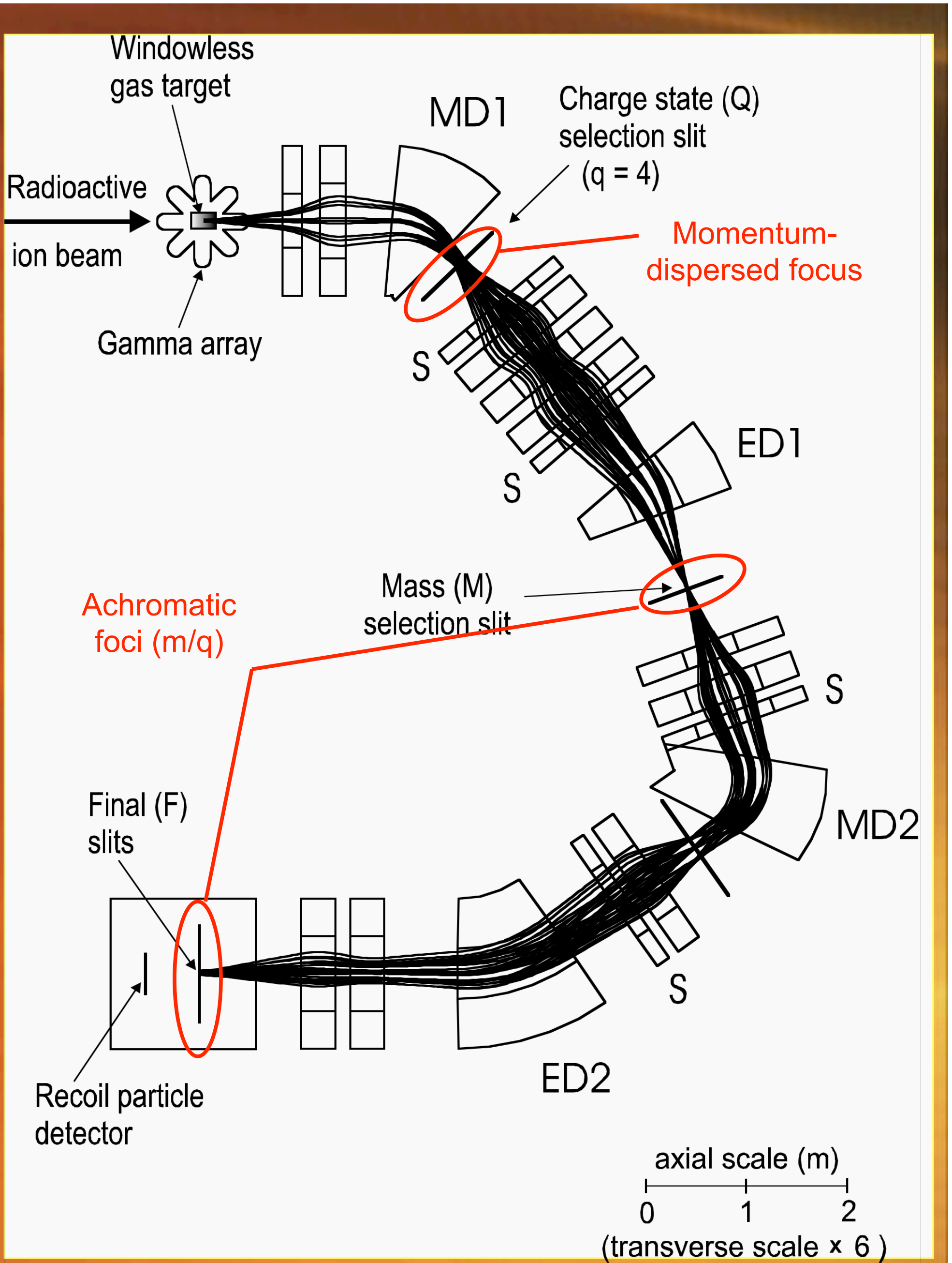
- MEME Design
- Limited by 1st Magnetic bender: 0.5 Tesla.m
- Also by Electric Dipoles: 200kV
- A<30, with post-stripping potentially A~80 (have done A=40)

Resonance strengths: tens of micro-eV to eV (at low E $\omega\gamma \sim \omega\Gamma_p$, higher E $\omega\gamma \sim \Gamma_\gamma$)



With yields as low as 10^{-14} reac/ion, need additional suppression (T.O.F γ -ion coincidence, local T.O.F)





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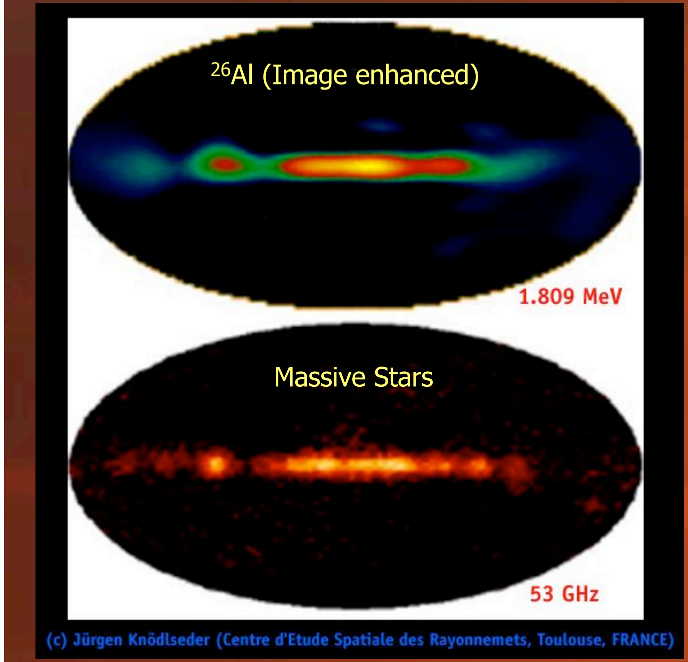
^{26g}Al and the ^{26g}Al(p,γ)^{27}Si reaction at DRAGON

