ANCs from nuclear breakup for nuclear astrophysics

Livius Trache, Texas A&M University
for the TLW collaboration
SAMURAI workshop, Wako-shi 03/10/11

Breakup of loosely bound nuclei at intermediate energies for nuclear astrophysics

… and the development of a position sensitive microstrip detector system and its readout electronics using ASICs technologies

(full title of grant by Office of Science, DOE, 2010 under:
"Research Opportunities at Rare Isotope Beam Facilities")

And proposal NP0609 RIBF13:

- Texas A&M University
- RIKEN Nishina Center, CNS Univ of Tokyo
- LPC Caen, IFIN-HH Bucharest, INFN Pisa, …

Proposal accepted at RIBF NP-PAC-05, June 2009

yesterday (Brain Roeder and Rebecca Shane)

Motivation

- Overlapping science interests with RIKEN groups, complementary methods and possibilities:
  - Nuclear astrophysics
  - indirect methods w RNBs:
    - Coulomb dissociation – RIKEN: T. Motobayashi and group: ^{8}B, ^{9}C, ^{23}Al, ^{27}P, ^{12}N, ^{13}N, ^{13}O, ^{11}Li, ^{17}B, ^{19}C, etc…
    - Nuclear dissociation – TAMU et al: ^{8}B, ^{9}C, ^{23}Al, ^{24}Si, … or transfer: ^{12}N, ^{13}O, ^{14}O, …
  - Facilities:
    - RIBF for RNBs E > 100-345A MeV vs.
    - MARS & TREX (Texas Reaccelerated EXotics) at TAMU E=10-50A MeV
  - from p-capture studies to n-capture and n-rich nuclei
  - Advanced detection systems
- Develop knowledge and tools for future use in rare isotope beam research in US and Japan
- Involve also scientists from Europe, expers and theoreticians

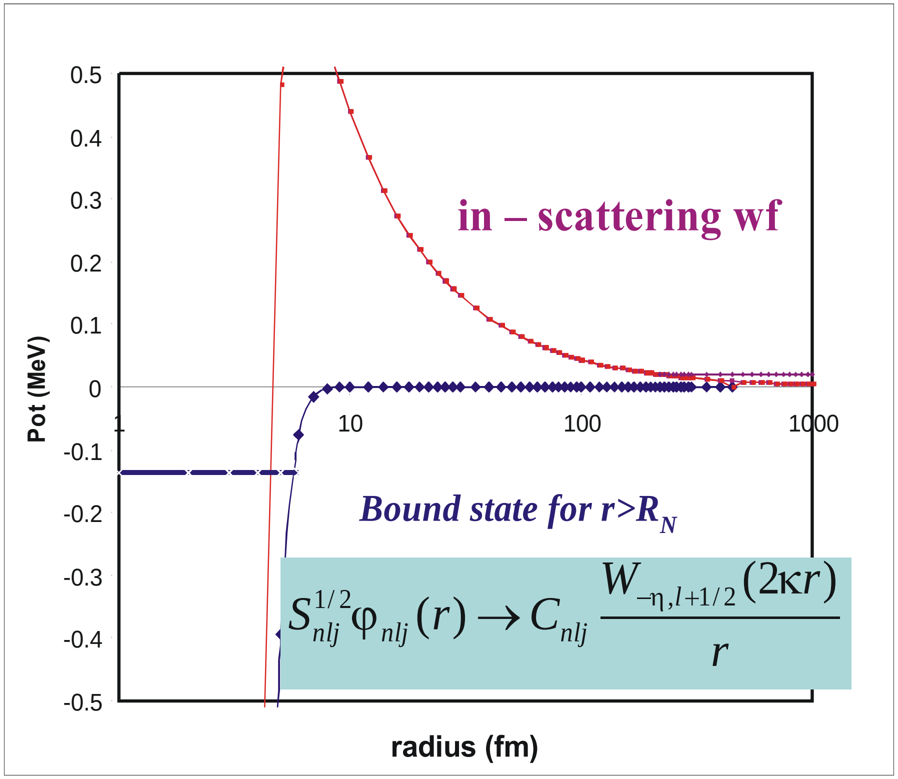
Nuclear astrophysics - indirect measurements

- One-nucleon-removal reactions – tool to study the single particle structure of unstable nuclei:
  - Use it to determine **ANC** and from there **(p,γ) rates for nuclear astrophysics**
- Obtain data to check theoretical models:
  - Momentum distributions
  - Configuration mixing
  - breakup mechanisms (stripping or dissociation)
- **Proposed nuclear breakup experiments @ 100 MeV/u (on light targets):**
  - ^{9}**C** **one**- and **two-proton** removal
    - Measure at 100 MeV/u on Be (or C) target **to obtain ANC**
    - Measure **nuclear and Coulomb dissoc at 300 MeV/u** to obtain direct and resonant S-factor (Be and Pb targets) for $^{8}B(p,\gamma)^{9}C$
    - Measure momentum distributions for one- and two-proton removal to study the reaction mechanism
  - ^{17}**F** one-proton removal
    - **To test method** by comparison with ANC extracted from transfer
    - Test method by **comparison with S-factors from existing direct measurements** $^{16}O(p,\gamma)^{17}F$
  - *^{27}**P** one-proton removal*
    - *For ANC to assess **$^{26}Si(p,\gamma)^{27}P$ reaction rate** (direct component) for explosive H-burning (p-process, XRB, …)*
    - *Determine **configuration mixing** in ^{27}P g.s.*

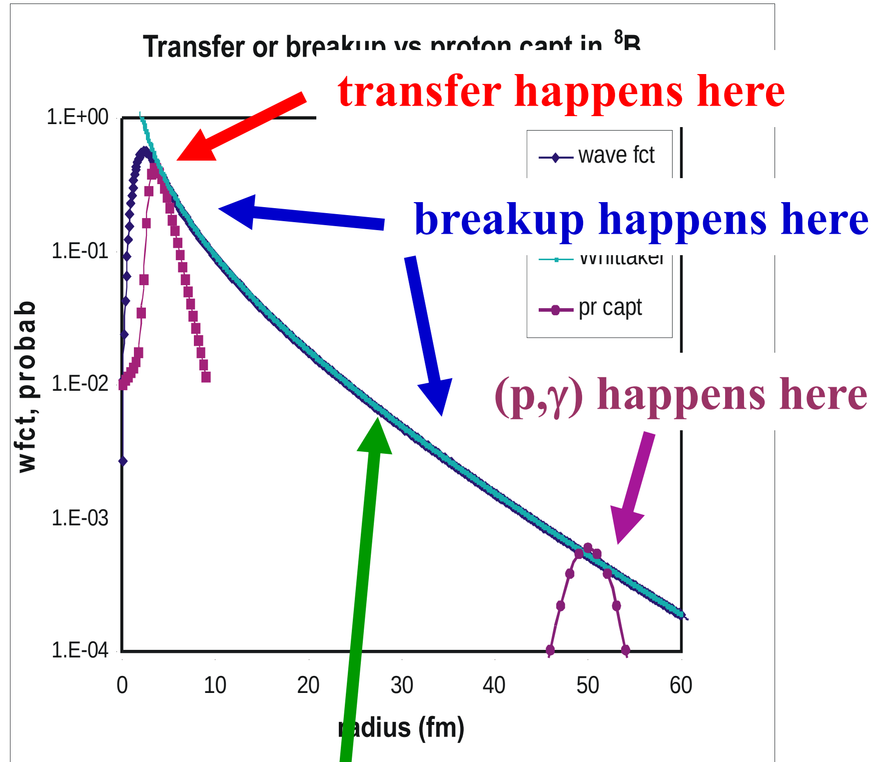
Nuclear astrophysics case

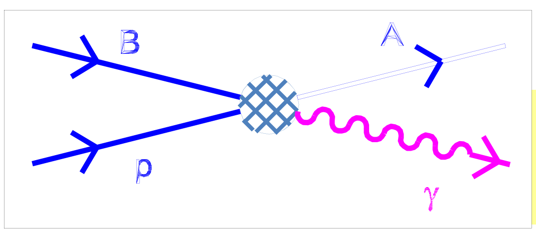
- Explosive H-burning
  - $^{8}B(p,\gamma)^{9}C$ – a possible path to hot *pp-IV* chain and rapid alpha proc *rap I* – at high temp and densities
  - $^{26}Si(p, \gamma)^{27}P$ – bottleneck in H-burning in novae.
    - Part of the effort to have ALL reaction rates from experimental data – for novae
- Use $^{9}C \rightarrow {}^{8}B+p$ and $^{27}P \rightarrow {}^{26}Si+p$ to determine the relevant structure parameters of ^{9}C, ^{27}P g.s.
- $^{17}F \rightarrow {}^{16}O+p$ - to test method (exp and calc)

ANC in peripheral reactions: radiative proton capture, transfer and breakup



$$S_{nlj}^{1/2}\varphi_{nlj}(r) \rightarrow C_{nlj}\frac{W_{-\eta,l+1/2}(2\kappa r)}{r}$$

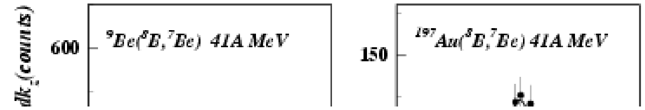


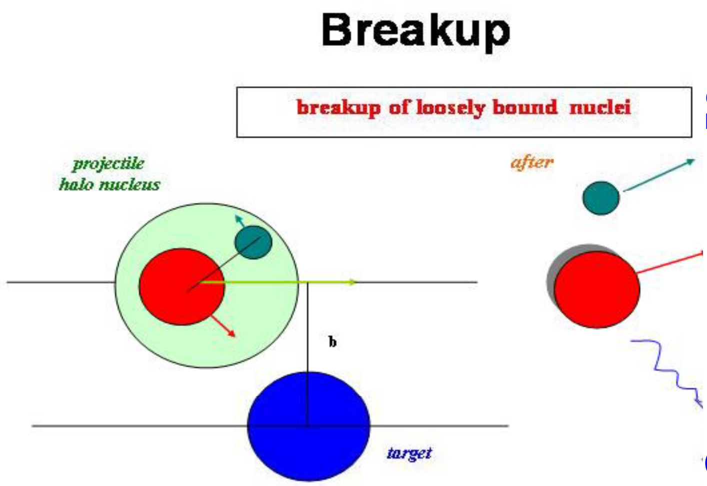


$$(T + V_{coul})Y(\hat{r})\varphi(r) = -\varepsilon Y(\hat{r})\varphi(r)$$

Shape in asymptotic region given by Whittaker fct.
Only normalization (**ANC**) unknown and needed!

