ANCs for nuclear astrophysics

Livius Trache, Texas A&M University
for the RIBF13 collaboration
JUSEIPEN workshop, Berkeley
09/09/09

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 proposal responding
Funding opportunity announcement by Office of Science, DOE, 2008:
"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 Bucharest, INFN Pisa, …

Letter of intent – Jan 2008
Proposal accepted at RIBF NP-PAC-05, June 2009
tomorrow

Motivation

- Overlapping science interests, complementary methods and possibilities:
  - Nuclear astrophysics – to understand stellar nucleosynthesis
  - 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.
    - 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, experimentalists and theoreticians

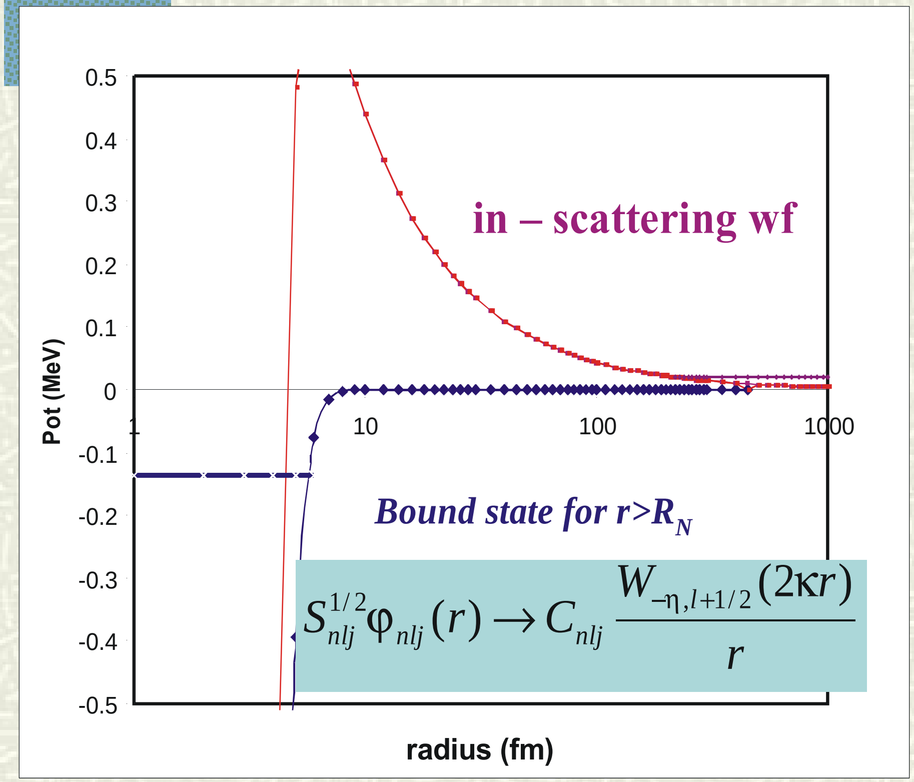
Nuclear astrophysics - indirect measurements

- One-proton-removal reactions at intermediate energies – the 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
- **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,γ)^{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,γ)^{17}F**
  - ***^{27}P*** *one-proton removal*
    - *For ANC to assess **^{26}Si(p,γ)^{27}P reaction rate** (direct component) for explosive H-burning (p-process, XRB, …)*
    - *Determine **configuration mixing** in ^{27}P g.s.*

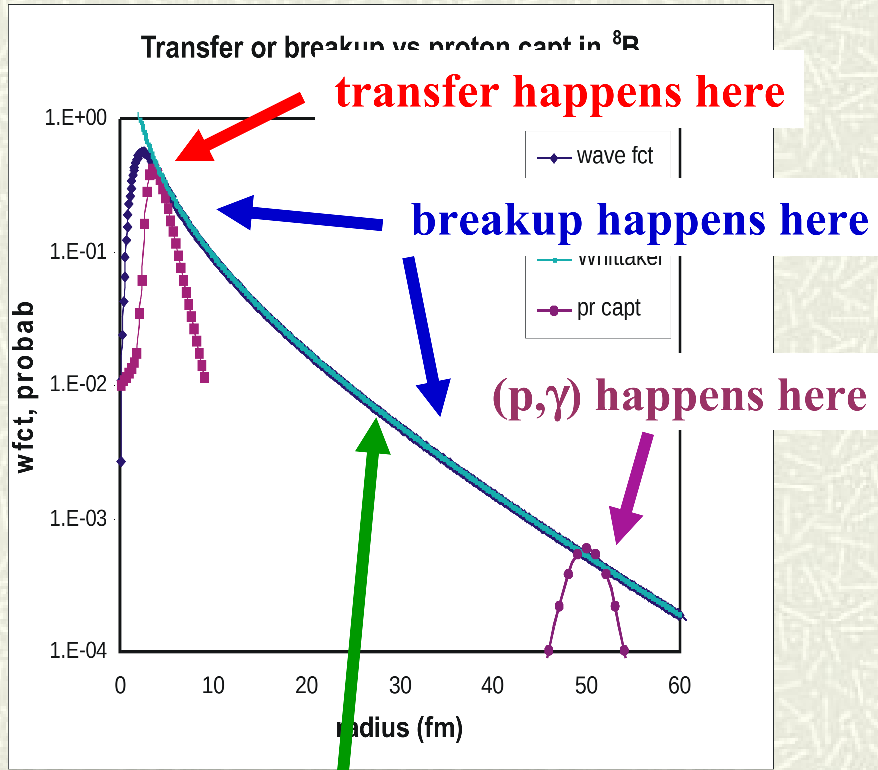
Nuclear astrophysics case

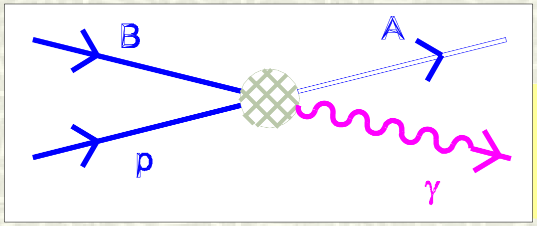
- Explosive H-burning
  - $^{8}B(p,\gamma)^{9}C$ – a possible path to hot *pp-IV* chain and rapid alpha proc *rap I* – at high temp and densities
  - $^{26}Si(p, \gamma)^{27}P$ – bottleneck in H-burning in novae.
    - Part of the effort to have ALL reaction rates from experimental data – for novae
-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

