Recent Radioactive Beam Experiments in Nuclear Astrophysics

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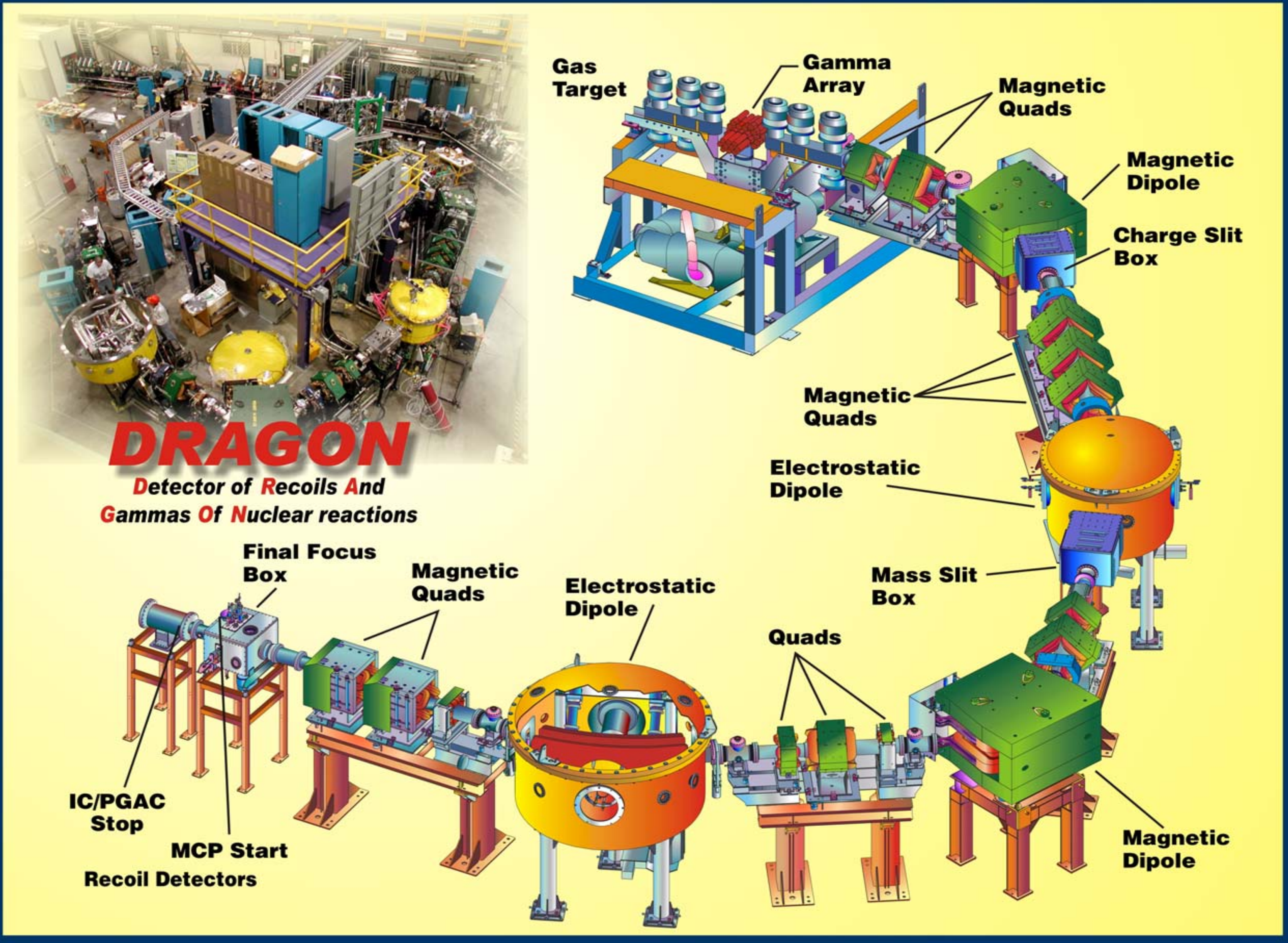
JINA Frontiers Meeting

21 August 2007

Caveats

- A personal, biased view
- Restricted to radioactive beam experiments, thereby excluding important stable beam measurements
- Focussed on recent measurements (if not results)
- Ignored experiments described at this workshop


DRAGON
Detector of Recoils And
Gammas Of Nuclear reactions
Gas
Target
Gamma
Array
Magnetic
Quads
Magnetic
Dipole
Charge Slit
Box
Magnetic
Quads
Electrostatic
Dipole
Mass Slit
Box
Quads
Magnetic
Dipole
Electrostatic
Dipole
Magnetic
Quads
Final Focus
Box
IC/PGAC
Stop
MCP Start
Recoil Detectors