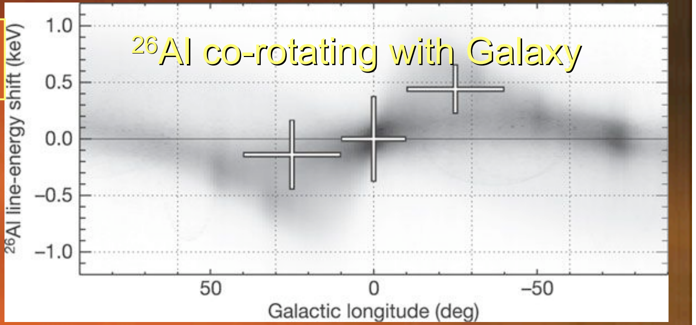


^{60}Fe/^{26}Al = 0.11± 0.03

Harris, M.J. Astronomy & Astrophysics 433 (2005)

Supernova rate derived (1.9±1.1 century^{-1})

7.5 stars born yr^{-1}



Diehl, R. *et al.* Nature 439/5 (2006)

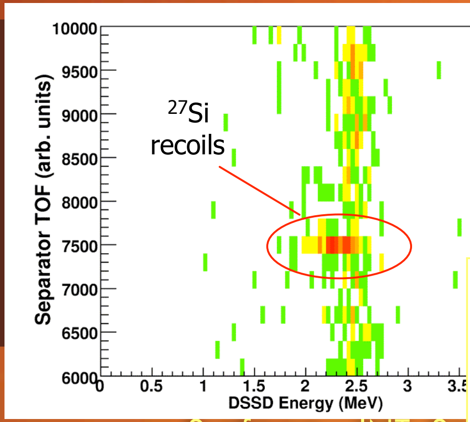
Nova models predicted significant ^{26g}Al production: at odds with observation. Problem:

a) large uncertainties with ^{26g}Al(p,γ)^{27}Si and ^{25}Al(p,γ)^{26}Si reactions

b) Uncertainty in lower nova mass limit

DRAGON measurement: 184 keV resonance

- very low cross-section
- 5 x 10^{9} /s peak intensity - record
- surface *and* laser ion sources

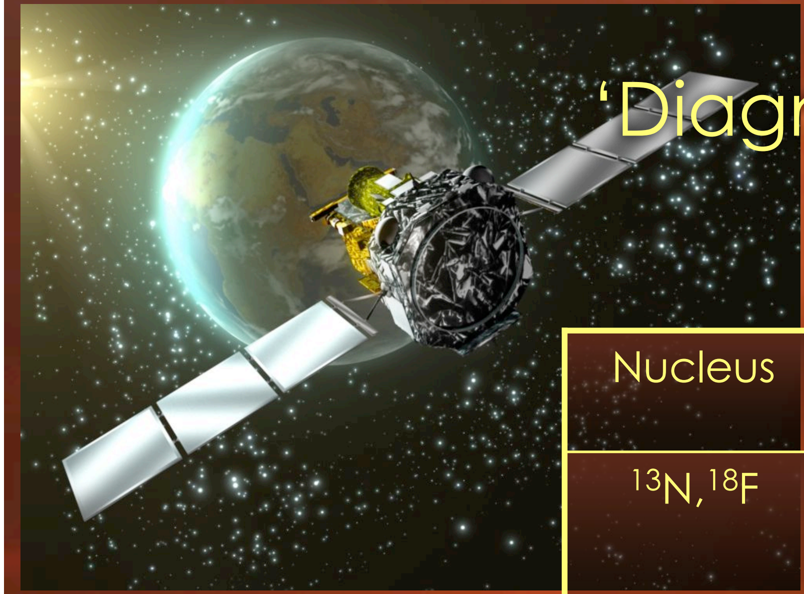


Small secondary amount of ^{26g}Al made by novae - but SNII dominate

PRL **96,** 252501 (2006) PHYSICAL REVIEW LETTERS week ending 30 JUNE 2006

Measurement of the $E_{\mathrm{c.m.}} = 184$ keV Resonance Strength in the ^{26g}Al(p, γ)^{27}Si Reaction

C. Ruiz,[1,*] A. Parikh,[2,†] J. José,[3,4] L. Buchmann,[1] J. A. Caggiano,[1] A. A. Chen,[5] J. A. Clark,[2] H. Crawford,[6] B. Davids,[1] J. M. D'Auria,[6] C. Davis,[1] C. Deibel,[2] L. Erikson,[7] L. Fogarty,[8] D. Frekers,[9] U. Greife,[7] A. Hussein,[10] D. A. Hutcheon,[1] M. Huyse,[11] C. Jewett,[7] A. M. Laird,[12] R. Lewis,[2] P. Mumby-Croft,[12] A. Olin,[1] D. F. Ottewell,[1] C. V. Ouellet,[5] P. Parker,[2] J. Pearson,[5] G. Ruprecht,[1] M. Trinczek,[1] C. Vockenhuber,[1] and C. Wrede[2]