Breakup reactions for nuclear astrophysics



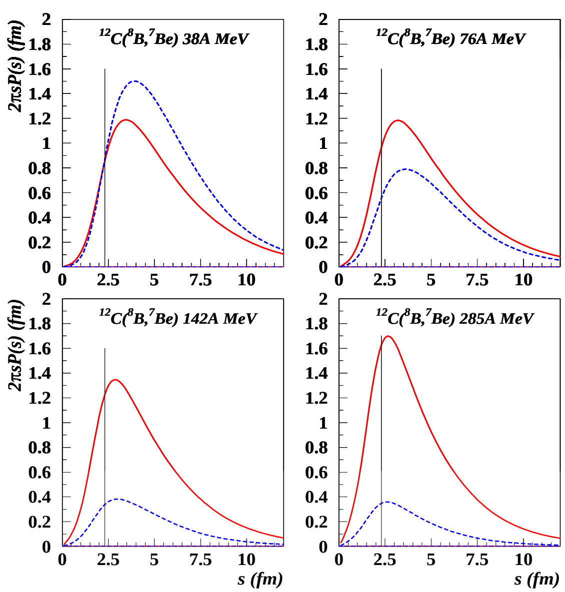


Spectroscopic factors:

$$S_{nlj} = \frac{\sigma_{\exp}}{\sigma_{calc}}$$

or ANC:

$$C_{nlj}^2 = b_{nlj}^2 \frac{\sigma_{\exp}}{\sigma_{calc}}$$



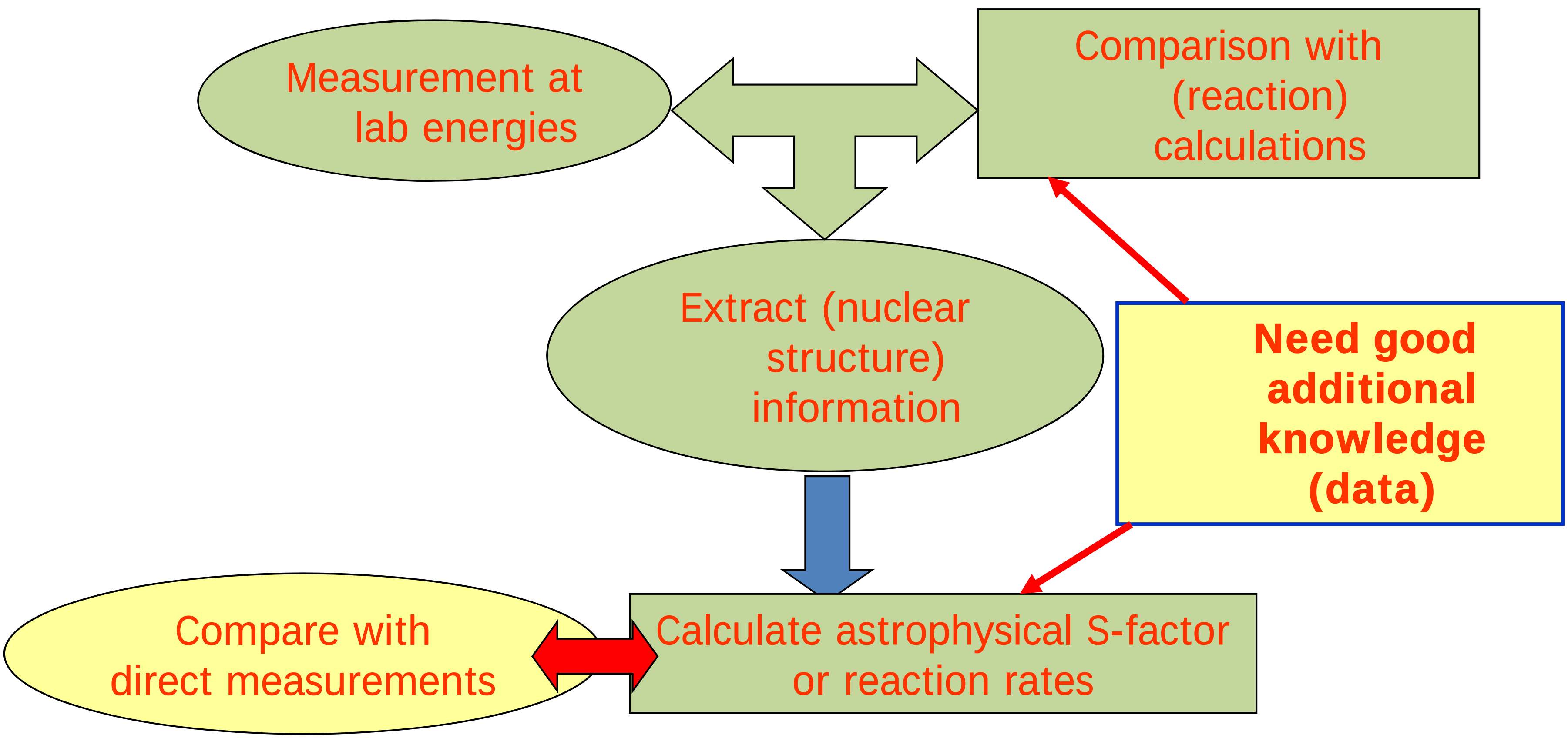
Periphe

Need good experimental data!

Need good, reliable, calculations!!!

and reaction mechanism model

Indirect methods for nuclear astrophysics



Example: Summary of the ANC extracted from ^{8}B breakup with different interactions

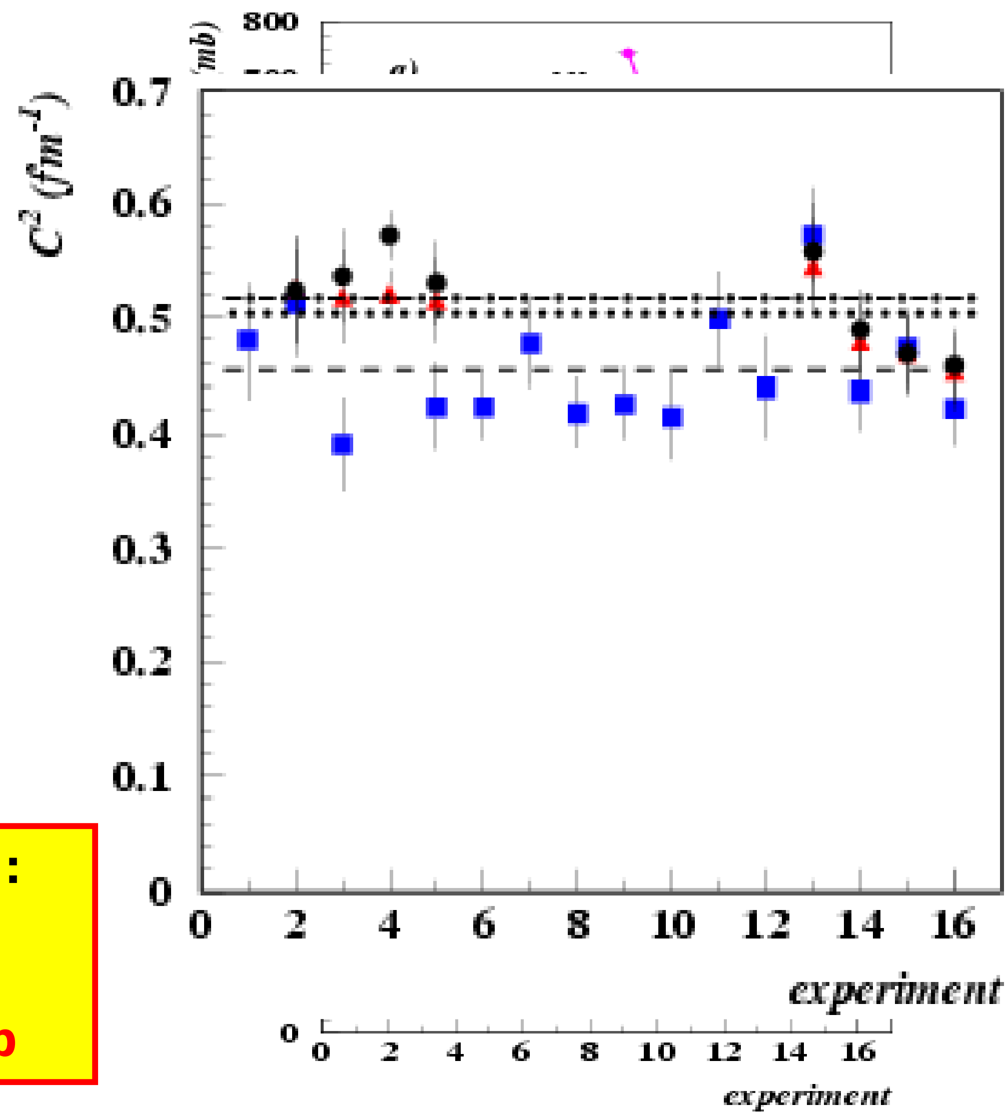
Data from:

F. Negoita et al, Phys Rev C 54, 1787 (1996)
B. Blank et al, Nucl Phys A624, 242 (1997)
D. Cortina-Gil e a, EuroPhys J. 10A, 49 **(**2001).
R. E. Warner et al. – BAPS 47, 59 (2002).
J. Enders e.a., Phys Rev C 67, 064302 (2003)

All available breakup cross sections on targets from C to Pb and energies 27-1000 MeV/u give consistent ANC values!