$^{26}Al(p,\gamma)^{27}Si$

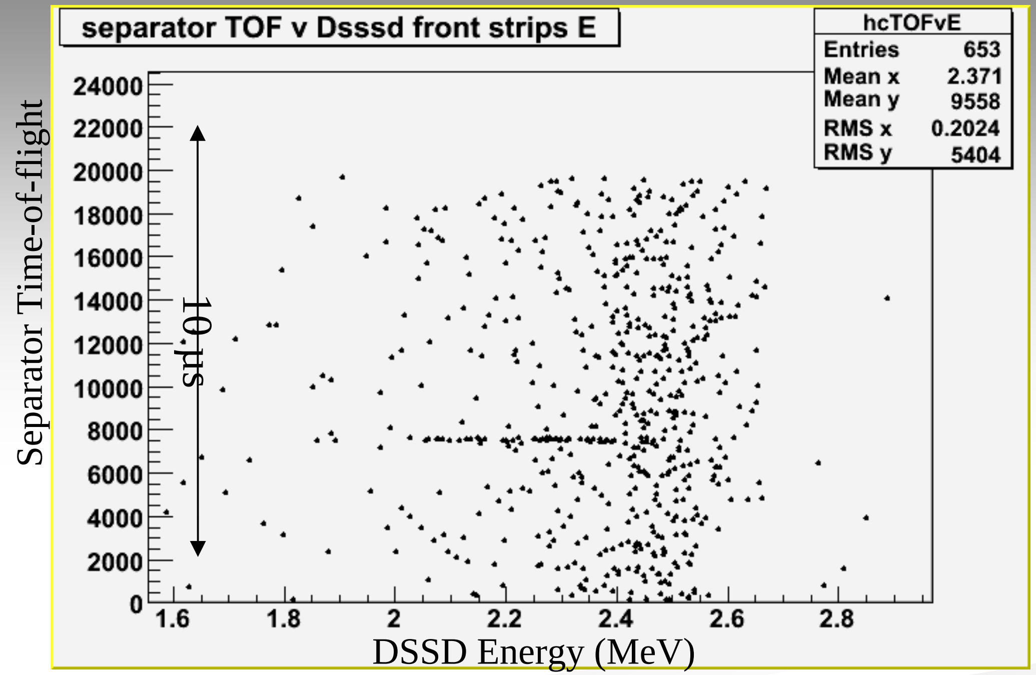
- Average intensity 3.4×10^9 ions/sec

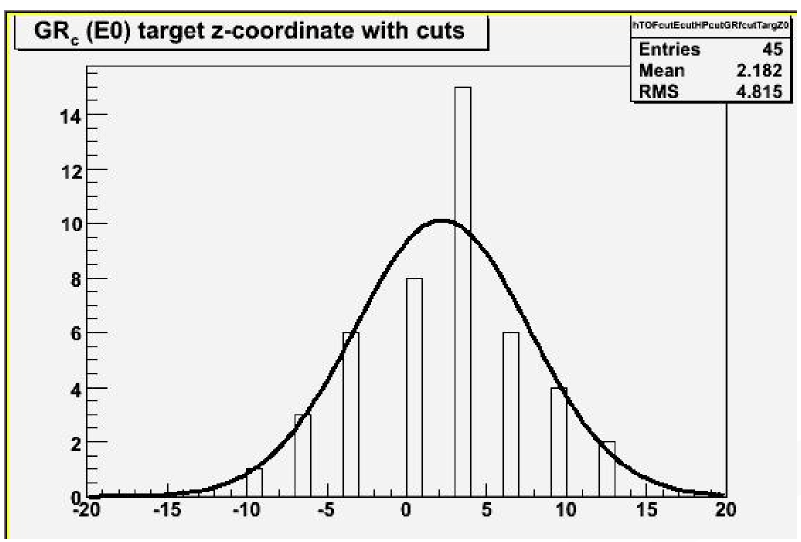
256 hours taken:

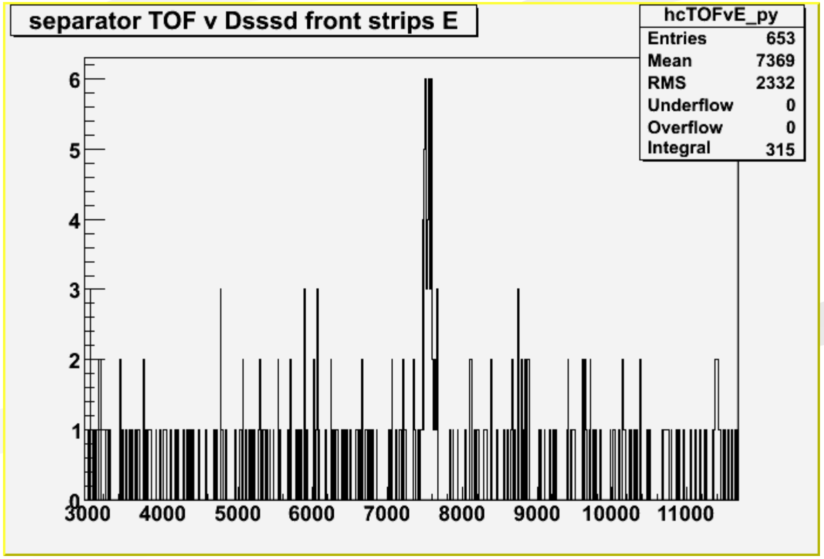
201 A keV, 196 A keV,

225 A keV (off-resonance)

- 138 coincidence events



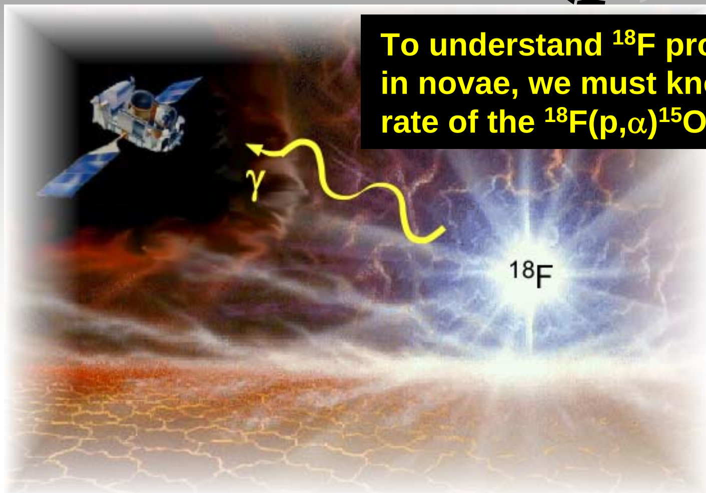




$^{26}Al(p,\gamma)^{27}Si$ Results

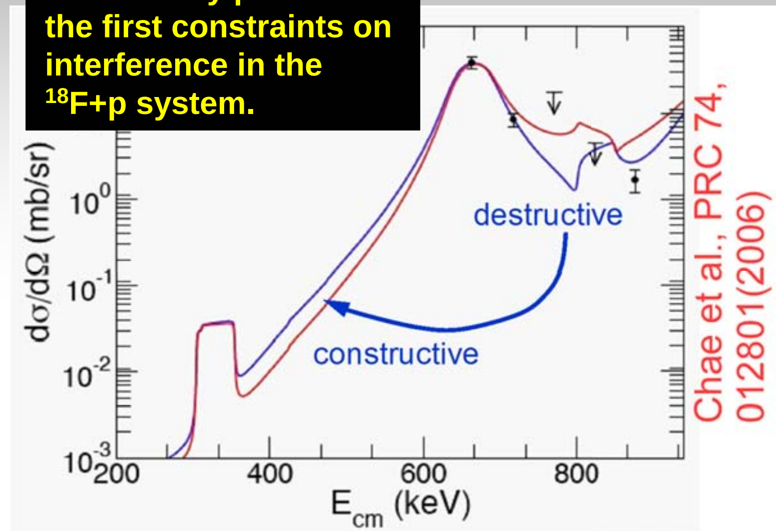
- $E_R = 184 \pm 1$ keV
- $\omega\gamma = 36 \pm 7\ \mu eV$
- Supports paradigm of secondary contribution from novae
- Exact contribution requires knowledge of the $^{25}Al(p,\gamma)^{26}Si$ rate
- Ruiz, Parikh, José et al. Phys. Rev. Lett. 96, 252501 (2006)

The $^{18}F(p,\alpha)^{15}O$ Reaction Rate

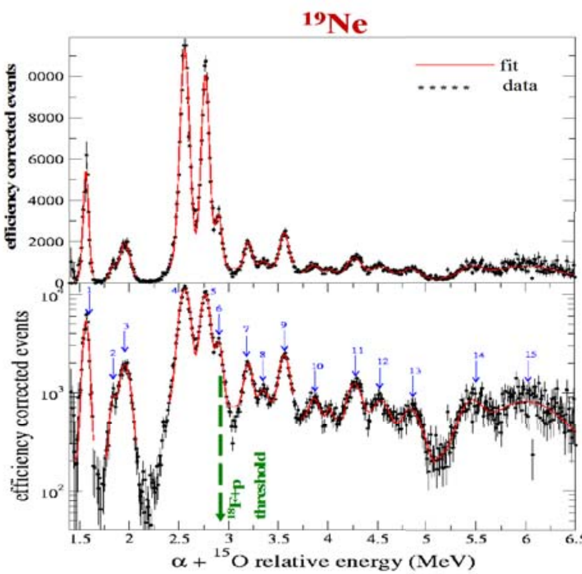


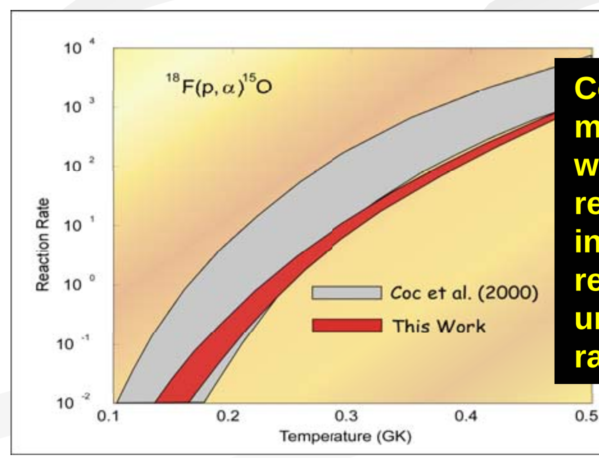
To understand ^{18}F production in novae, we must know the rate of the $^{18}F(p,\alpha)^{15}O$ reaction.

We recently provided the first constraints on interference in the ^{18}F+p system.