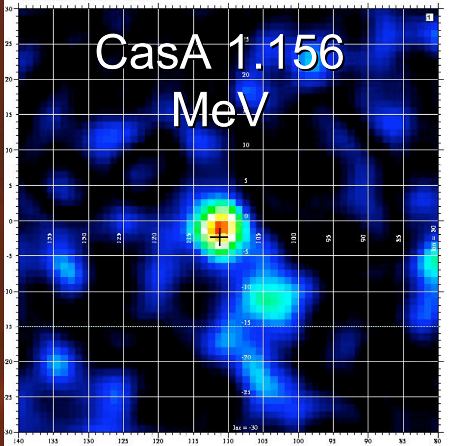


‘Diagnostic’ γ rays from novae and supernovae

Nucleus	Half-life	Important sources	Nature of radiation	Observed
^{13}N,^{18}F	10m, 1.8h	Novae	511 keV annihilation γ rays	No
^{22}Na	2.6yr	Novae	1275 keV γ ray	No
^{26g}Al	710kyr	SNII, Novae, AGB	1809 keV γ ray	Yes
^{44}Ti	60yr	SNII	1157 keV γ ray	Yes
^{60}Fe	1.5Myr	SNII	1333 keV, 1173 keV γ rays	Yes

DRAGON has measured reactions relevant to three of these, including two that have been observed with satellites

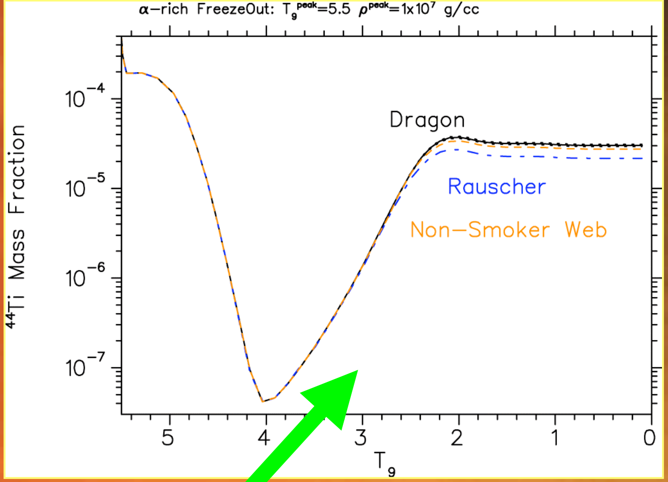
^{40}Ca(α,γ)^{44}Ti at DRAGON
^{44}Ti: youngest indicator of nucleosynthesis



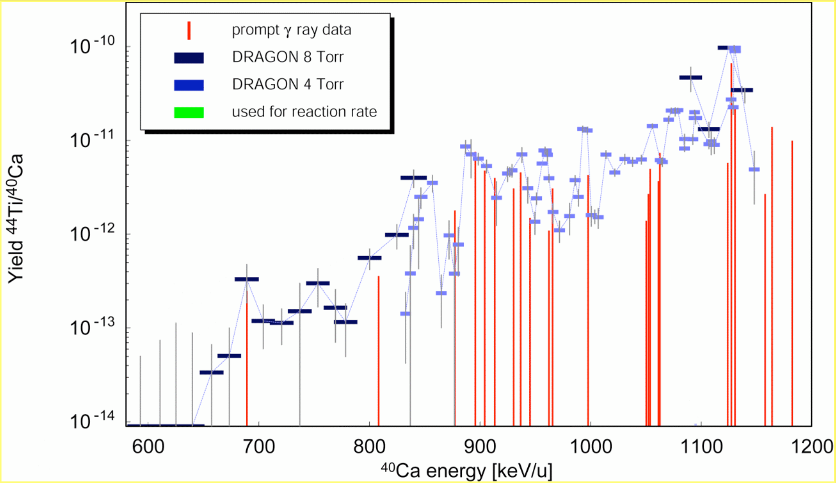
60-year half-life, observed in Cas A, SN1987A

^{44}Ti produced by ^{40}Ca(α,γ)^{44}Ti in 'alpha-rich freeze-out'

Large discrepancy between previous experiments



DRAGON measurement (C. Vockenhuber)



40% increase of ^{44}Ti yield compared to empirical model (Rauscher *et al.* 2000)