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



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

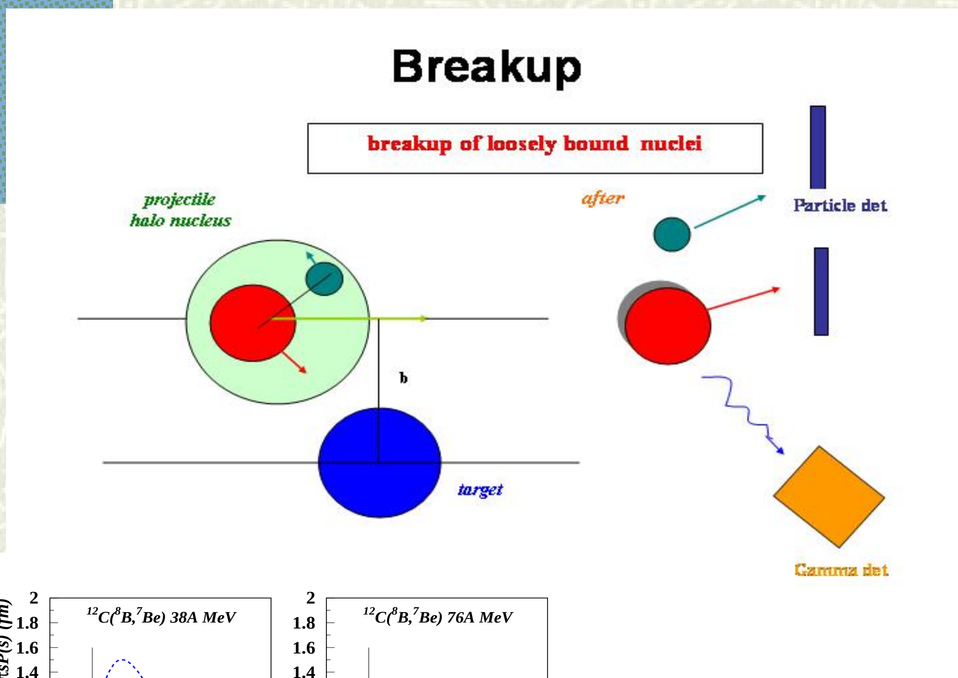


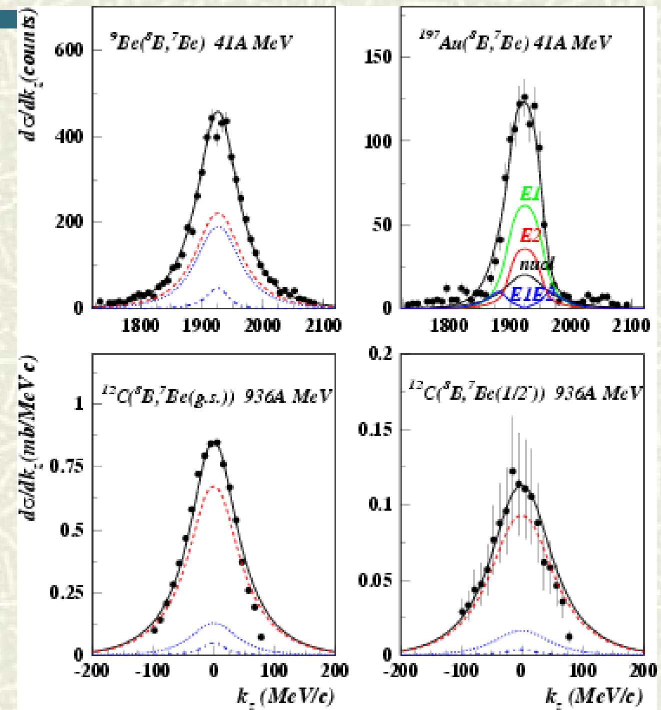


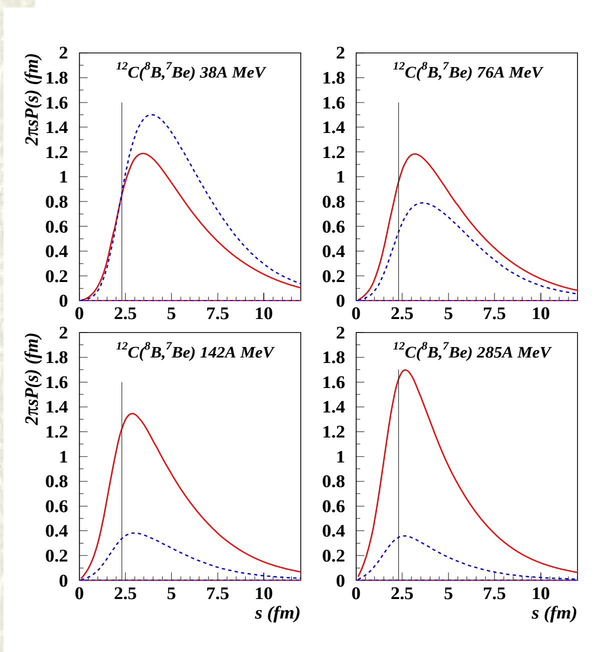
$$(T+V_{coul})Y(\hat{r})\varphi(r) = -\varepsilon Y(\hat{r})\varphi(r)$$

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

Breakup reactions for nuclear astrophysics





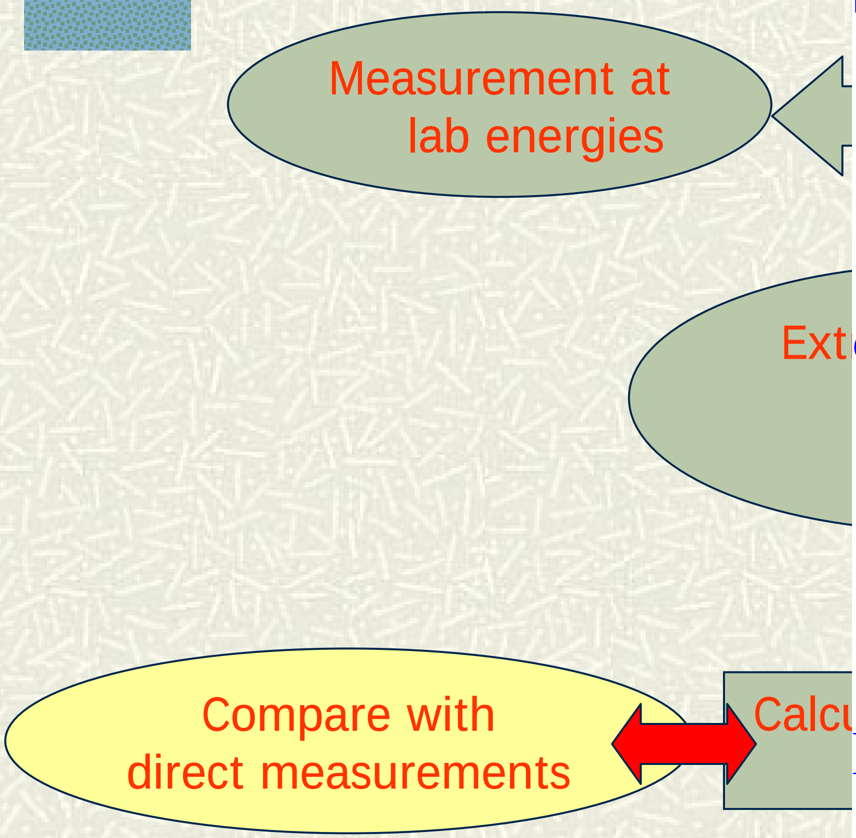


Peripheral

Momentum distributions → *nlj*
Gamma rays → config mixing
Cross section → ANC (only!!!)