Summary of results:

The calculations with 3 different effective nucleon-nucleon interactions



^{7}Be(p,γ)^{8}B (solar neutrinos probl.):
p-transfer: $S_{17}(0)$=18.2±1.7 eVb
Breakup: $S_{17}(0)$=18.7±1.9 eVb
Direct meas: $S_{17}(0)$=20.8±1.4 eVb

Coulomb Dissociation vs direct

- pioneering ^{6}Li->α+d, ^{7}Li->α+t …
- CD of ^{8}B $\rightarrow$ ^{7}Be+p at GSI, GANIL, MSU, RIKEN, …
- CD gives results comparable with direct capture ^{7}Be(p,γ)^{8}B measurements
- Important: uncertainties are totally different => reliable data for input in solar model
- More CD: w. other nuclei – determine the energy dependence of S(E), including resonances and their location and strength

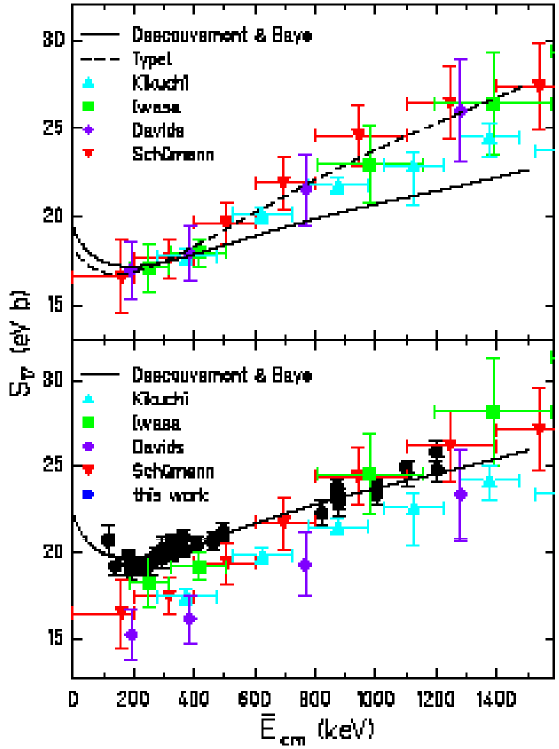
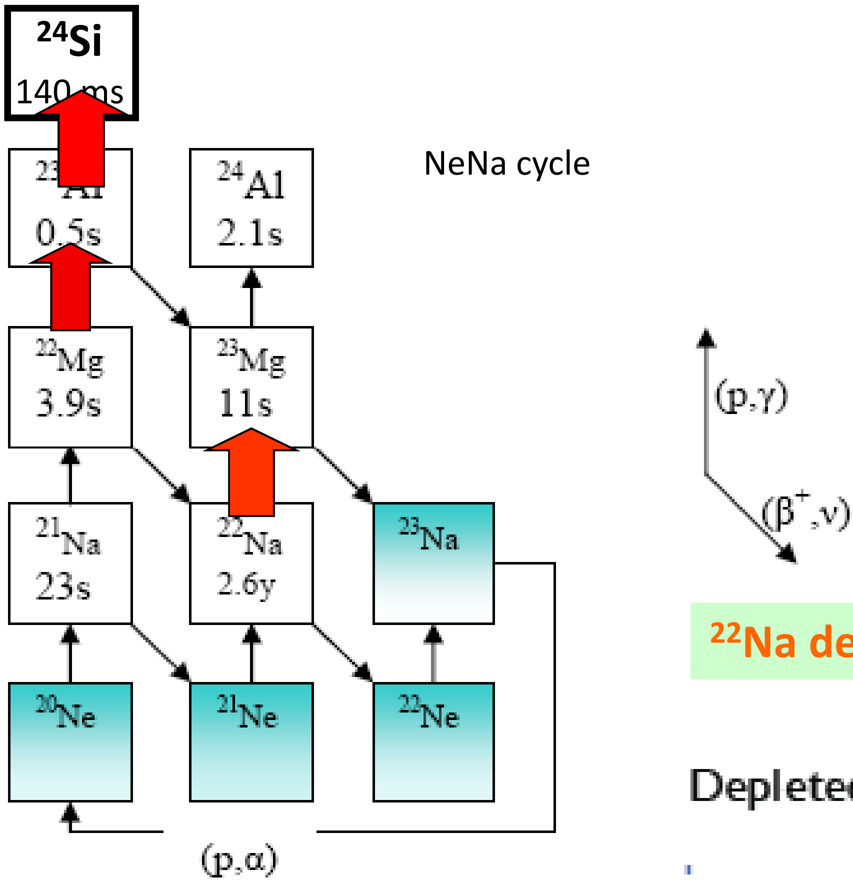
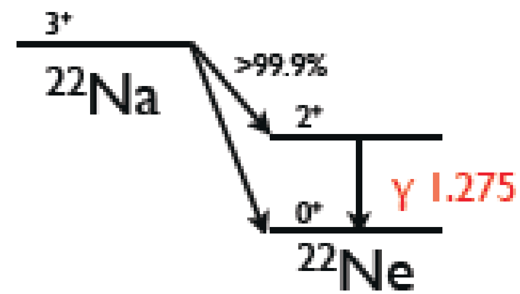


FIG. 19: E1 ^{7}Be(p,γ)^{8}B S-factors inferred from Coulomb dissociation (CD) experiments. Bottom panel: absolute CD S-factors, together with our direct results (with the 1^{+} resonance subtracted) and the best-fit DB curve to our direct low-energy data. Top panel: CD data plotted with a common normalization based on the mean value of 19.3 eV b for $S_{17}(0)$ determined by fitting each data set to the DB theory below 400 keV. Solid curve: DB calculation; dashed curve: Typel calculation. The experimental error bars shown in all cases are relative, and do not include scale-factor uncertainties.

Explosive H-burning in novae: "^{22}Na puzzle"

- novae: explosive H-burning of accreting material in binaries star-WD. ~ 30/yr.
- E=1.275 MeV γ ray following the decay of ^{22}Na predicted, but not observed by space gamma-ray telescopes





^{22}Na depletion in novae: how does it happen?

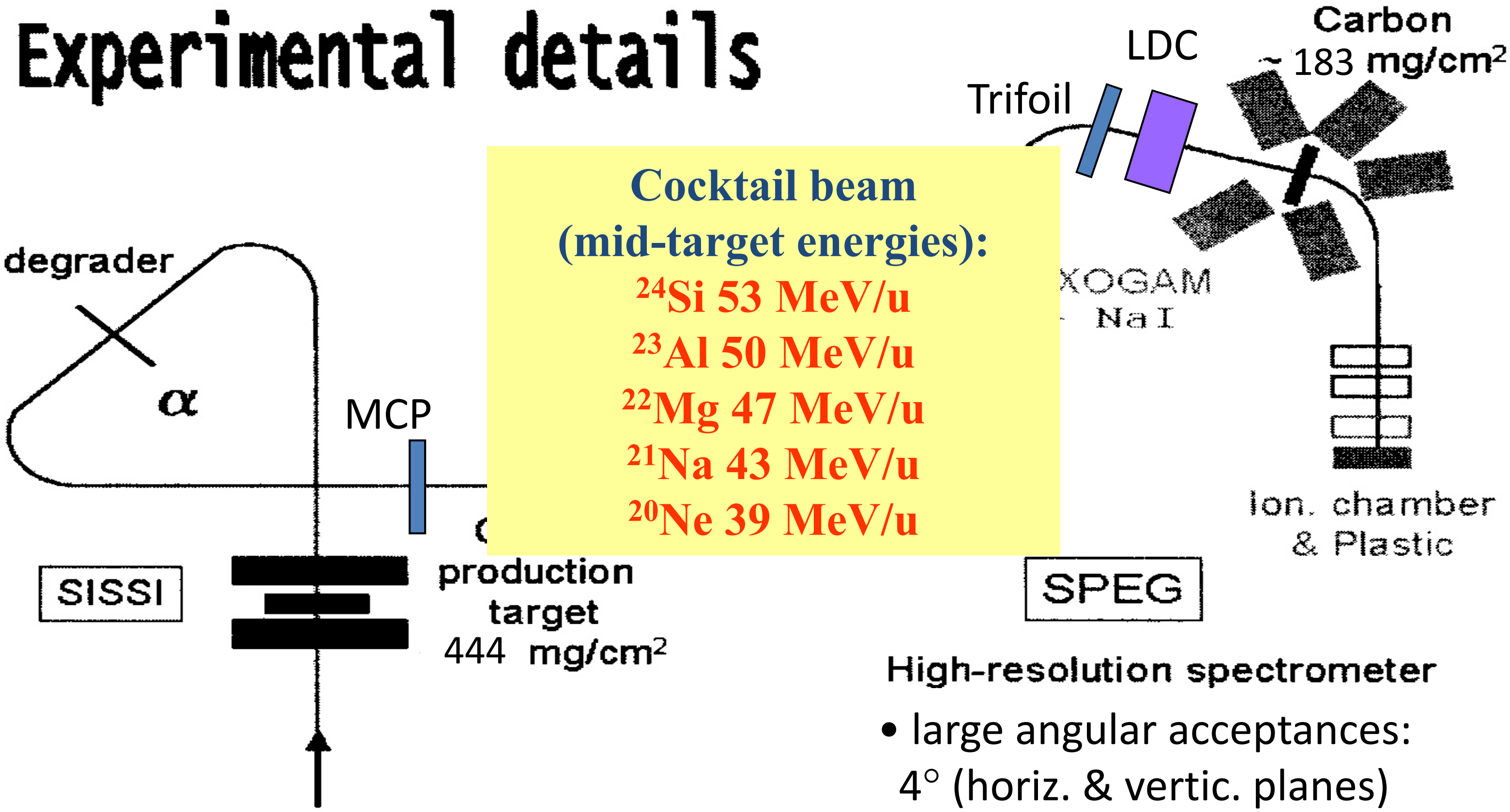
Depleted via? {
^{22}Mg(p,γ)^{23}Al ↔ direct & res. capture
^{22}Na(p,γ)^{23}Mg ↔ resonant capture

- what are the stellar reaction rates for the **^{22}Mg(p,γ)^{23}Al** and **^{22}Na(p,γ)^{23}Mg**?