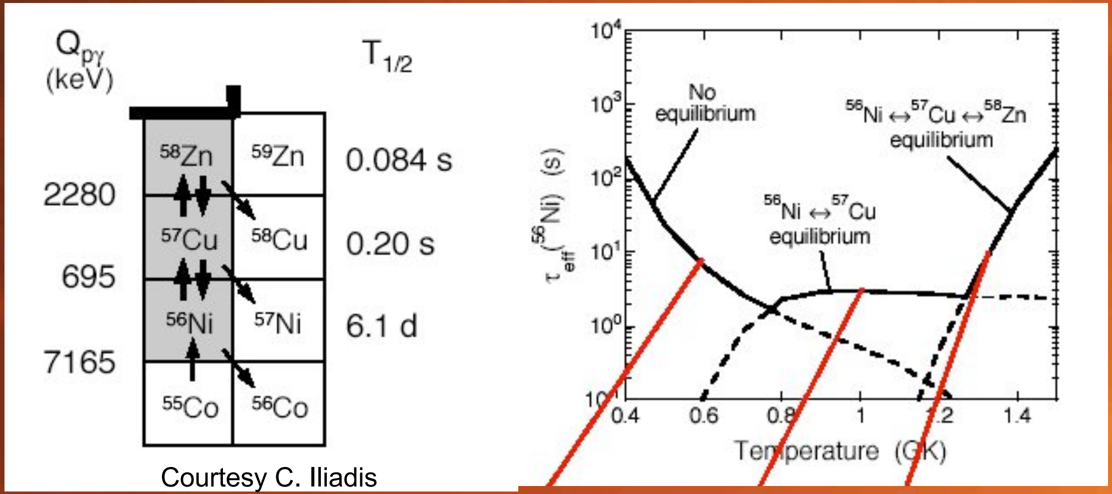
DRAGON measured uncertainty of the reaction rate = **+/- 3%** in ^{44}Ti yield

^{44}Ti yield and a ^{44}Ti/ ^{56}Ni ratio agree better with observations in Cas A and SN1987A. [cf. Nassar *et al.*, *Phys. Rev. Lett.* 96 (2006)]

To be published 2007

X-ray bursts (rp-process)??

- ^{56}Ni waiting point - ^{57}Cu(p,γ)^{58}Zn (200 ms)

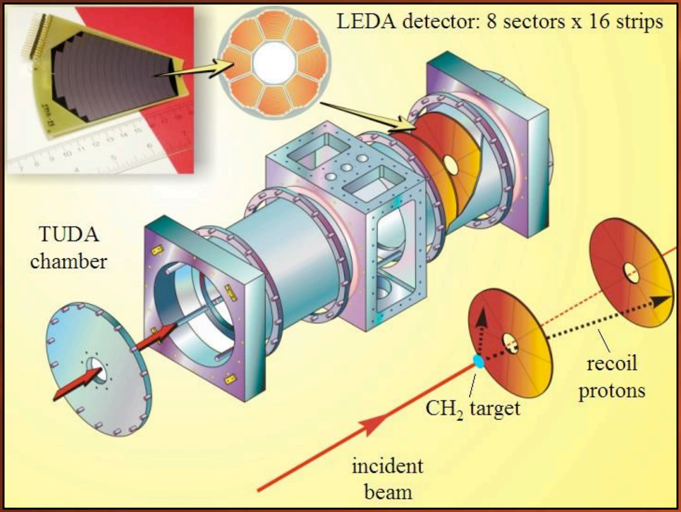


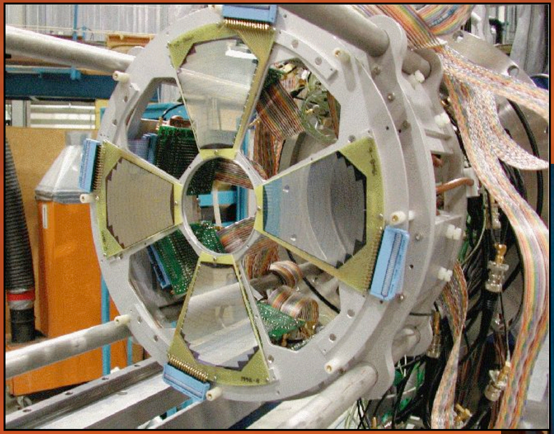
Courtesy C. Iliadis

- ^{65}As(p,γ)^{66}Se (128 ms)???
- Beyond present ISOL target-ion-source capabilities
- ^{19}Ne(p,γ)^{20}Na
- ^{43}Sc(p,γ)^{44}Ti, ^{59}Cu(p,γ)^{60}Zn (candidates for laser ionization),………

TUDA - Direct and Indirect Measurements

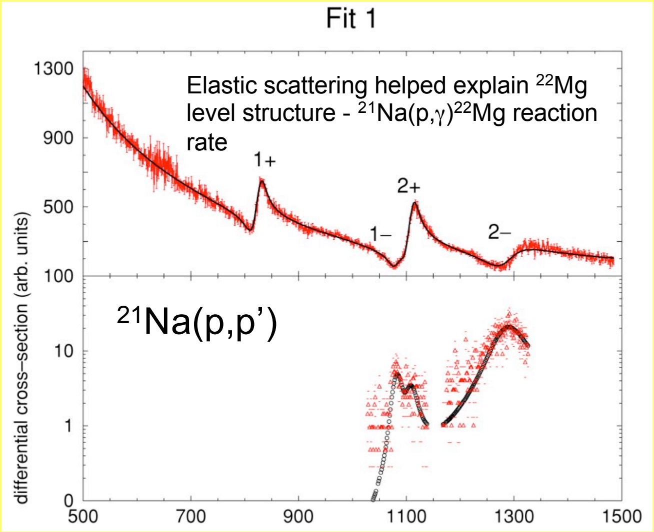
TRIUMF-UK Detector Array





“LEDA” detectors

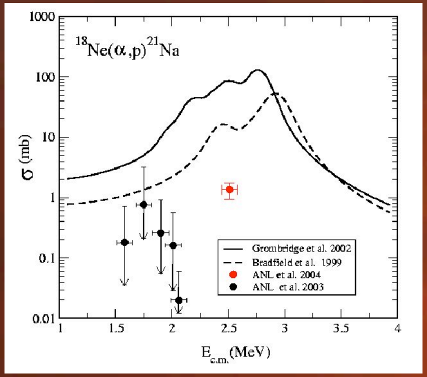
“Copper Shack”