Need: $V_{p\text{-target}}$ & $V_{core\text{-target}}$
and reaction mechanism model

Indirect methods for nuclear astrophysics



Spectroscopic factors:

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

or ANC:

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

Need good experimental data!

Need good, reliable, calculations!!!

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

Data from:

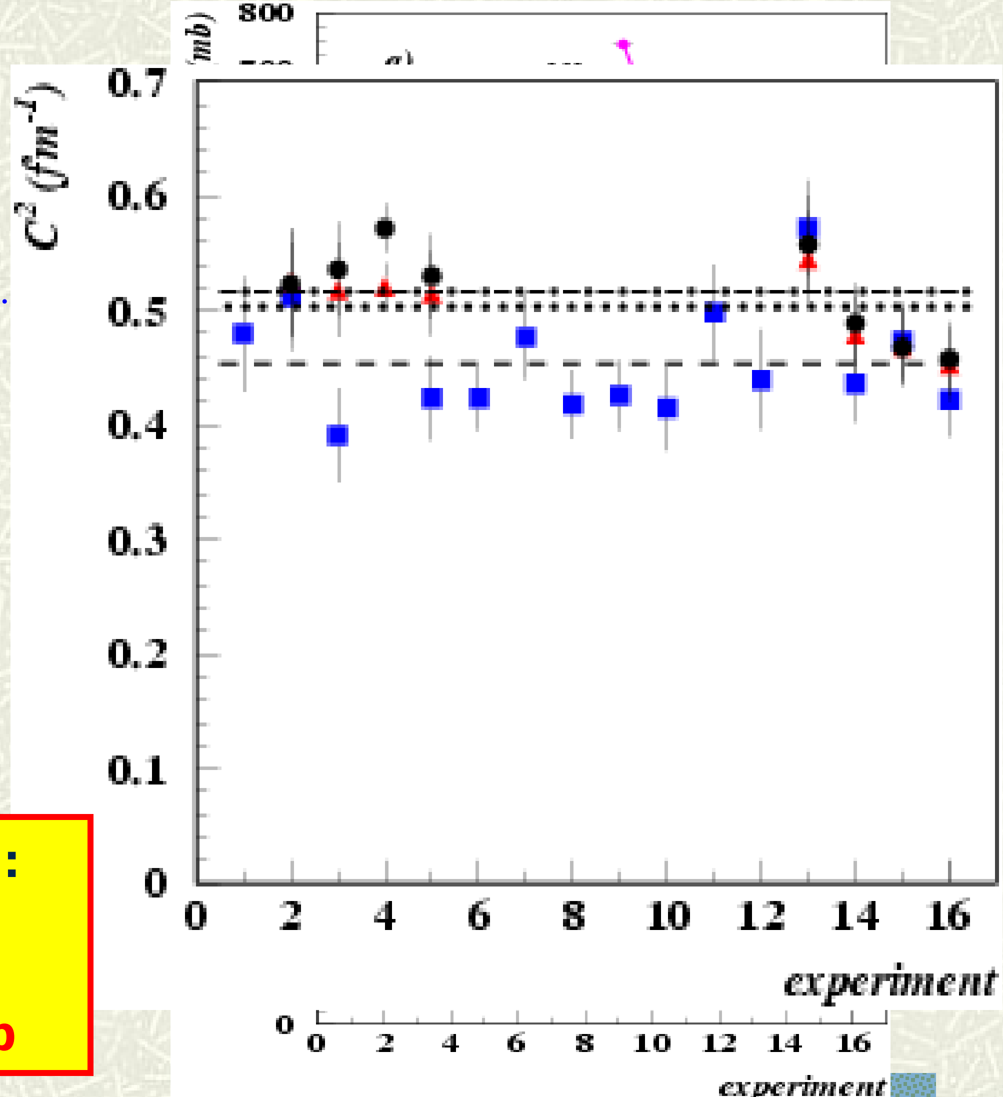
- **F. Negoita et al, Phys Rev C 54,** 1787 (1996)
- **B. Blank et al, Nucl Phys A624,** 242 (1997)
- **D. Cortina-Gil e a, EuroPhys J. 10A,** 49 (2001).
- **R. E. Warner et al. – BAPS 47,** 59 (2002).
- **J. Enders e.a., Phys Rev C 67,** 064302 (2003)

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: $S_{17}(0)=18.2\pm1.7$ eVb
Breakup: $S_{17}(0)=18.7\pm1.9$ eVb
Direct meas: $S_{17}(0)=20.8\pm1.4$ eVb



Coulomb Dissociation vs direct

- After pioneering ^{6}Li->α+d …
- 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

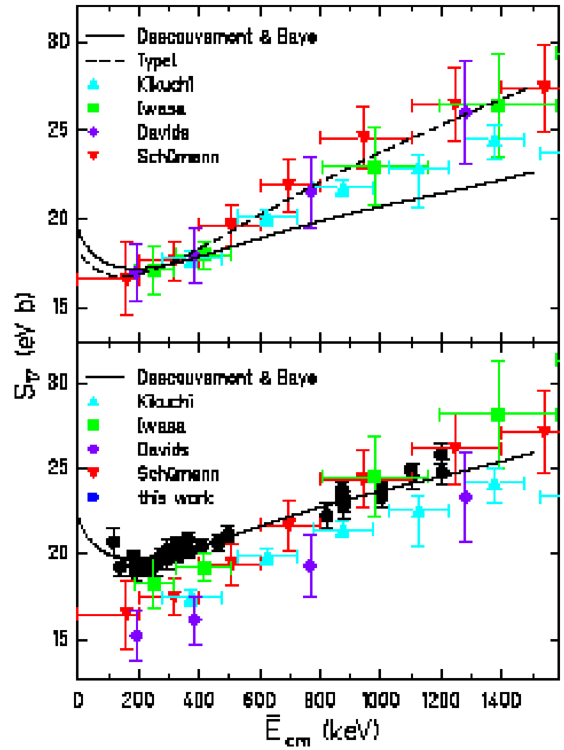
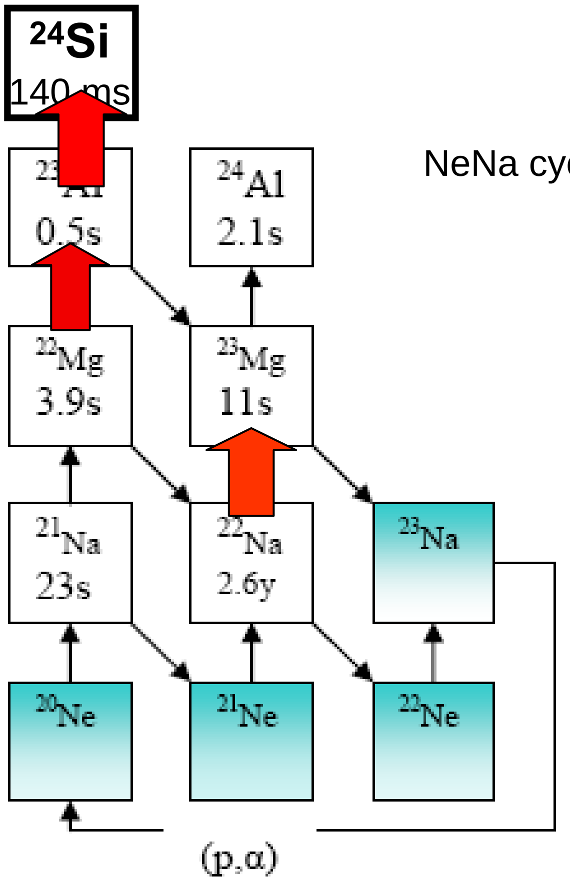
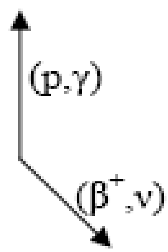