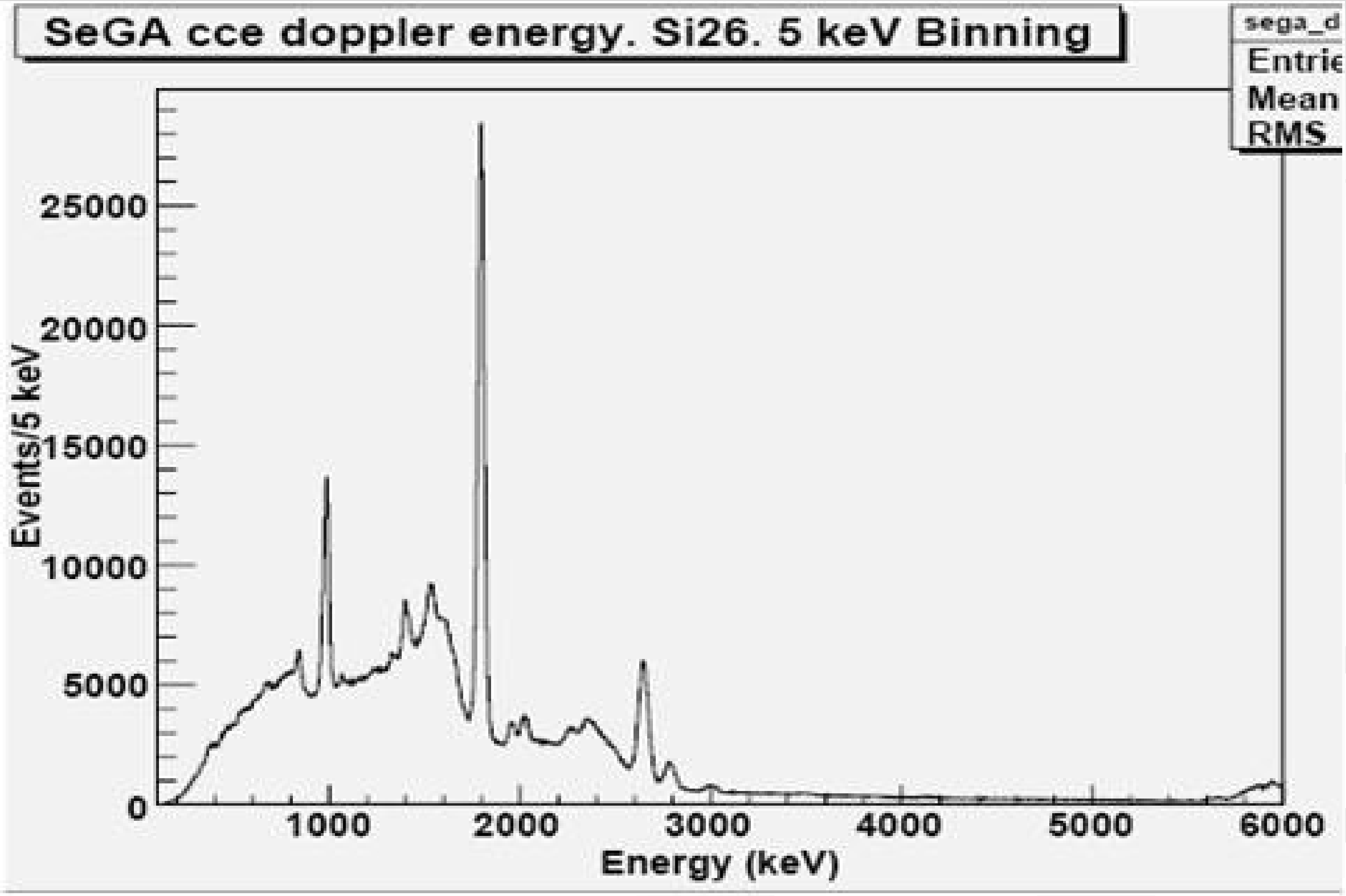
Adekola, Brune et al. made the first proton-transfer measurement on ^{18}F to measure spectroscopic factors for low-energy ^{18}F+p resonances.





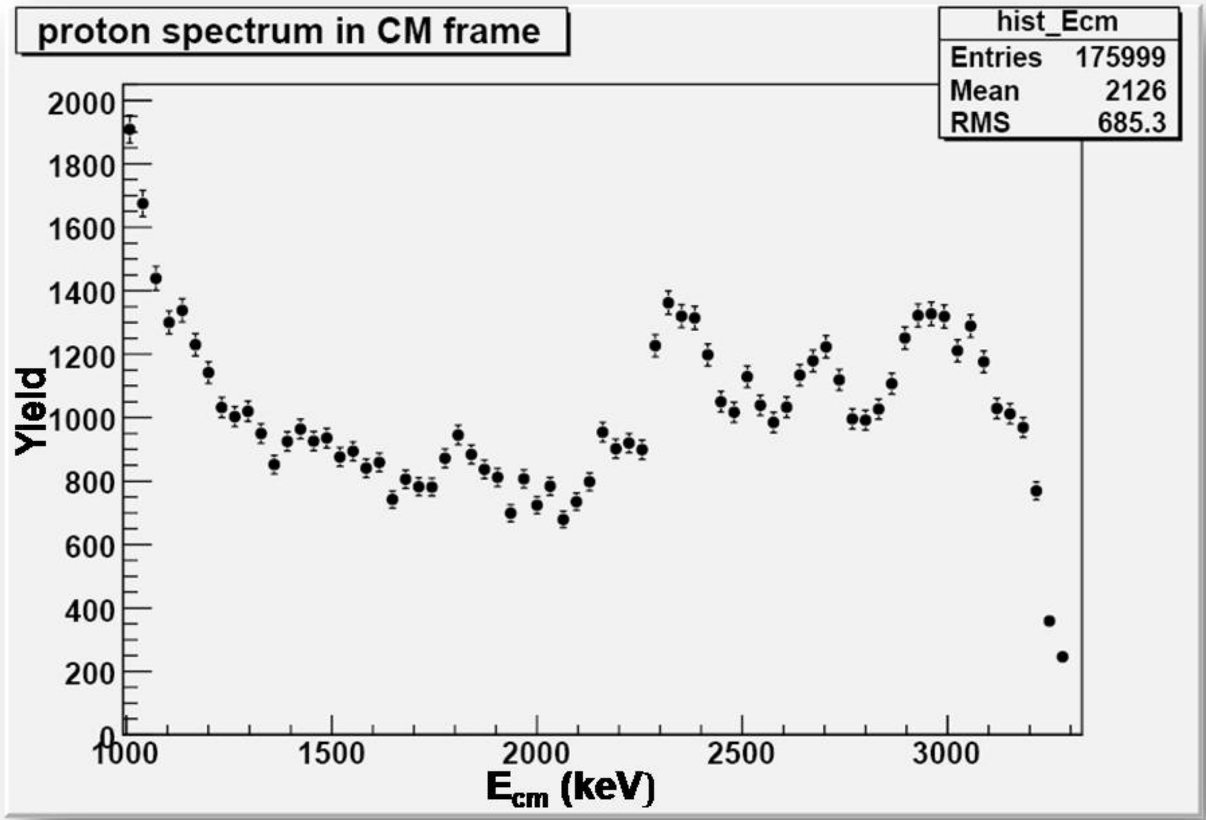
Combining these measurments with previous results resulted in a dramatically-reduced uncertainty in the rate.