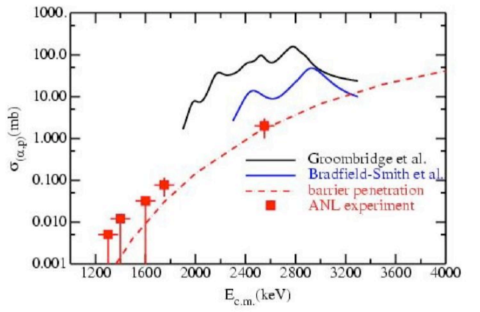


Elastic scattering helped explain ^{22}Mg level structure - ^{21}Na(p,γ)^{22}Mg reaction rate

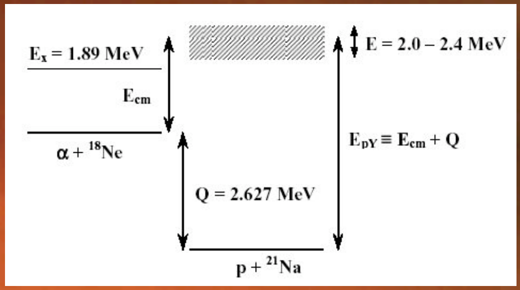
- Large solid-angle highly segmented arrays
- 512 channels
- High data-rate (~10kHz) low dead-time
- High resolution, v. good signal:noise
- Solid or gas targets
- Elastic scattering, reaction spectroscopy (e.g (^{3}He,p)), direct measurements

^{18}Ne(α,p)^{21}Na

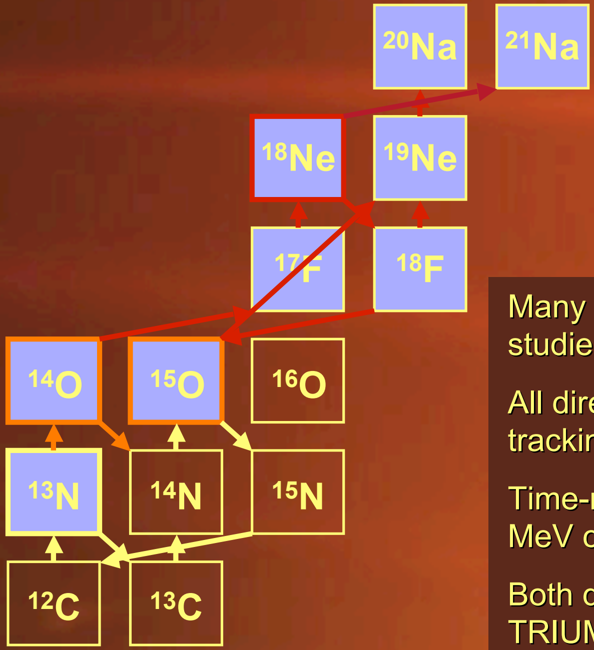


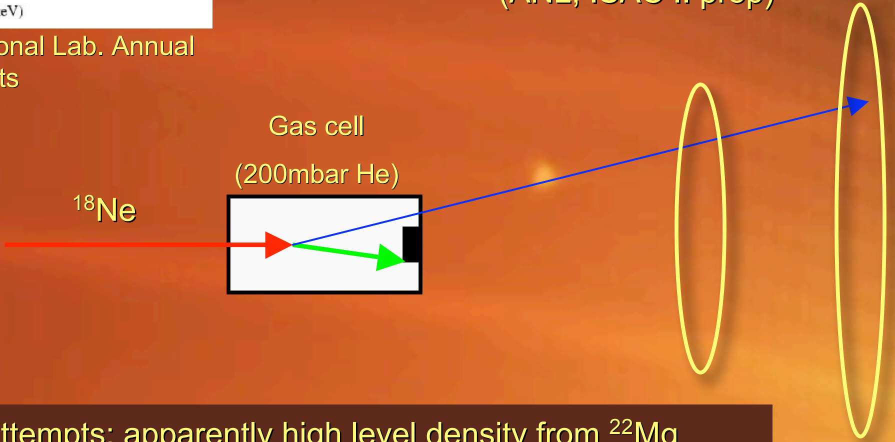


2003/4 Argonne National Lab. Annual Reports



Time-reversed approach: ^{21}Na(p,α)^{18}Ne (ANL, ISAC II prop)





Gas cell

(200mbar He)

^{18}Ne

Segmented silicon detectors for tracking

Many indirect attempts: apparently high level density from ^{22}Mg studies

All direct studies (Groombridge, Bradfield-Smith) used attempted tracking for inclusive excitation function

Time-reversed approach from ANL shows huge discrepancy at 2.5 MeV cf direct measurement.