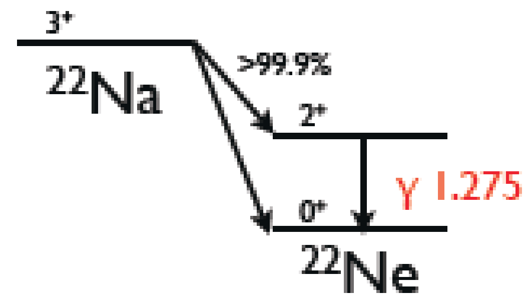
FIG. 19: E1 ^{7}Be(p,γ)^{8}B S-factors inferred from Coulomb dissociation (CD) experiments. Bottom panel: absolute CD S-factors, together with our direct results (with the 1^{+} resonance subtracted) and the best-fit DB curve to our direct low-energy data. Top panel: CD data plotted with a common normalization 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.

<u>Explosive H-burning in novae</u>: "^{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?

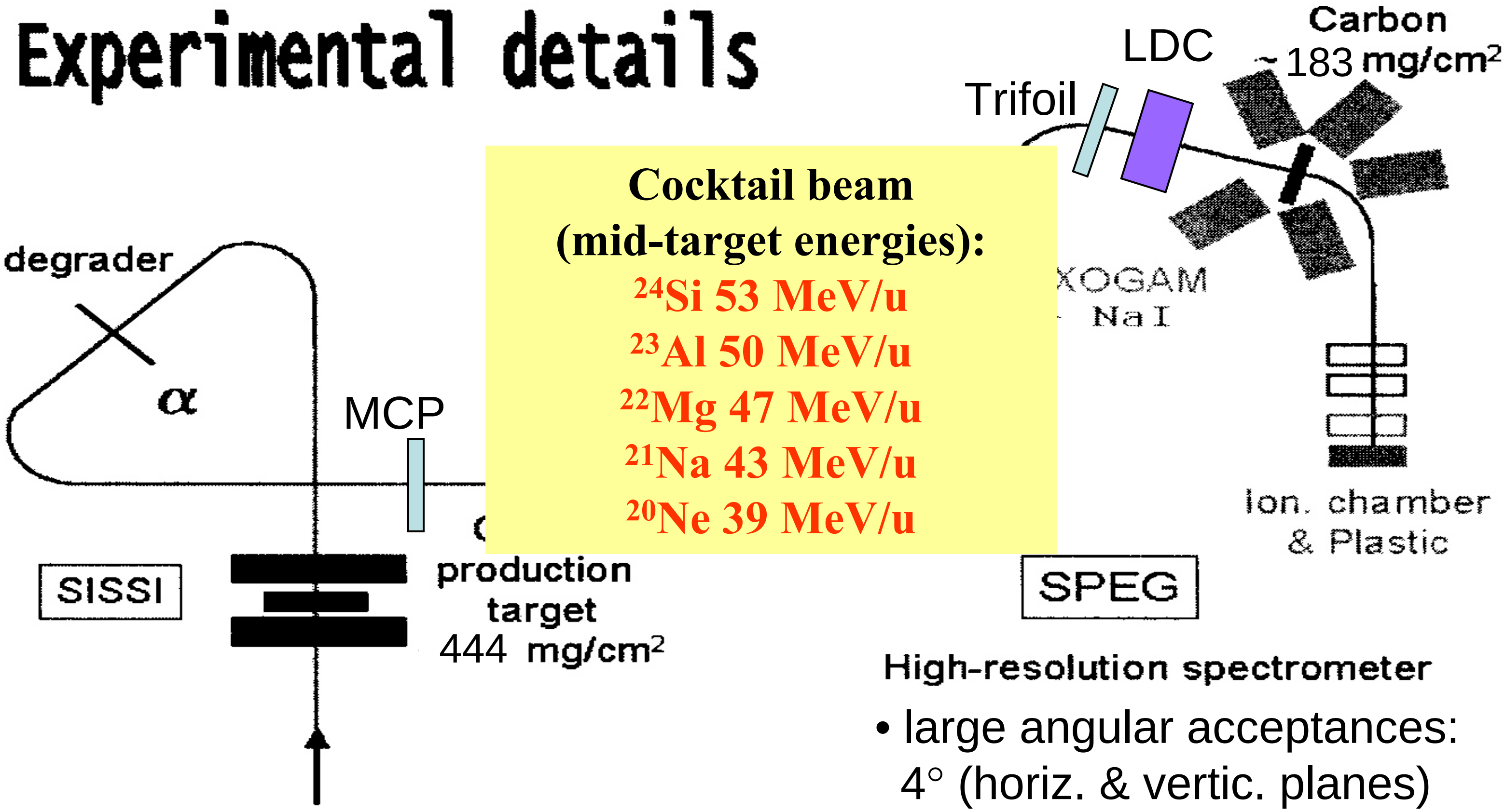
Depleted via? {
^{22}Mg(p,γ)^{23}Al ↔ direct & res. capture
^{22}Na(p,γ)^{23}Mg ↔ resonant capture

- 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.