$^{25}Al(p,\gamma)^{26}Si$ via $^{27}Si(p,d)^{26}Si$



Experiment of McMaster group (Chen & Chen) @ NSCL

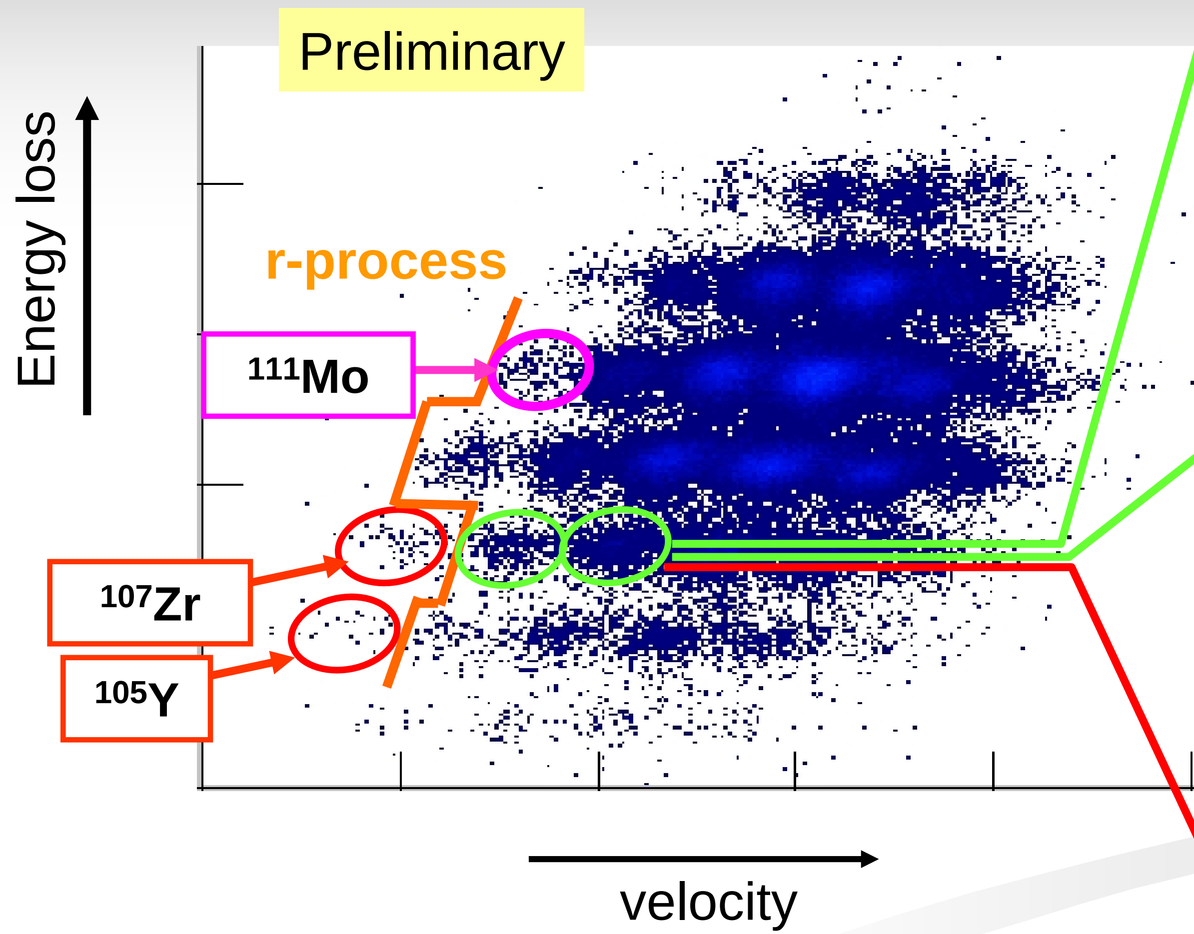
^{25}Al Elastic Scattering @ CRIB

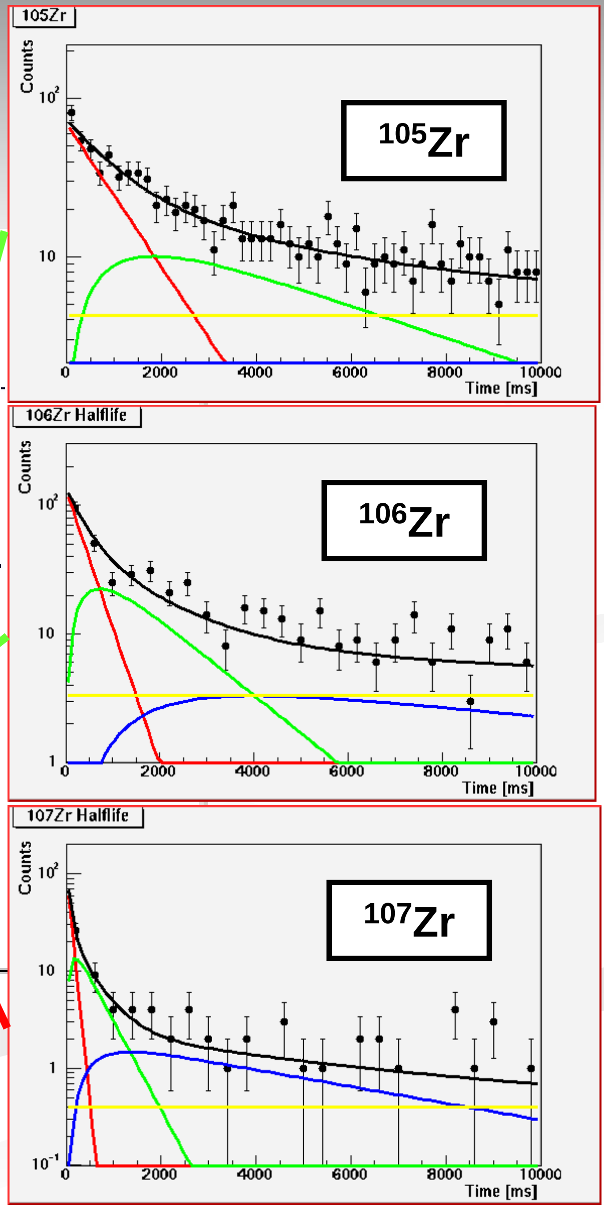