- what about ^{23}Al(p,γ)^{24}Si?

E491 exp. @ GANIL

Gamma-ray detectors:
8 EXOGAM clovers 4% effic.
12 NaI crystals 6% effic.



Cocktail beam (mid-target energies):
^{24}Si 53 MeV/u
^{23}Al 50 MeV/u
^{22}Mg 47 MeV/u
^{21}Na 43 MeV/u
^{20}Ne 39 MeV/u

High-resolution spectrometer

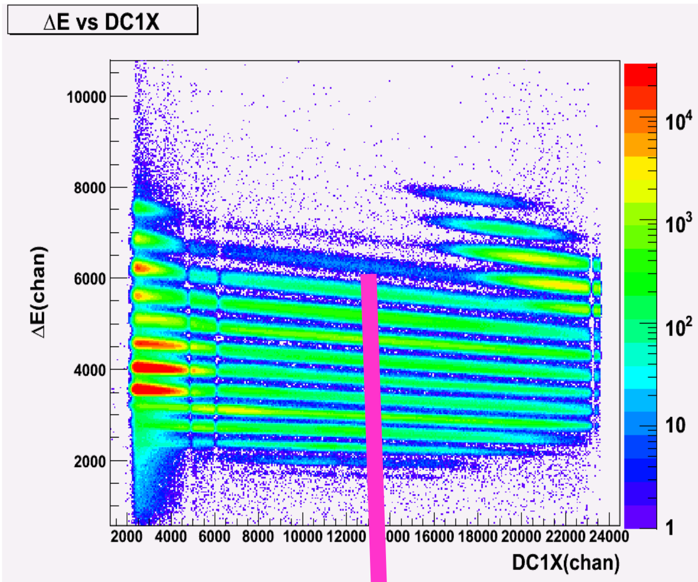
- large angular acceptances: 4° (horiz. & vertic. planes)
- broad momentum acceptance: $\Delta p/p = 7\%$

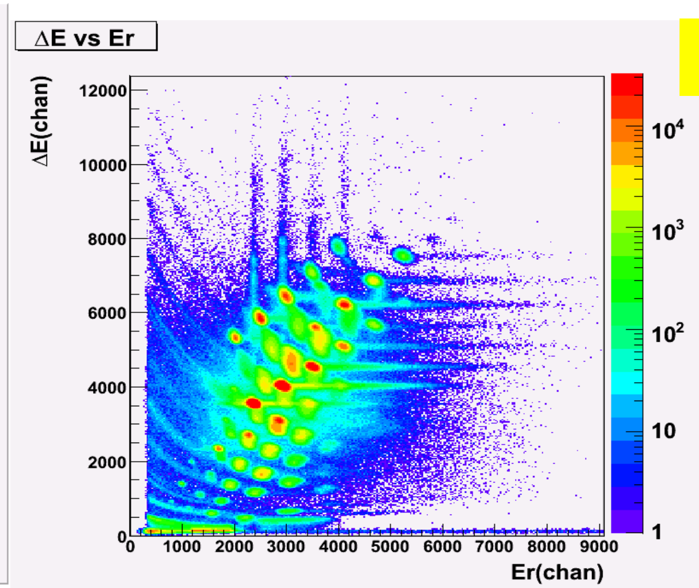
^{32}S primary beam
95 MeV/u, ~ 400 W

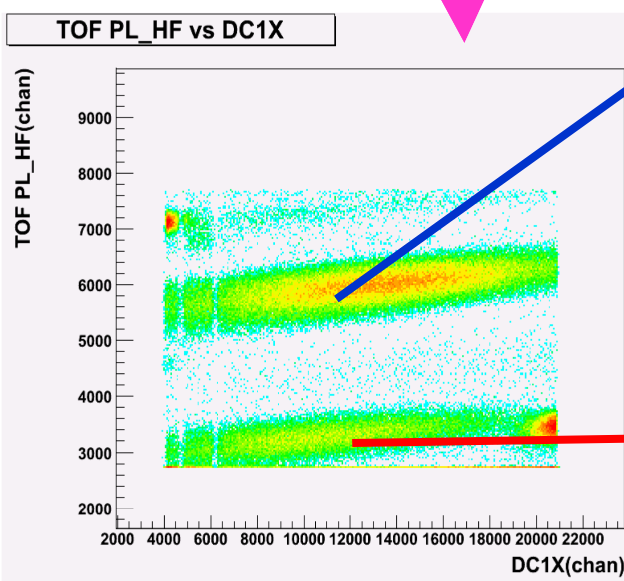
With Nigel Orr et al.

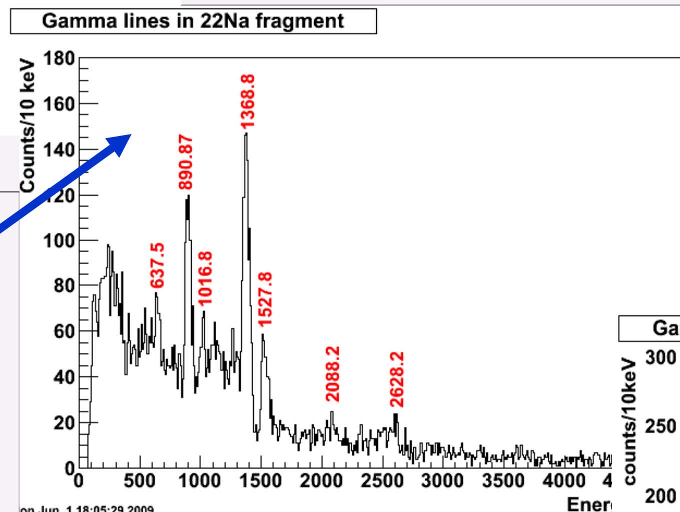
A. Banu et al., NIC10 Symposium 2008 & to be published

GANIL E491 exp







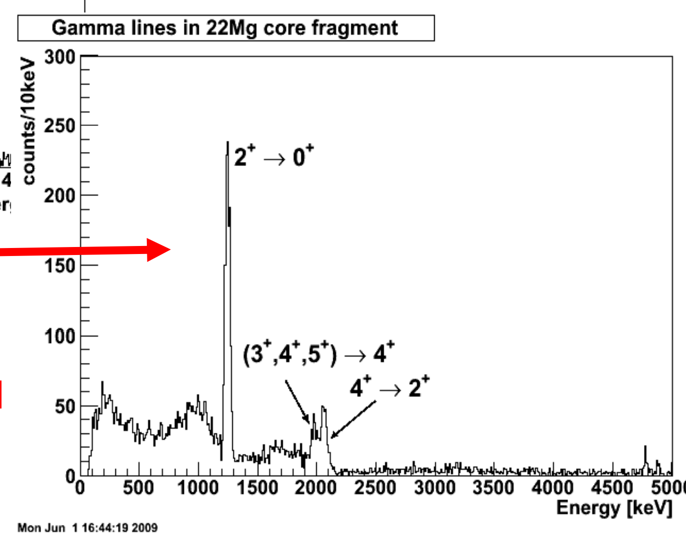


$^{12}C(^{22}Mg,^{22}Na)^{12}N$

Charge exchange (new & unexpected)

$^{23}Al \rightarrow ^{22}Mg+p$

Proton removal (sought)