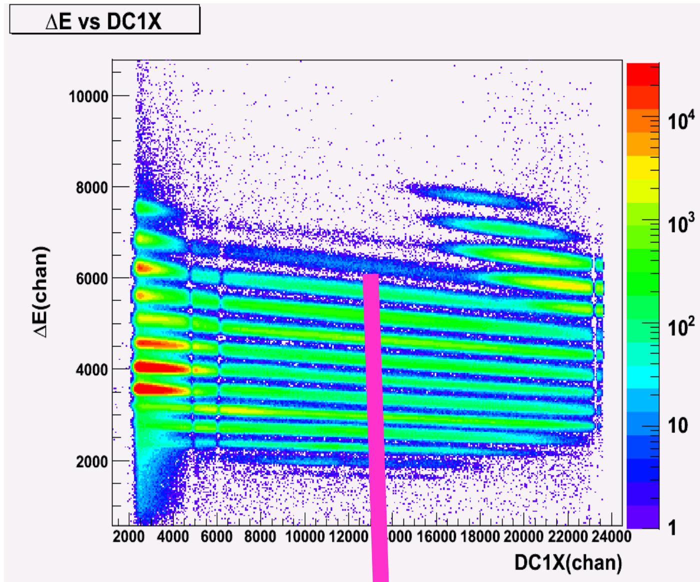
Cocktail beam
(mid-target energies):
^{24}Si 53 MeV/u
^{23}Al 50 MeV/u
^{22}Mg 47 MeV/u
^{21}Na 43 MeV/u
^{20}Ne 39 MeV/u

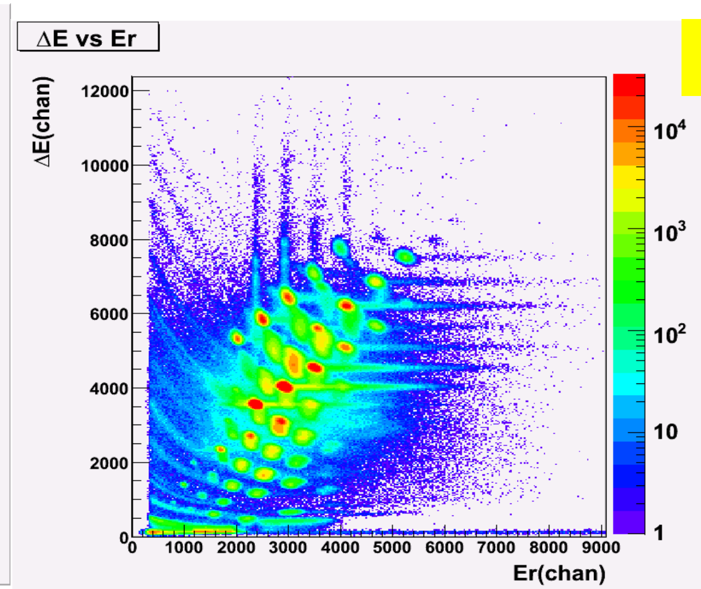
^{32}S primary beam
95 MeV/u, ~ 400 W

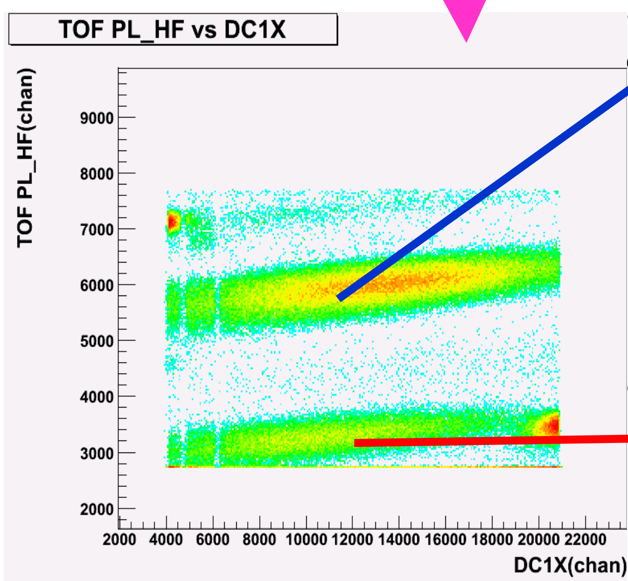
- large angular acceptances: 4° (horiz. & vertic. planes)
- broad momentum acceptance: $\Delta p/p$ = 7%

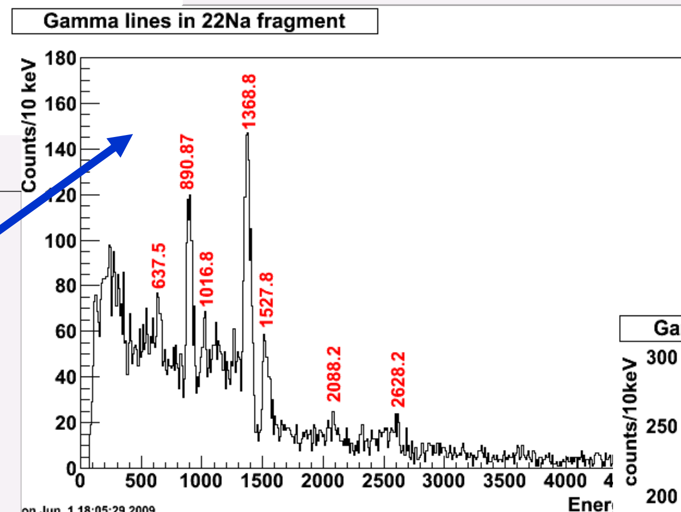
A. Banu et al., NIC10 Symposium 2008 & to be published