McMaster/CNS collaboration

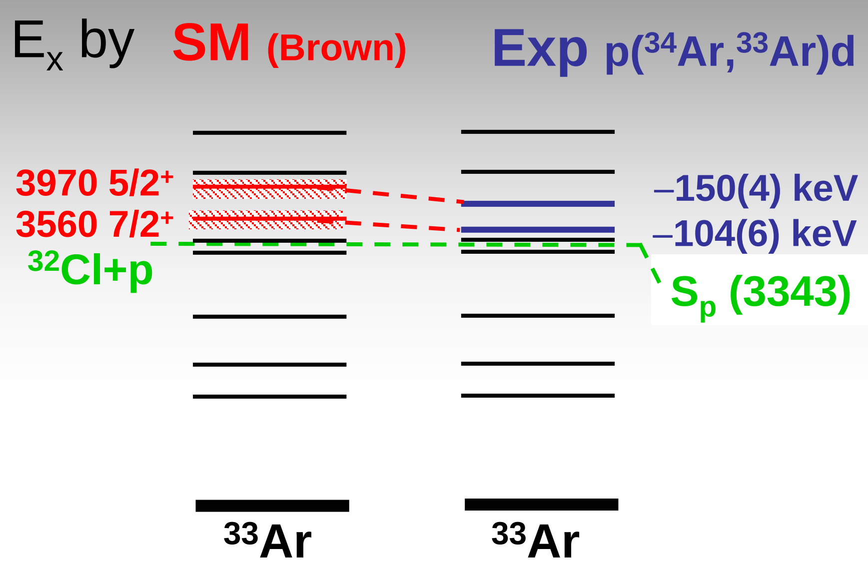
Half-lifes and Pn values in the r-process (Pereira, Hennrich, et al.)

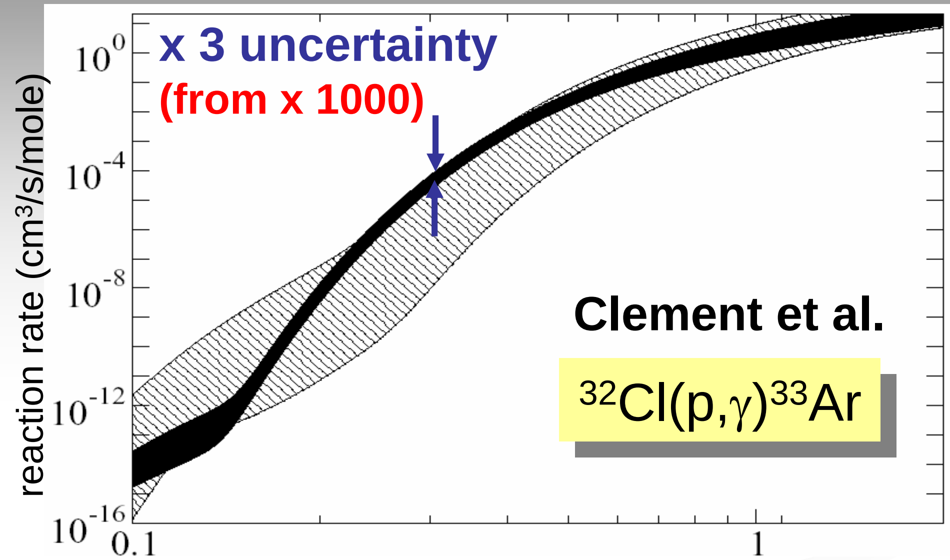
NSCL Experiments
Notre Dame – NSCL – Mainz collaboration