Both direct measurement and time-reversed will be measured at TRIUMF (^{21}Na 4-6 MeV/u ISAC II, 5x10^6 pps)

^{18}Ne requires minimum 5x10^6 pps, preferentially 5x10^8 pps

Proposals to do ^{22}Mg(α,p)^{25}Al, ^{26}Si(α,p)^{29}P, ^{30}S(α,p)^{33}Cl and ^{34}Ar(α,p)^{37}K via time-reversed approach (ISAC II)

ν-rp process

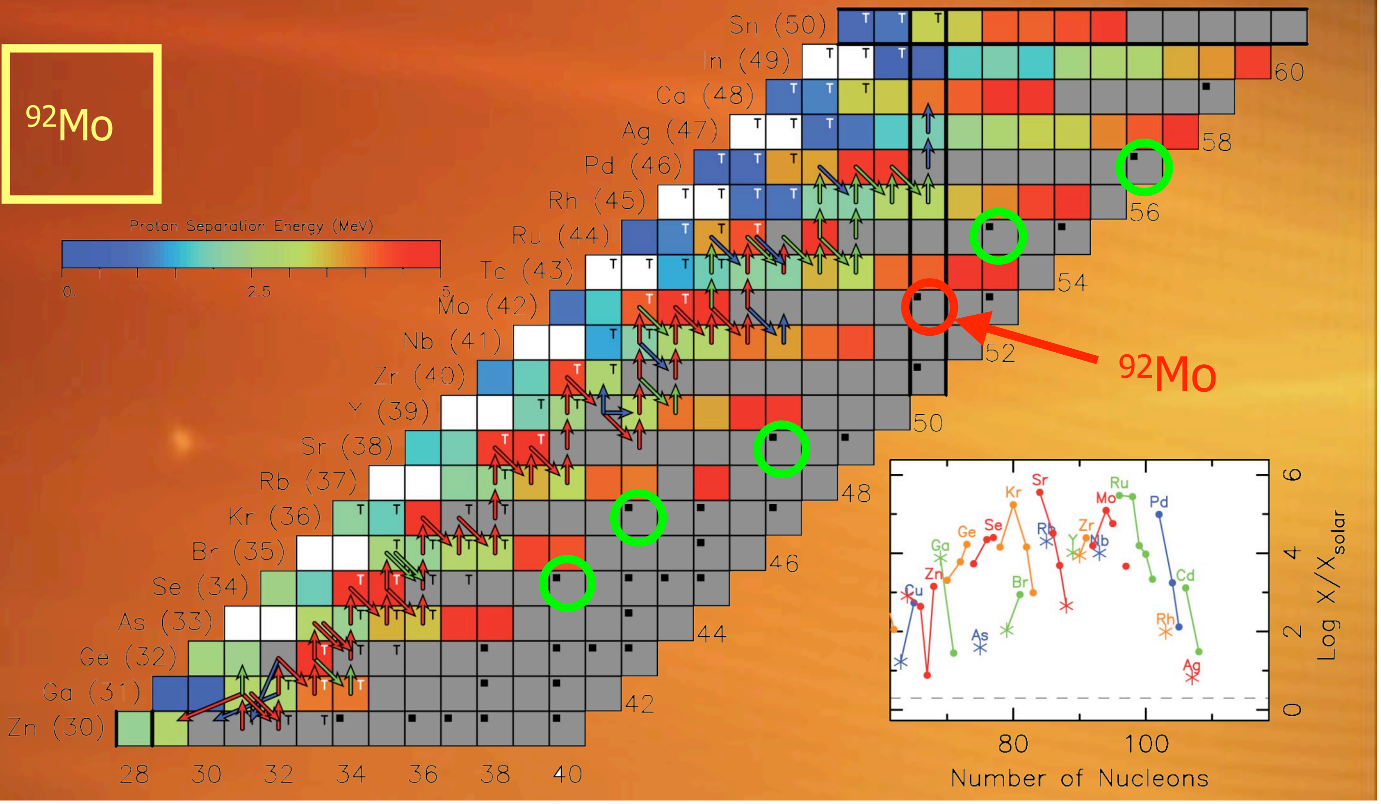
New nucleosynthesis process for p-nuclei. Problem: ^{92}Mo

- Flow diverted to N=47,48 isotones due to small $S_p(^{91}Rh)$
- ^{92}Rh,^{92}Ru progenitors
- All masses from extrapolation (AWE 2003) ΔM ~ 0.4-0.8 MeV
- Sensitivity study performed:
- $S_p(^{91}Rh)$ increased – ^{92}Mo within x 12
- $S_p(^{93}Rh)$ decreased – ^{92}Mo within x 3!, but ^{94}Mo down to x 20
- Combination of these two produced ^{92}Mo x 4 and ^{94}Mo x 7 :-)

Measure lower 6 M in this grid!!

Beams: LaC_2, Ta

High priority!