GANIL E491 exp



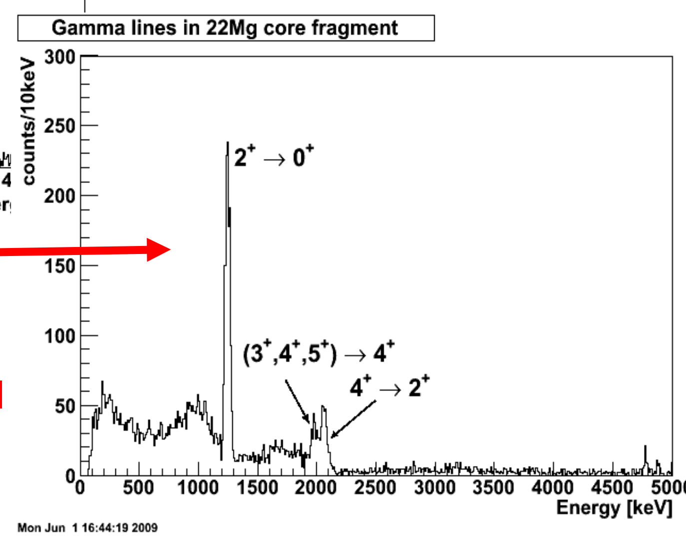






$^{12}C(^{22}Mg,^{22}Na)^{12}N$

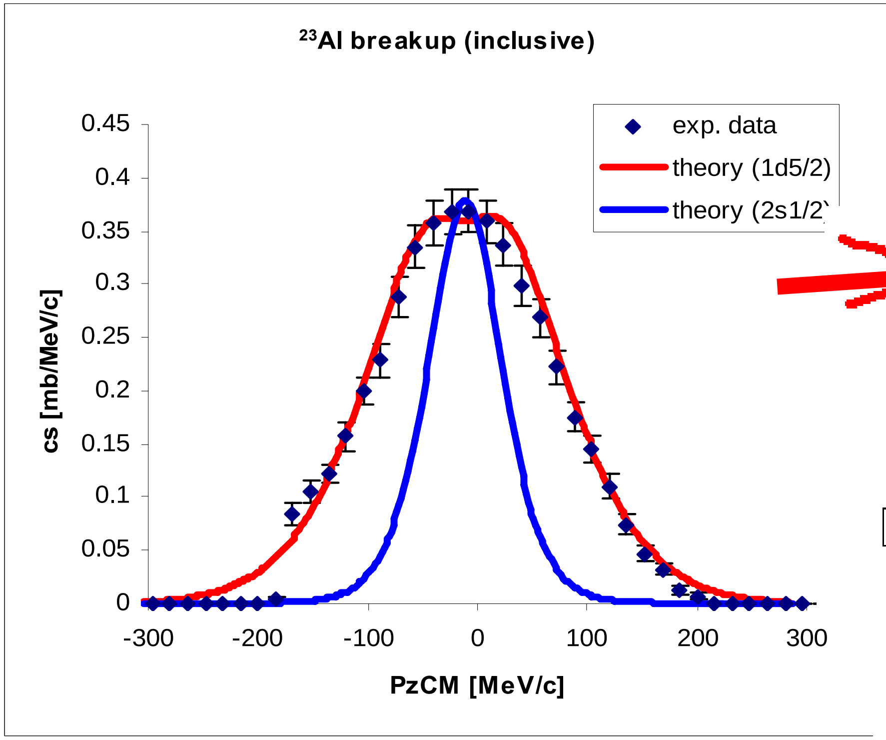
Charge exchange (new & unexpected)



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

Proton removal (sought)

Results from ^{23}Al breakup



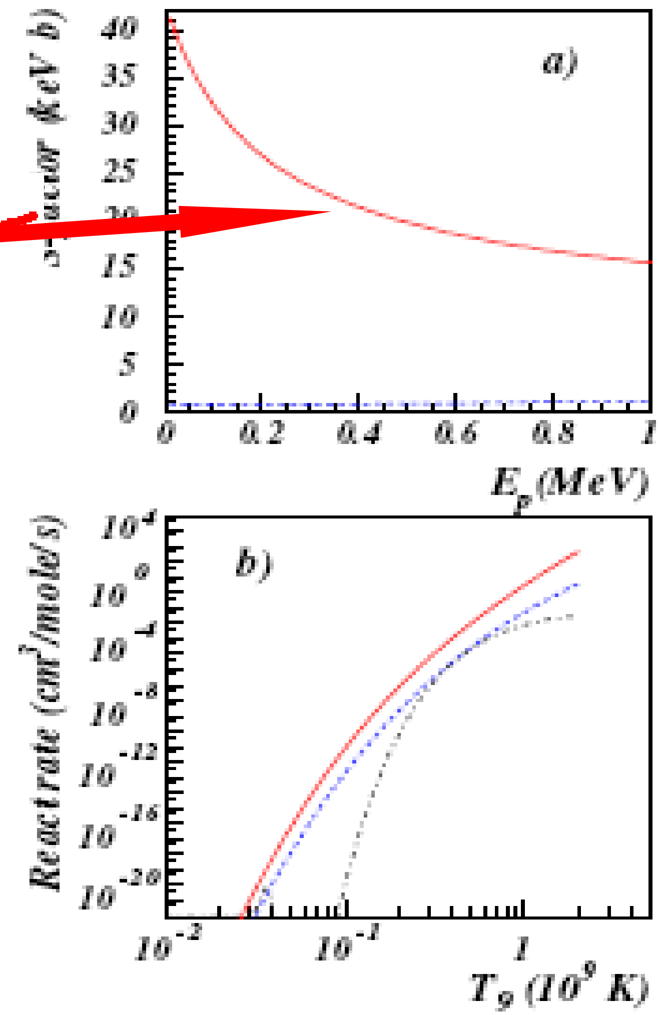
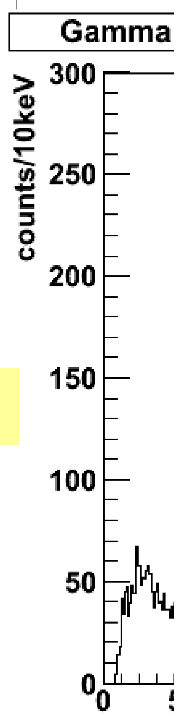


Fig. 8. a) The astrophysical S-factor for the ^{22}Mg(p,γ)^{23}Al reaction, calculated assuming $J^\pi = 5/2^+$ (dashed line), or $J^\pi = 1/2^+$ (orbital inversion, full line) for the g.s. of ^{23}Al. b) The corresponding reaction rate calculated for the case of non-inversion (dashed), or inversion (full line). The dash-dotted line shows the resonant contribution of the 1st excited state in ^{23}Al.

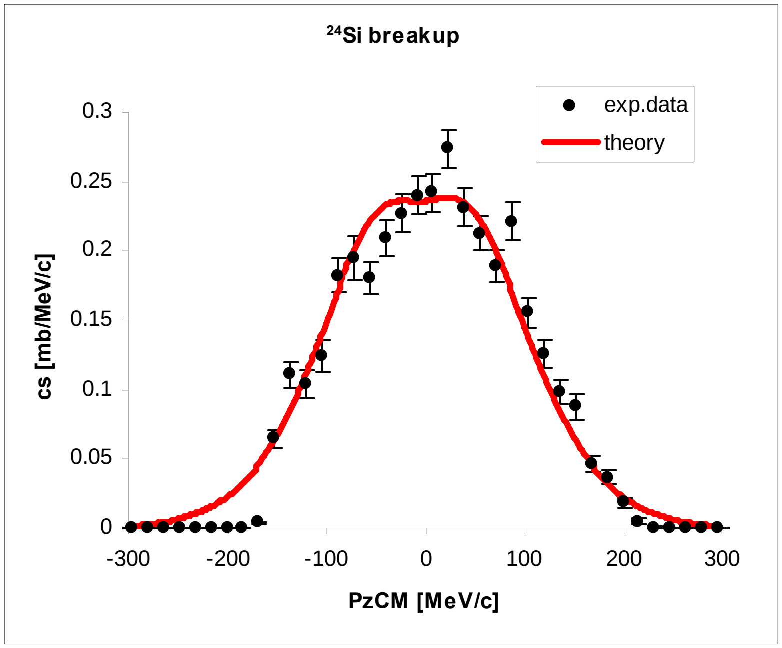


$J^\pi = 1/2^+$ $\Gamma \sim 60$ MeV/c

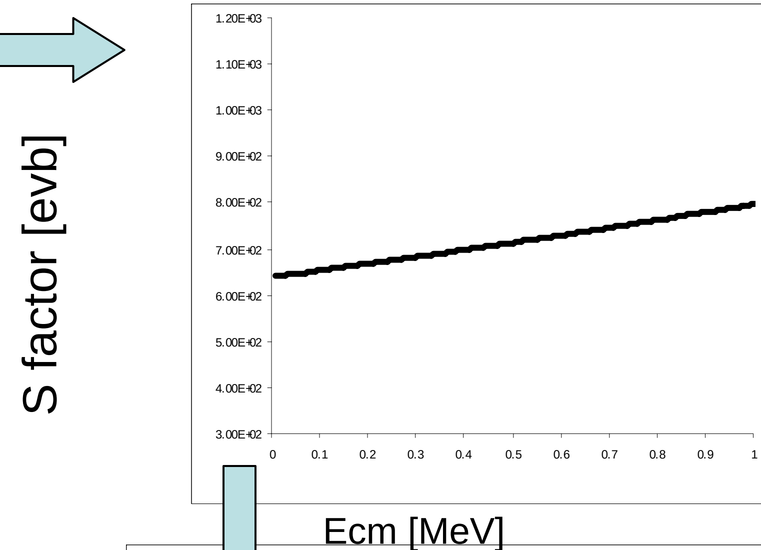
$\Gamma(^{23}Al) \sim 200$ MeV/c $\Rightarrow J^\pi = 5/2^+$