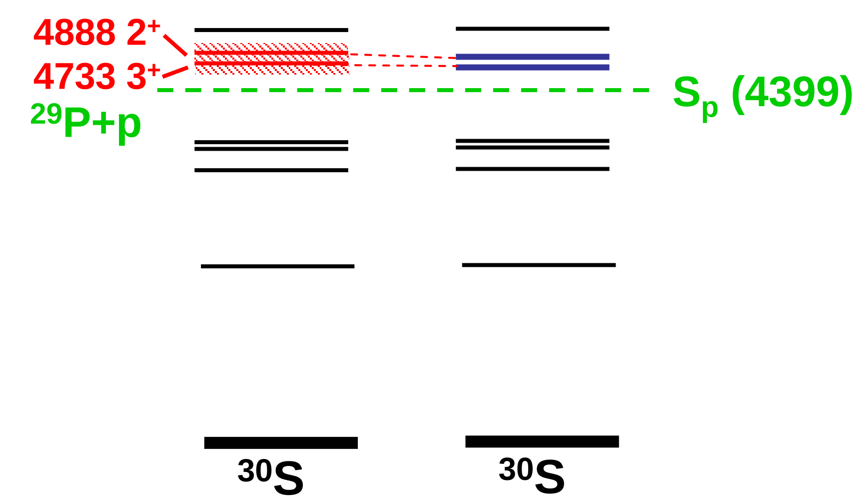


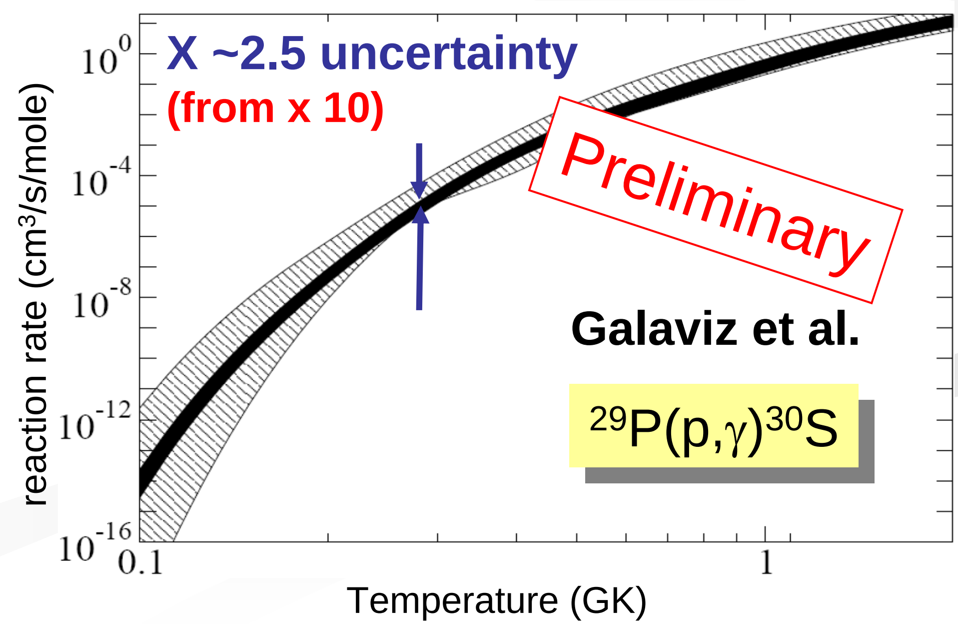


Level energies from (p,d) in inverse kinematics at the NSCL









High-energy Coulomb-dissociation experiments at GSI

1. Cases studied at KaoS (1996 – 2001):

- $^{7}Be(p,\gamma)^{8}B$: published [Schümann et al., PRC 73, 015806 (2006)]
- $\alpha(d,\gamma)^{6}Li$: still under analysis
  Coulomb-nuclear interference
  new theory calculations by S.Typel, re-analysis by M.Heil

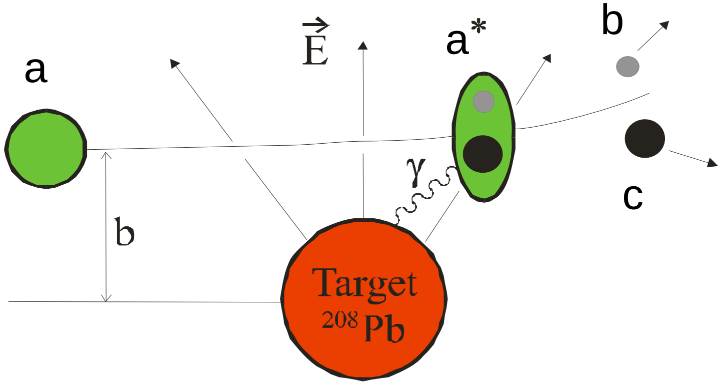
2. Cases studied at ALADIN/LAND:

- $^{14}C(n,\gamma)^{15}C$: published [Datta Pramanik et al., PLB 551, 63 (2003)]
- $^{26}Si(p,\gamma)^{27}P$: performed 24-May to 05-Jun-2007
- $^{15}O(2p,\gamma)^{17}Ne$ performed 05-Aug to 14-Aug-2007

Coulomb dissociation – a tool for nuclear astrophysics

CD can be a useful tool to study radiative-capture reactions via the time-reversed process:

$$b + c \rightarrow a + \gamma \qquad a + Z \rightarrow b + c + Z$$



Get capture cross section by detailed balance.

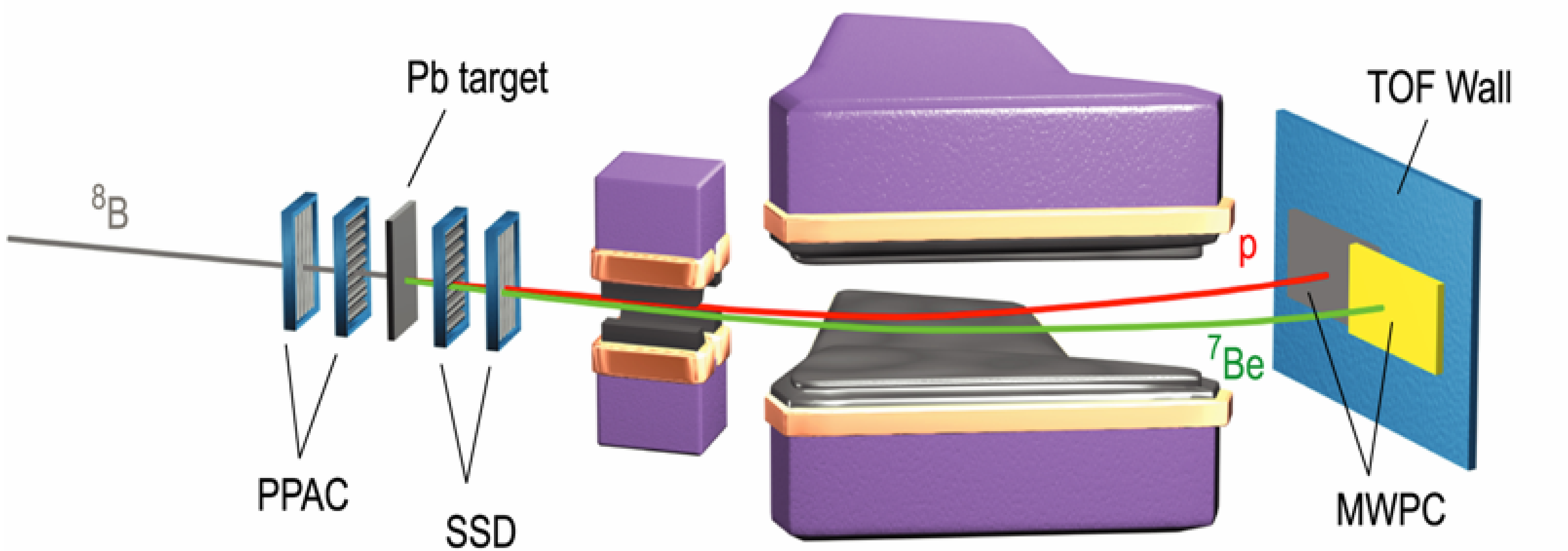
Advantages:
- high virtual photon flux
- large cross section at low E_{cm}
- charged particle detection, kinematic focussing
- experiments with radioactive ion beams possible