Results from ^{23}Al breakup

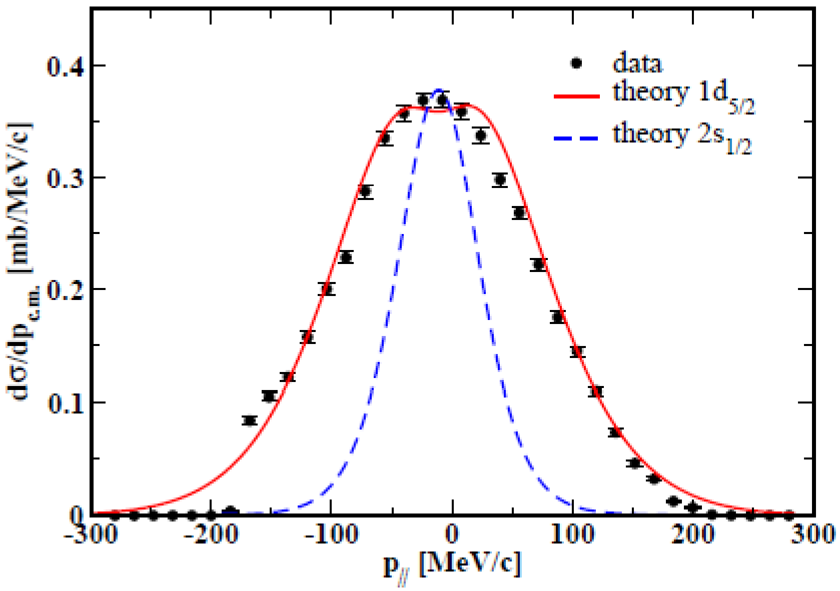
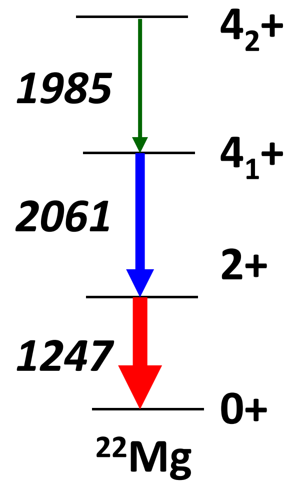
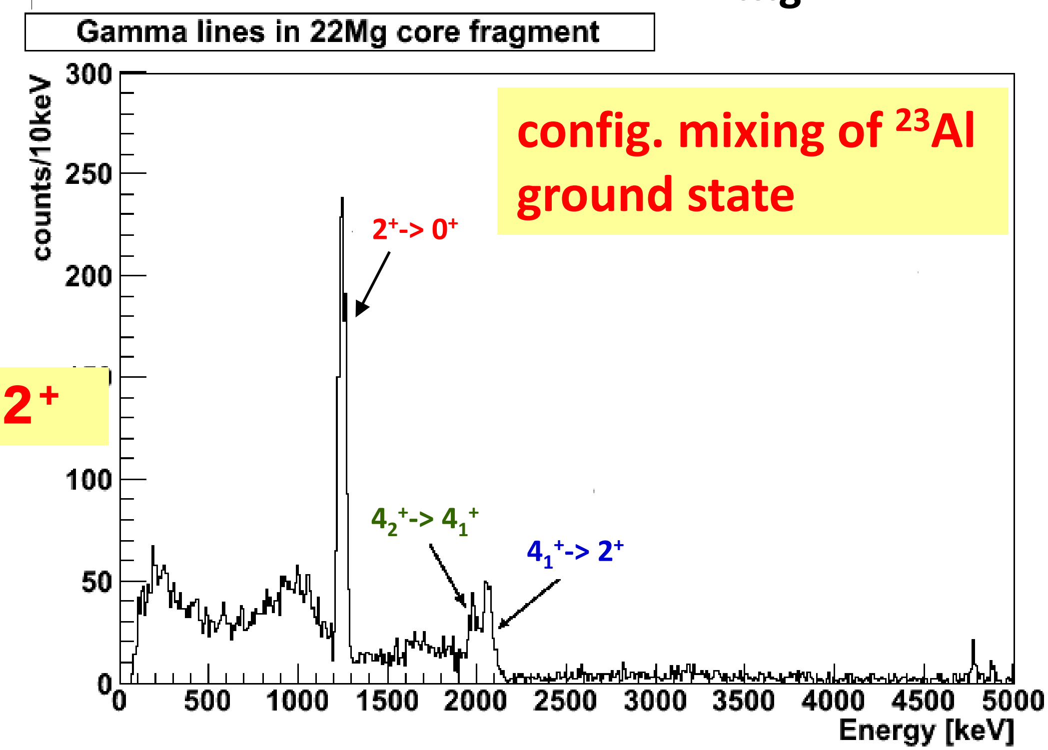


FIG. 1. (Color online) Experimental inclusive momentum distribution of ^{22}Mg cores (points), in the center-of-mass





$\Gamma(^{23}\mathrm{Al}) \sim 200$ MeV/c and $J^{\pi} = 5/2^{+}$

A. Banu et al, PRC, submitted

Complementarities: Coulomb and nuclear dissociation

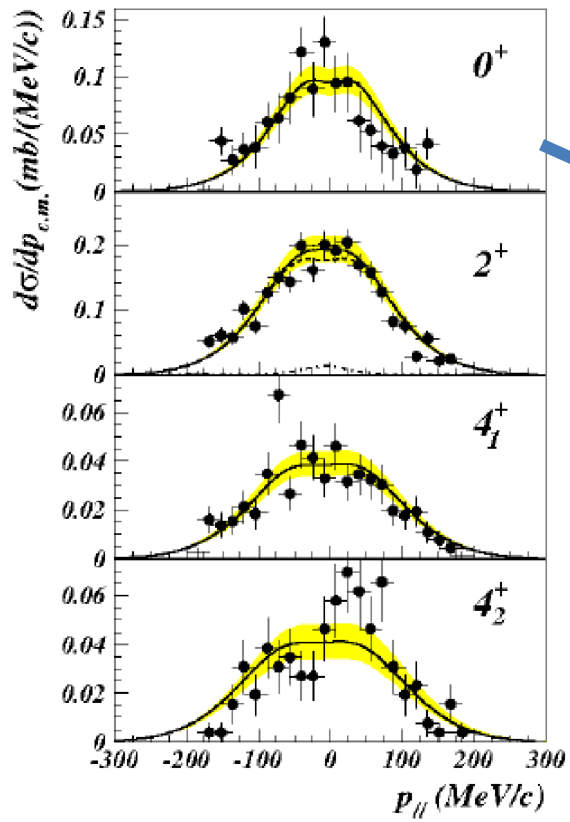
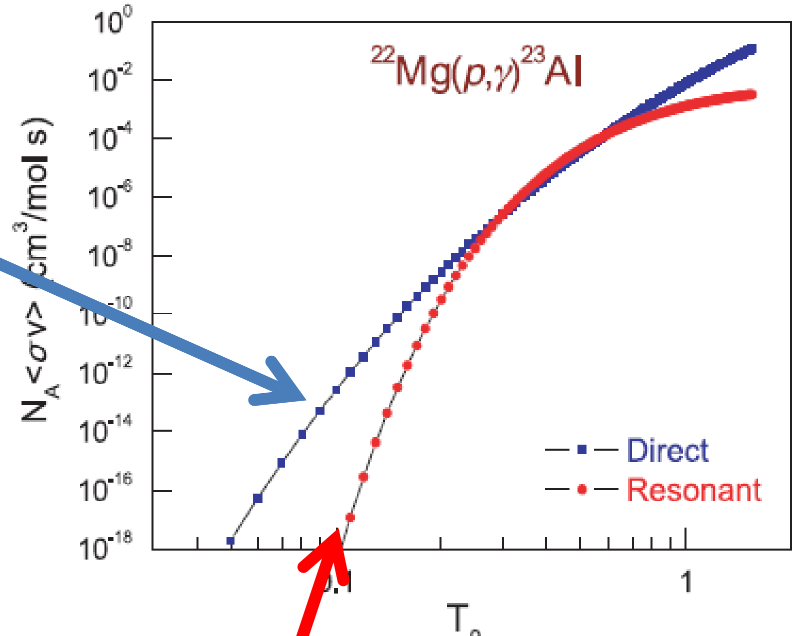


FIG. 3. (Color online) Experimental exclusive momentum distributions determined in the center-of-mass frame for ^{22}Mg



$\Gamma_\gamma = 7.2 \pm 1.4 \times 10^{-7}$ eV, which was obtained from the Coulomb dissociation of ^{23}Al at 50 MeV/u [46], is adopted here to evaluate the resonant reaction rate, which is given by

$$N_A\langle\sigma\upsilon\rangle = 0.12 T_9^{-3/2} \exp\left(-\frac{4.47}{T_9}\right). \qquad (9)$$

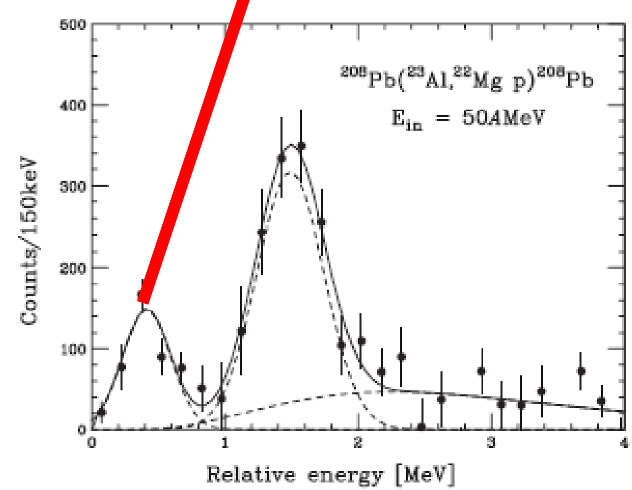
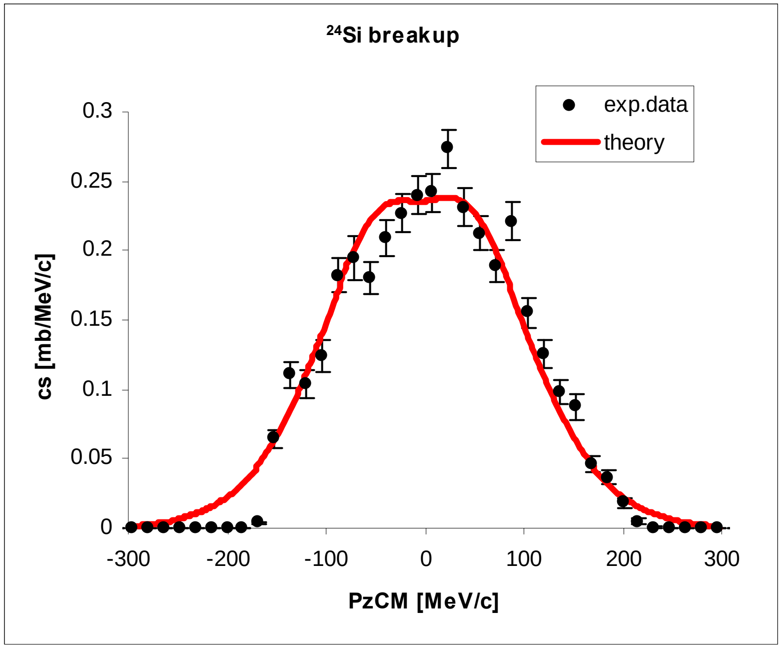


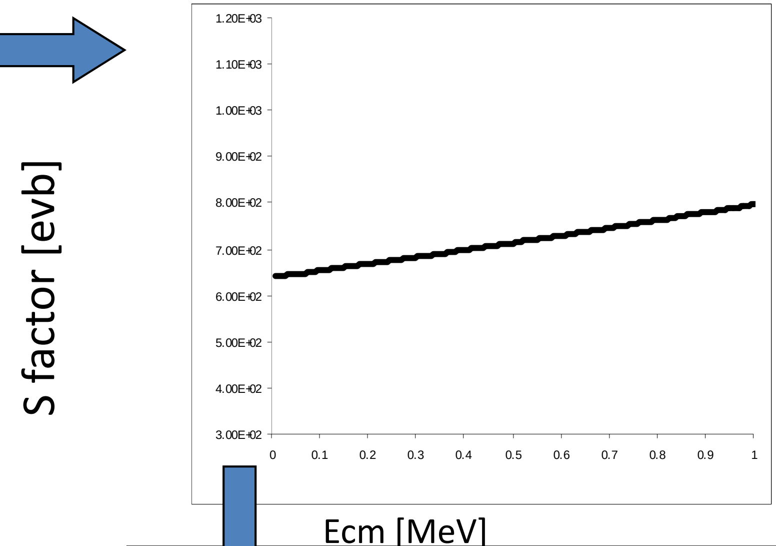
Figure 2. Relative energy spectrum between ^{22}Mg and proton obtained for the ^{23}Al + ^{208}Pb reaction. The solid curve represents the result of a fit with two Gaussian functions and a distribution assuming a non-resonant component. The dashed curves show each component.