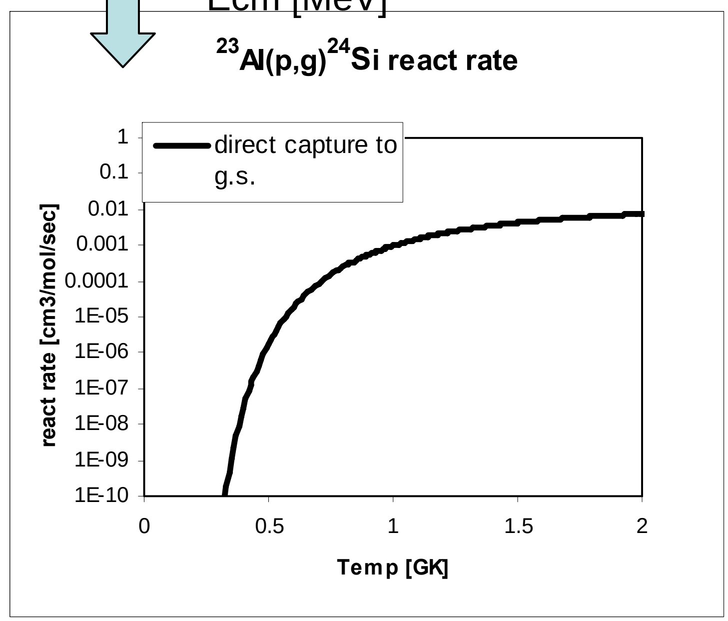
Conclusion: ^{22}Mg(p,g)^{23}Al does not produce ^{22}Na depletion

Results for ^{24}Si breakup



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





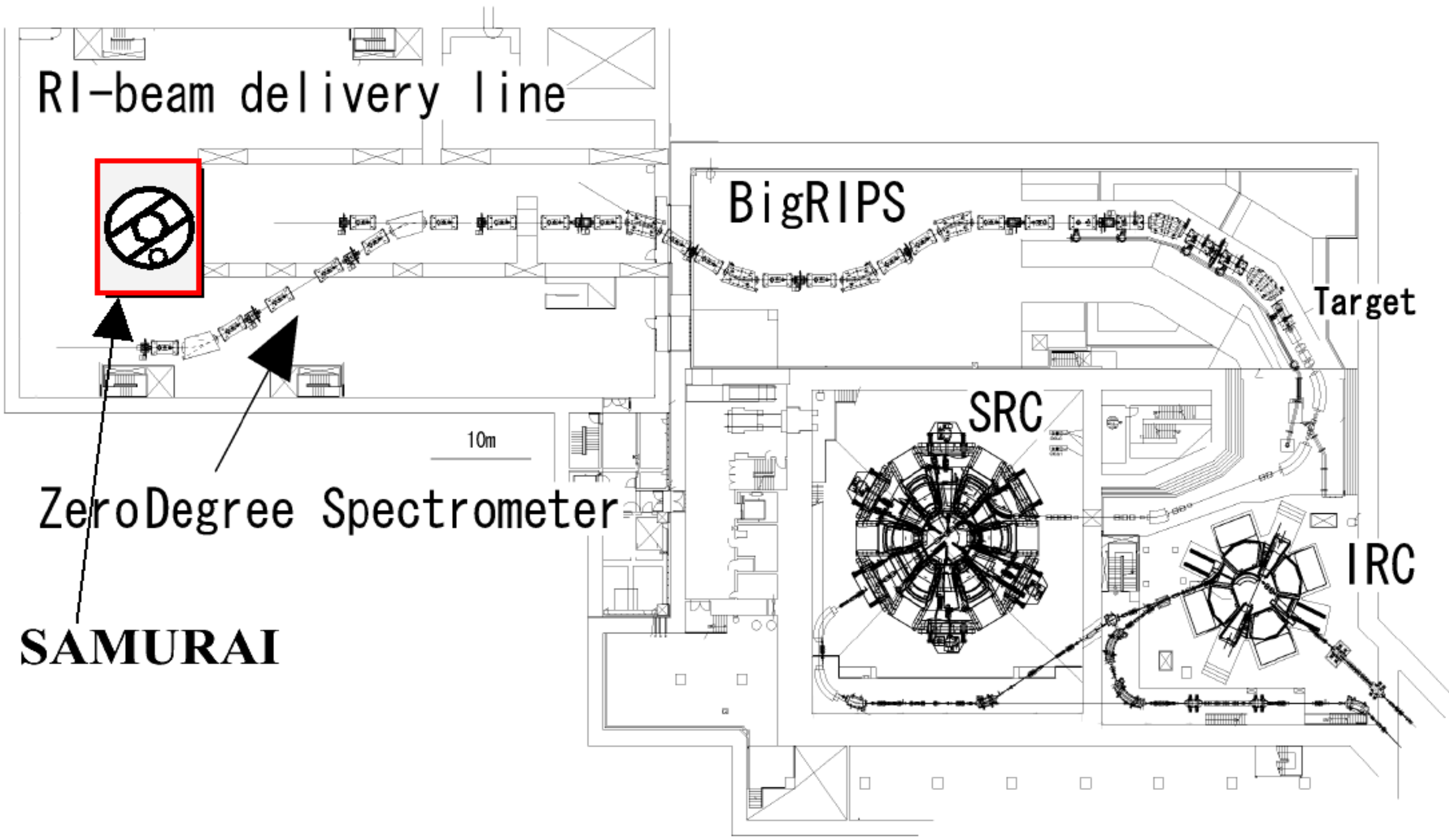
$$SF = \frac{\sigma_{\exp}}{\sigma_{th}}$$

SF = 2.5-2.9
(spect. factor)