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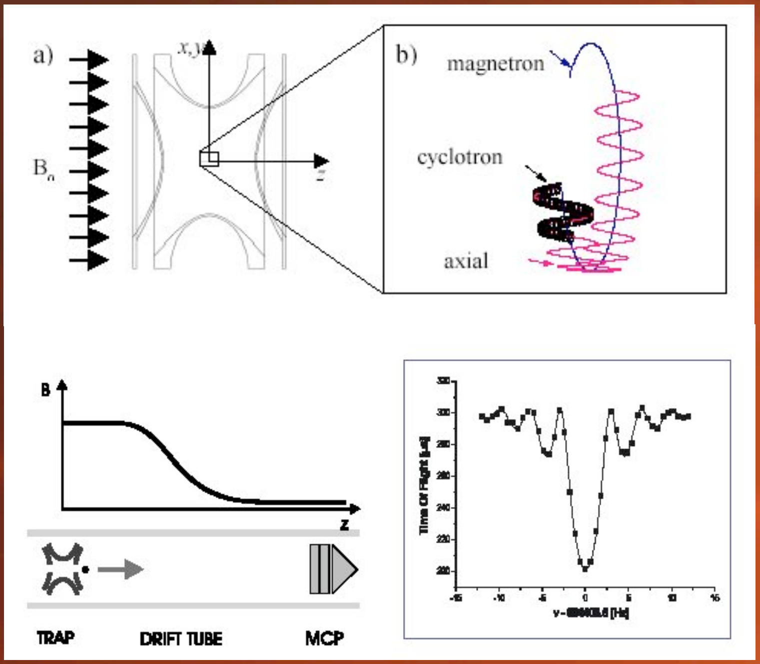
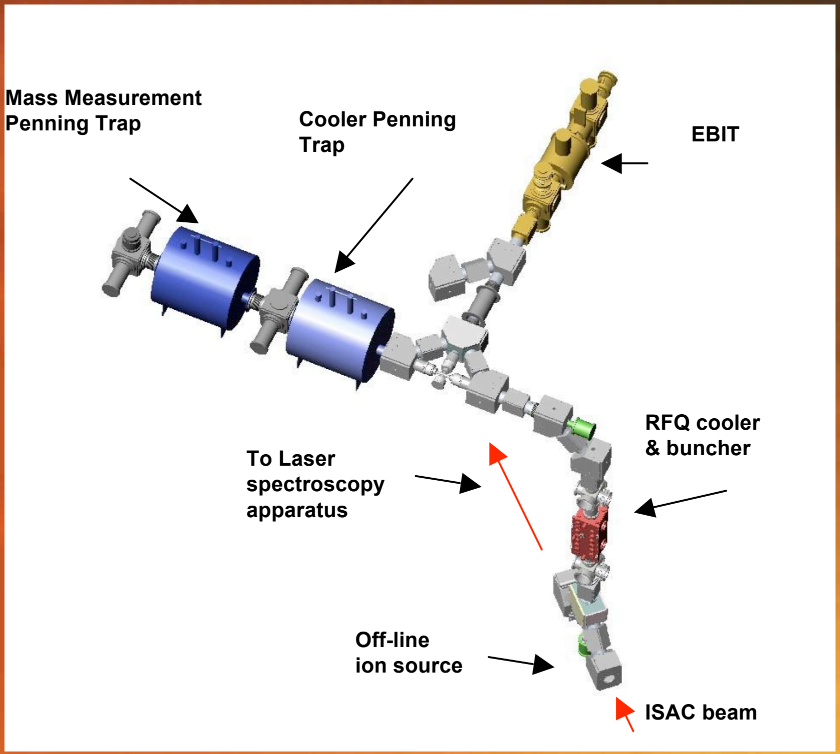
Mass Measurements: TITAN
TRIUMF Ion Trap for Atomic and Nuclear Science





30 keV beam cooled & bunched to 1-2 keV

Stored in EBIT, charge-bred (~ms)

Wien Filters - single q+, isobar selection

Injection into Trap. Excitation. Ejection.