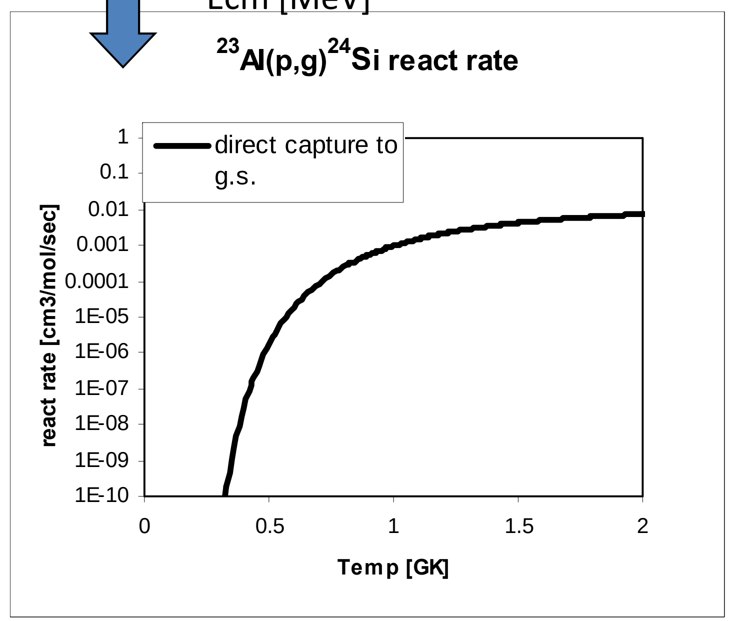
[46] T. Gomi, T. Motobayashi et al, JPG 31 (2005)

Results for ^{24}Si breakup



Astroph S-factor for ^{23}Al(p,γ)^{24}Si





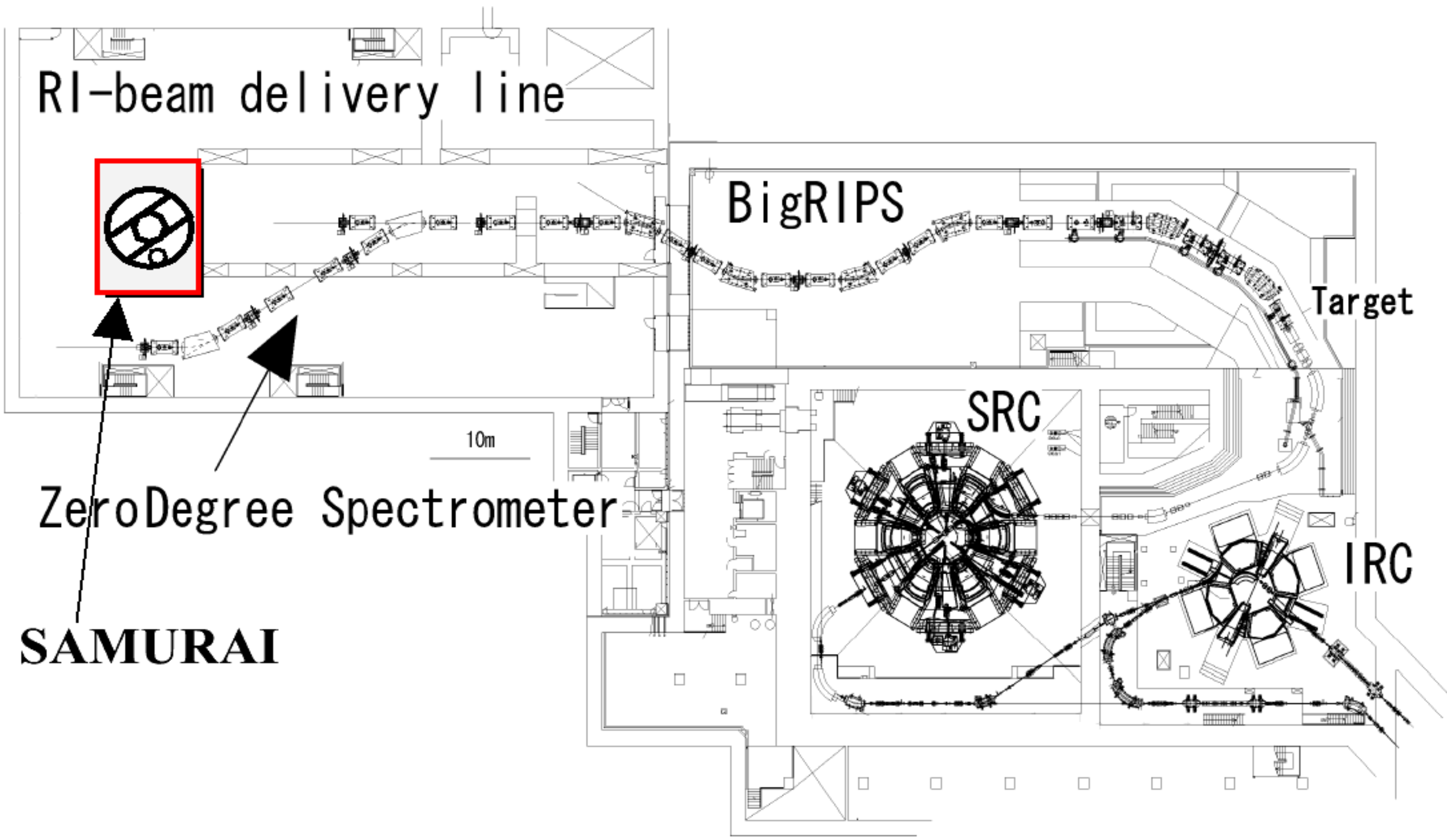
$$SF = \frac{\sigma_{exp}}{\sigma_{th}}$$

SF = 2.5-2.9 (spect. factor)

$C^2(^{24}Si_{gs}) = 62.4 \pm 7.1$ fm^{-1}

=> first exp det of direct comp of ^{23}Al(p,γ)^{24}Si

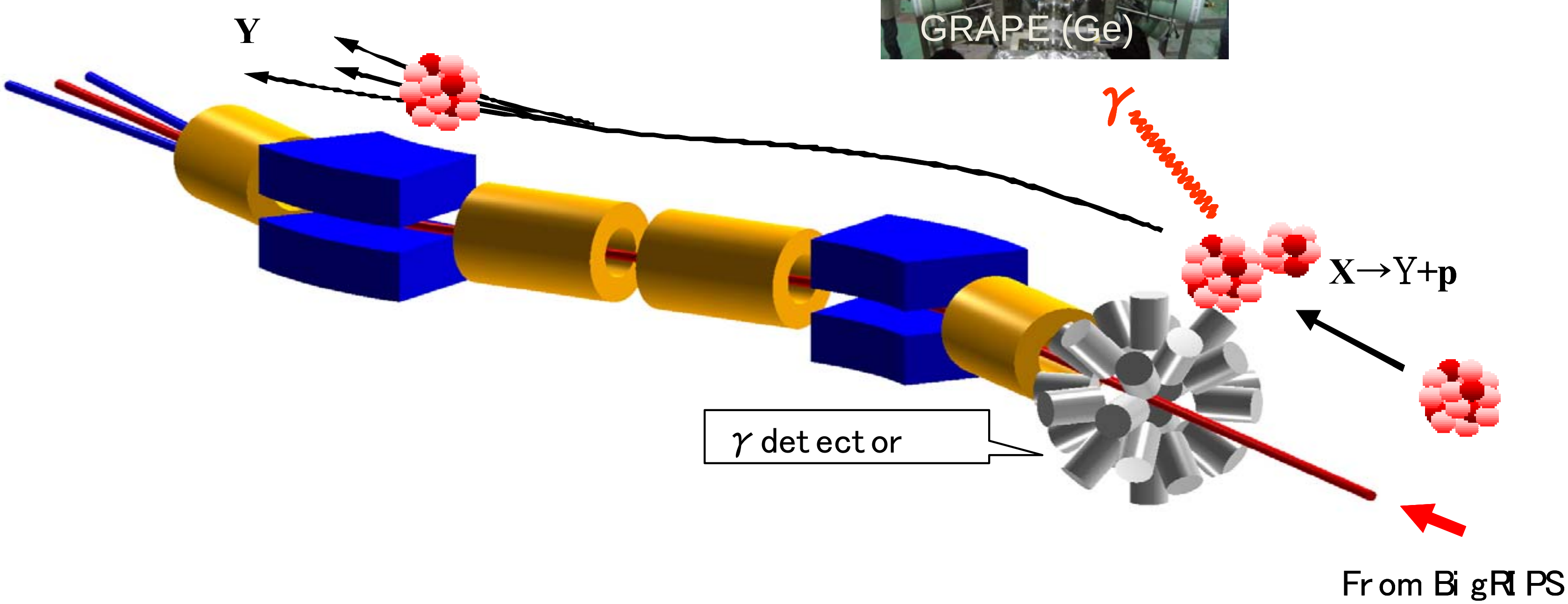
Measurements at BigRIPS-ZD and SAMURAI



SAMURAI – allows separation of stripping and dissociation mech.