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

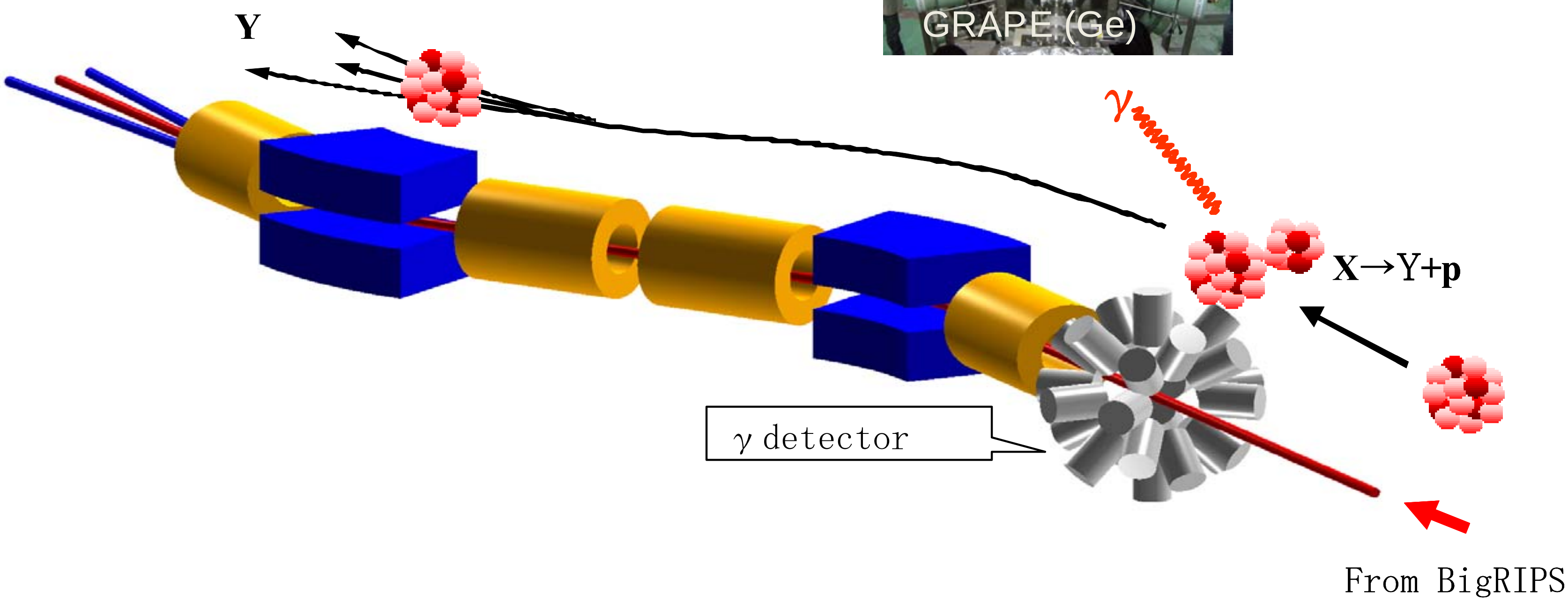
=> first exp det of direct comp of $^{23}Al(p,\gamma)^{24}Si$

Measurements at BigRIPS-ZD



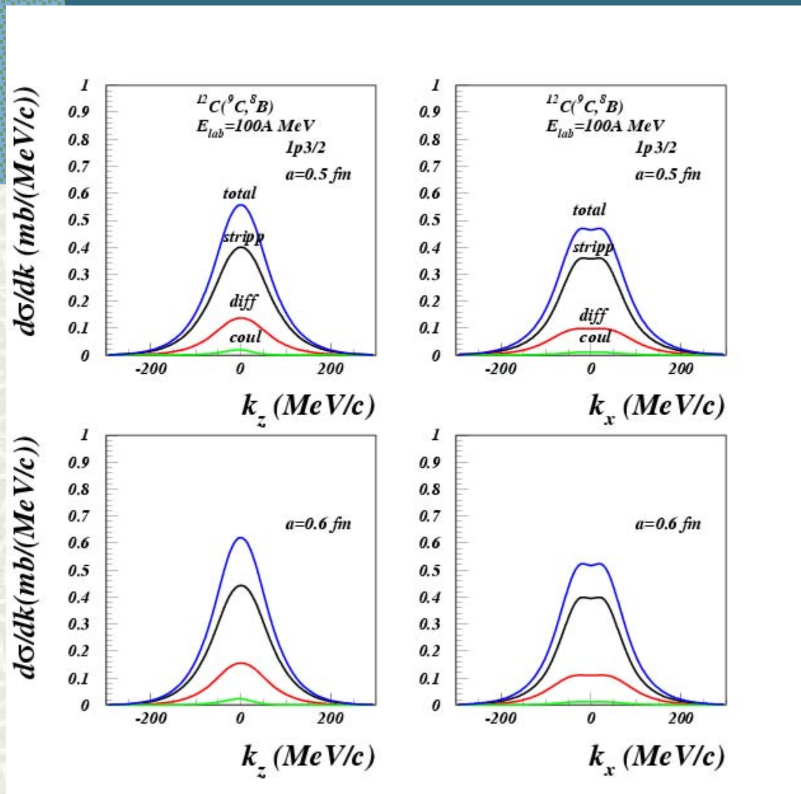
Zero Degree Spectrometer

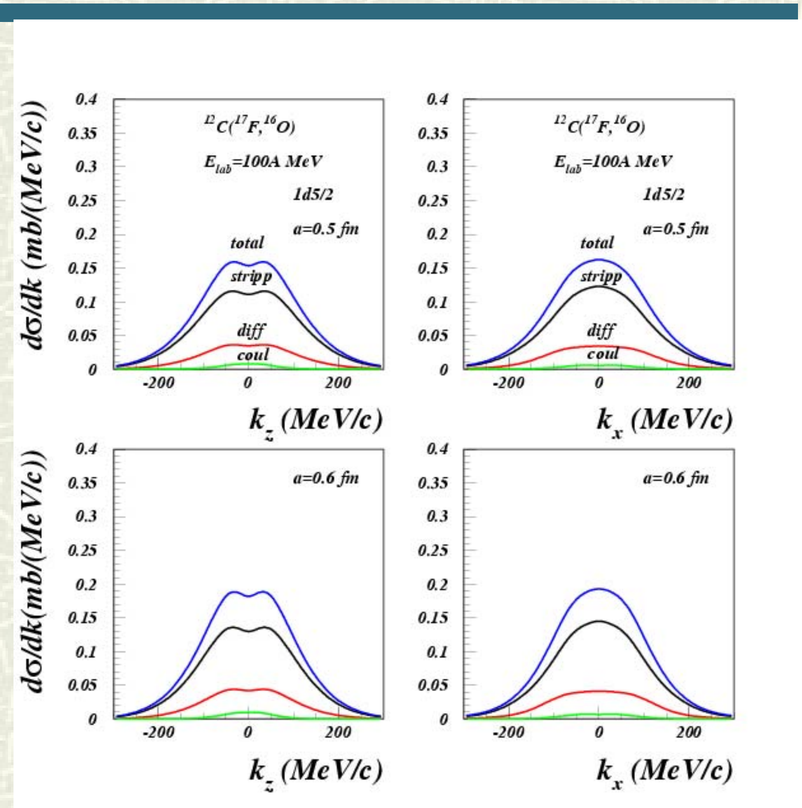
particle ID / momentum analysis
Core-gamma ray coincidences



(from T. Motobayashi, OMEG07)

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





Calculated momentum distributions from 1p-breakup of ^{9}C at 100 MeV/u on a C target. 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).

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)

- 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*