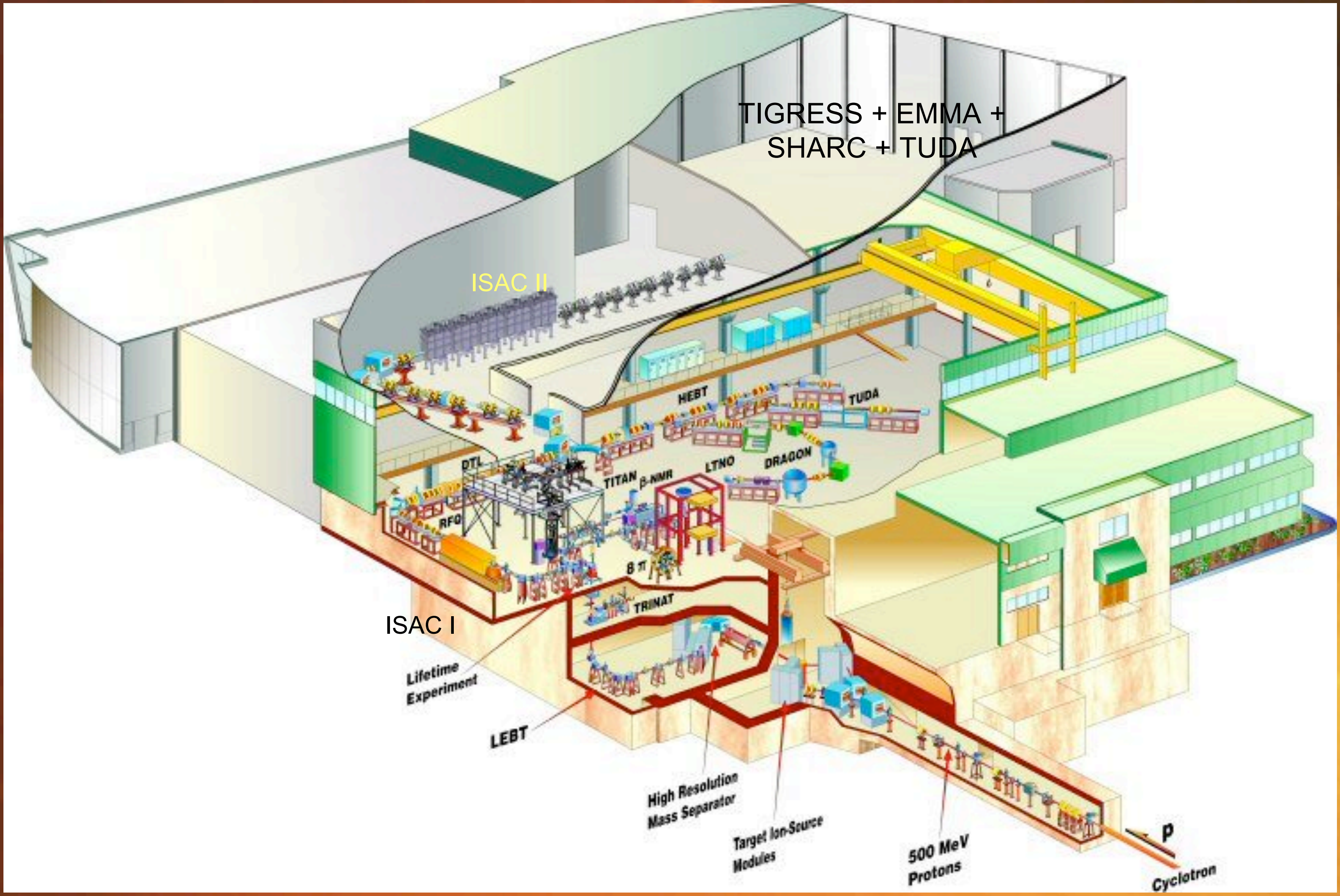
Ion accelerated ∝ magnetic moment in B field.

Time-of-flight measurement

$$\nu_c = \frac{1}{2\pi} \cdot \frac{q}{m} \cdot B \qquad \frac{\delta m}{m} \approx \frac{m}{T_{RF} \cdot q \cdot B \cdot \sqrt{N}}$$

Estimated 1-5 keV error !!

ISAC

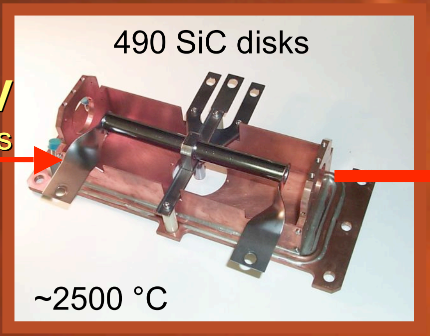

TIGRESS + EMMA + SHARC + TUDA
ISAC II
HEBT
TUDA
DTL
TITAN
β-NMR
LTNO
DRAGON
RFQ
8 π
TRINAT
ISAC I
Lifetime Experiment
LEBT
High Resolution Mass Separator
Target Ion-Source Modules
500 MeV Protons
p
Cyclotron

Beam production (example: ^{26}Al)

TRIUMF cyclotron

500 MeV protons

70 μA

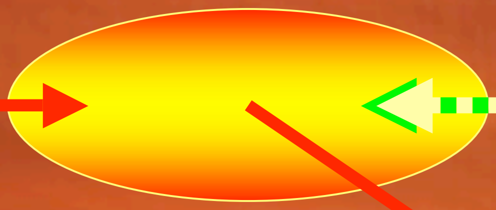


490 SiC disks

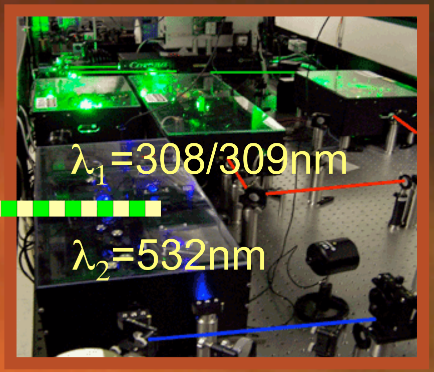
~2500 °C

ISAC high-power SiC target

rhenium surface ion source



Laser Ion Source



λ_1=308/309nm

λ_2=532nm

^{26g}Al$^+$

RFQ

0.15 MeV/u

^{26g}Al^{6+}

DTL

< 1.8 MeV/u

- ISOL Method: driver beam on production-target/ion-source, mass separation during extraction
- Target material somewhat custom isotope
- Diffusion limited
- carbides chosen for thermal properties
- oxides chosen for favorable release (e.g ^{18}Ne)
- Laser source relies on favorable ionization energy
- Other sources: ECR, FEBIAD

Beam challenges

- Most important resonances often hardest to measure
- Direct measurements require high (>10^7 pps) intensity
- ISOL method limited by chemistry and lifetimes (>500 ms)
- Need low-energy accelerator + recoil separator or scattering facility
- Contamination in ISOL beams often problem
- Solution is focused target/ion-source development
- ISAC + DRAGON/TUDA most hopeful for direct measurements