Zero Degree Spectrometer

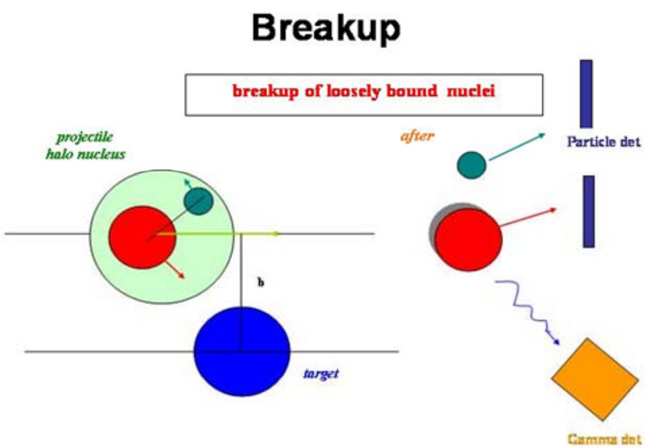
particle ID / momentum analysis
Core-gamma ray coincidences



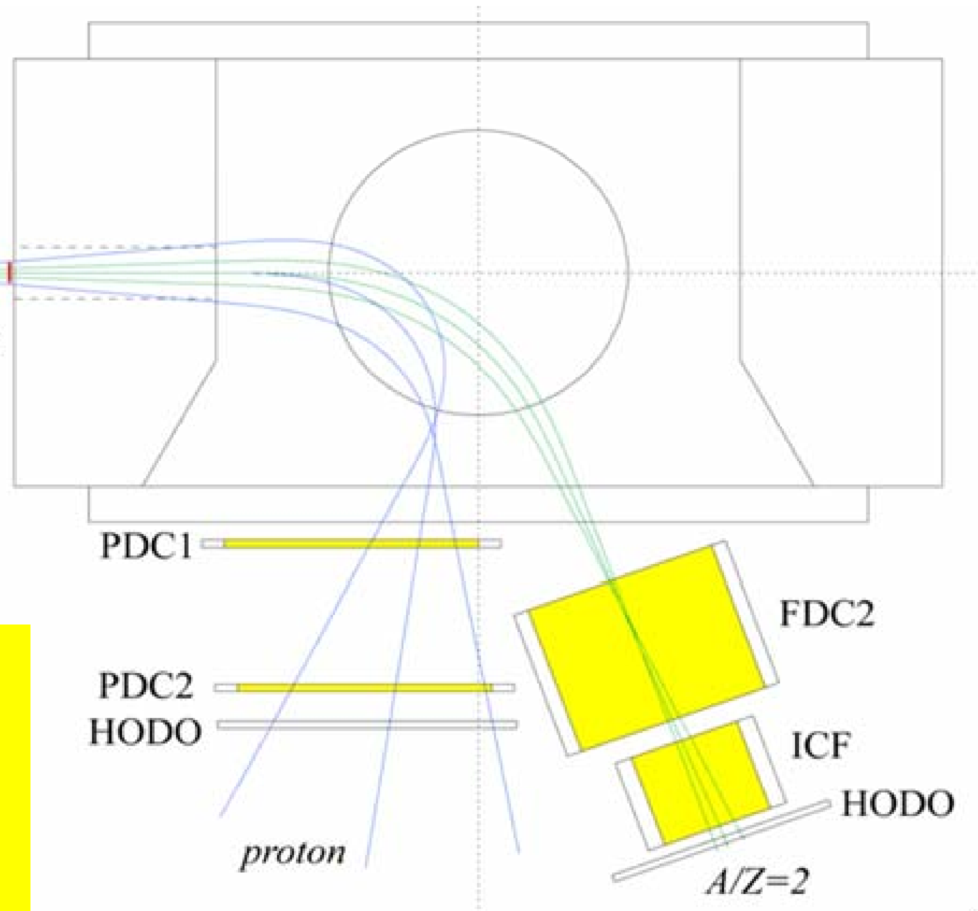
(from T. Motobayashi, OMEG07)

AT RIKEN

Secondary beam ➔ target ➔ LI +HI tracking ➔ SAMURAI ➔ proton and HI hodoscopes



DSSSD x 2



XY – (W?) - UV Si planes

Either

a) SSD-SSD ---SSD --- SSD-SSD

b) DSSD ---- SSD ---- DSSD

b) Preferred due to:

i) Delta e- problem & ii) p threshold issue

Test rigs at WU and TAMU with existing PCB mounting

We have started to test with the 2D TTT (300 um)

AREA → 97.3 x 97.3 mm

strips → 128 x 128 → 256 per Si, 512 per pair

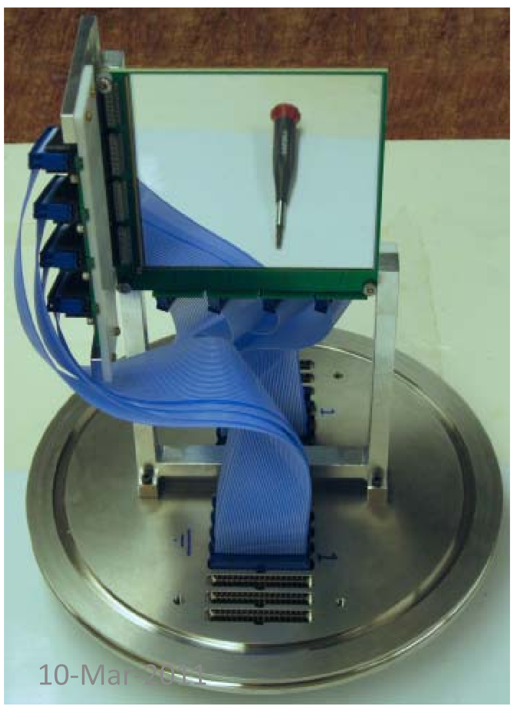
Pitch → 756 um

Si type → available in both n and p (intrinsic). We have one of each

Thickness → available in both 300 and 500 μm, we have 300 μm.

pf → 300 μm: 0.35 pf/mm^2 = 26 pf/st; 500 μm: 0.21 pf/mm^2 = 15.4 pf/st

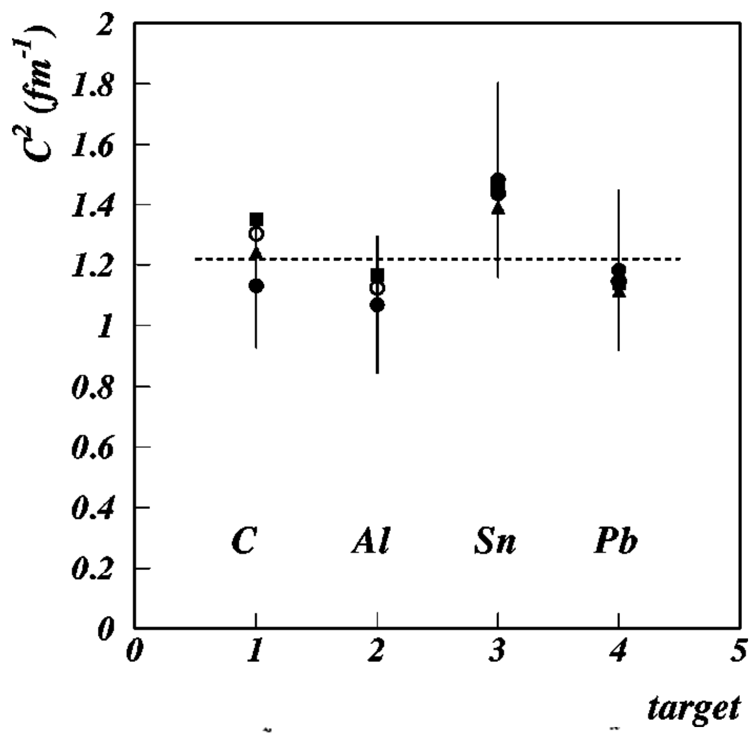
Si –TTT (WU)

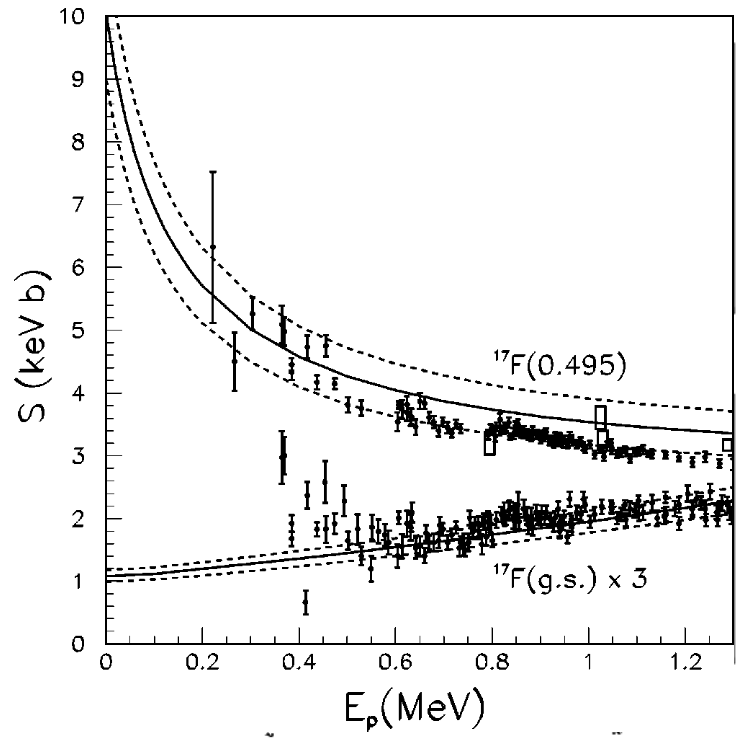


Si in chamber (TAMU)

External view (WU)

^9C, ^{17}F breakup @ 100MeV/u. Theor estimates by F. Carstoiu





Note: ^9C ->^7Be+2p large cs

Calculations with two different geometries of the binding potential for the last proton are shown (see text for details).

Calculated momentum distributions from 1p-breakup of ^{17}F at 100 MeV/u on a ^{12}C target. Calculations with two different geometries of the binding potential for the last proton are shown (see text for details).

Interested in the accuracy of absolute values of cross sections.
What different models, parameters , codes (and theoreticians) give?!

$^{9}C \rightarrow$ ^{8}B+p breakup for $^{8}B(p,\gamma)^{9}C$

The reaction is important in the hot pp chains, in explosive H burning, at large temperatures, for creating alternative paths across the A=8 mass gap
(see e.g. M. Wiescher et al., Ap. J. 343 (1989)352.)

pp IV $^{8}B(p,\gamma)^{9}C(\beta^{+}\nu)^{9}B(p)^{8}Be(\alpha)^{4}He$ and
rap I $^{8}B(p,\gamma)^{9}C(\alpha,p)^{12}N(p,\gamma)^{13}O(\beta^{+}\nu)^{13}N(p,\gamma)^{14}O$.

Use breakup of $^{9}C \to {}^{8}B+p$ at intermediate energies to obtain $^{8}B(p,\gamma)^{9}C$ at astrophysical energies.

Analyze existing data from

B. Blank et al., Nucl Phys A624 (1997) 242

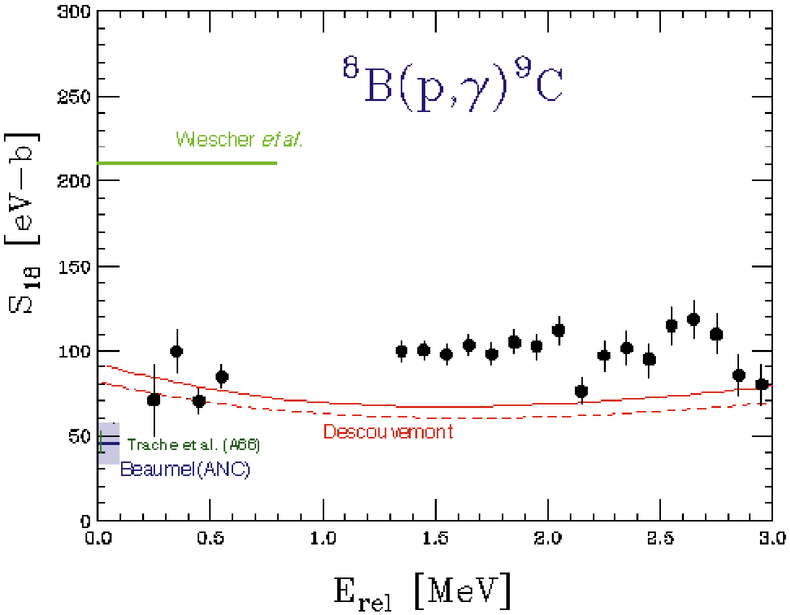
^{9}C @285 MeV/u on C, Al, Sn and Pb targets

Find new reaction rate:

$$R = N_A <\sigma v> = T_9^{-2/3} \exp\left(-\frac{B}{T_9^{1/3}}\right)(A_0 + A_1 T_9^{1/3} + A_2 T_9^{2/3}) \quad \text{cm}^3\text{/s/mol}$$

with B=11.94, A_0=6.64e5, A_1=8.50e4, A_2=-2.41e5.

Astrophysical S-factor



T Motobayashi

July 2002 NIC-7

More complementarities:

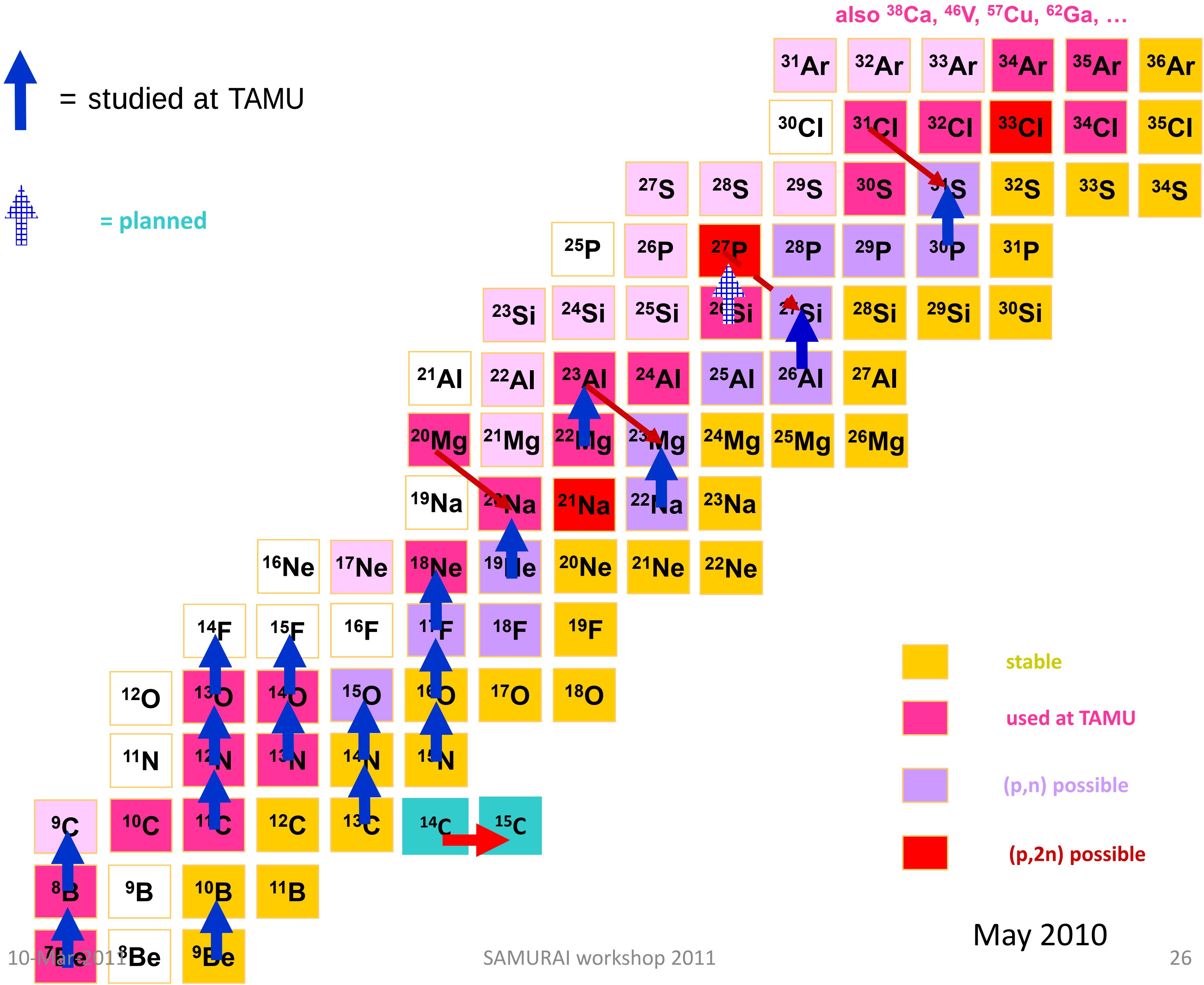
- $^{9}C \rightarrow {}^{7}Be + p + p$ at TAMU? E~ 25A MeV
- $^{13}C(^{26}Mg,^{27}Mg)$ n−transfer at 10A MeV & mirror symmetry for $^{26}Si(p,\gamma)^{27}P$
- Combine nuclear and Coulomb breakup to get S(0) and resonance widths Γ_{γ}
- Reaction theory developments
  - C. Bertulani, K. Ogata (Kyushu Univ), F Carstoiu, A Bonaccorso, D. Brink

Reaction theory advances (promised, some done already)

- Reaction theories and codes need improvements to treat r. with marginally stable and short-lived nuclear systems
- Better connection structure-reactions
- Study of approximations and effective interactions used; effect of truncations in Hilbert space and of antisymmetrization; coupling to continuum
- Relativistic corrections, kinematic and dynamical

Team

- L. Trache, R.E. Tribble, A. Banu, B. Roeder + 3 students - *Texas A&M University*
- T. Motobayshi, K. Yoneda, N. Togano, N. Aoi, S. Takeuchi – *RIKEN Nishina Center*
- S. Shimoura, E. Ideguchi, S. Go – *CNS, Univ Tokyo*
- C. Bertulani – *Texas A&M Univ Commerce (JUSTIPEN participant)*
- N. Orr, J. Gibelin, L. Achouri - *LPC Caen*
- F. Carstoiu – *IFIN Bucharest*
- A. Bonaccorso *– INFN Pisa*



also 38Ca, 46V, 57Cu, 62Ga, …
= studied at TAMU
= planned
31Ar 32Ar 33Ar 34Ar 35Ar 36Ar
30Cl 32Cl 33Cl 34Cl 35Cl
27S 28S 29S 30S 32S 33S 34S
25P 26P 28P 29P 31P
23Si 24Si 25Si 28Si 29Si 30Si
21Al 22Al 24Al 25Al 26Al 27Al
20Mg 21Mg 24Mg 25Mg 26Mg
19Na 21Na 23Na
16Ne 17Ne 20Ne 21Ne 22Ne
14F 16F 18F 19F
12O 15O 17O 18O
11N
9C 10C 12C 15C
9B 11B
8Be
stable
used at TAMU
(p,n) possible
(p,2n) possible
May 2010