Disadvantages:
- Indirect method, needs theory
- bad energy resolution
- role of multipole admixtures must be clarified
- nuclear contributions

CD is not a universal method but for selected cases important information can be obtained for nuclear astrophysics

Coulomb dissociation at Kaos

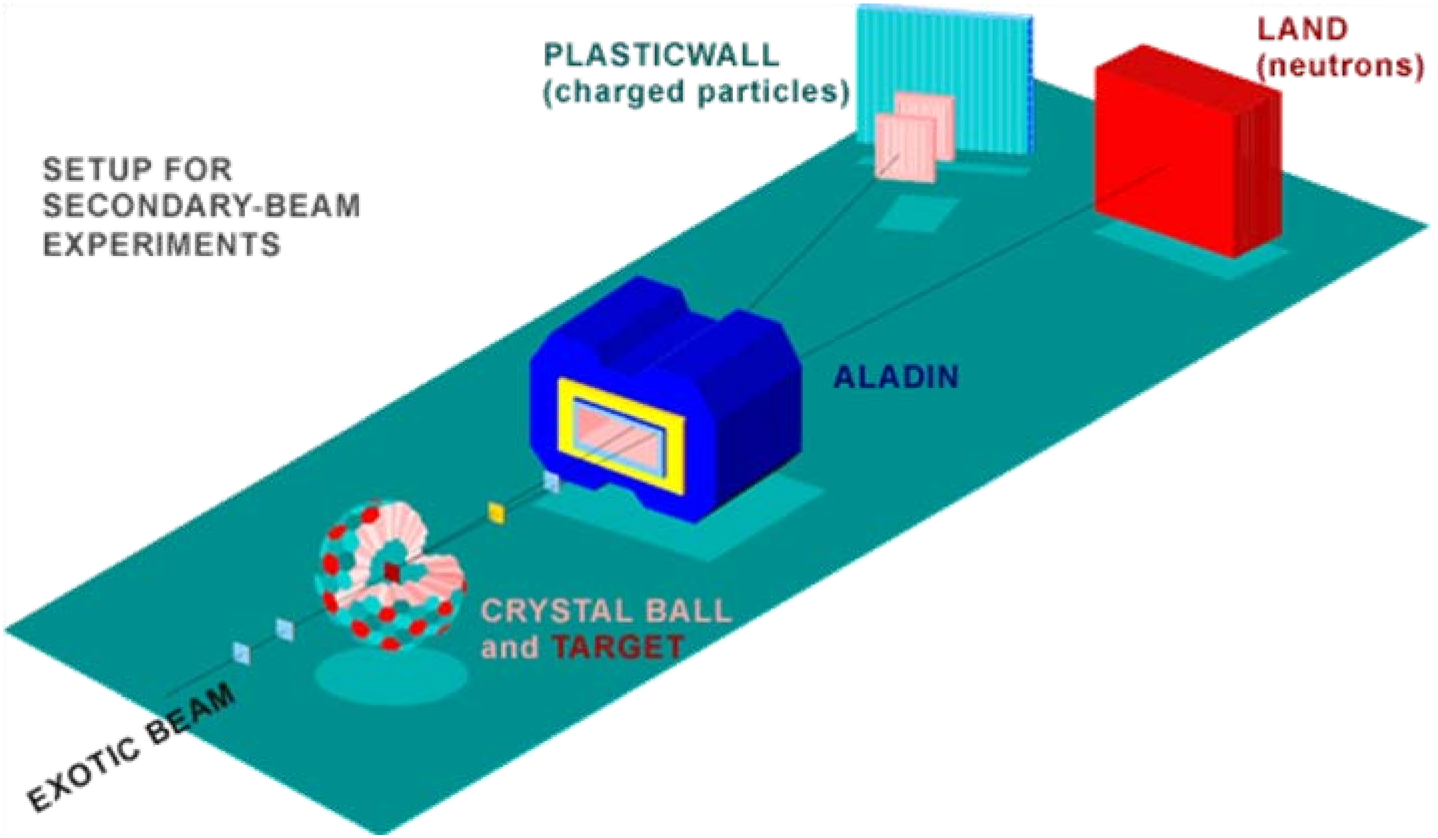
Setup used so far:



Examples:

- $^7Be(p,\gamma)^8B$
- $D(\alpha,\gamma)^6Li$

FRS / ALADIN / LAND setup

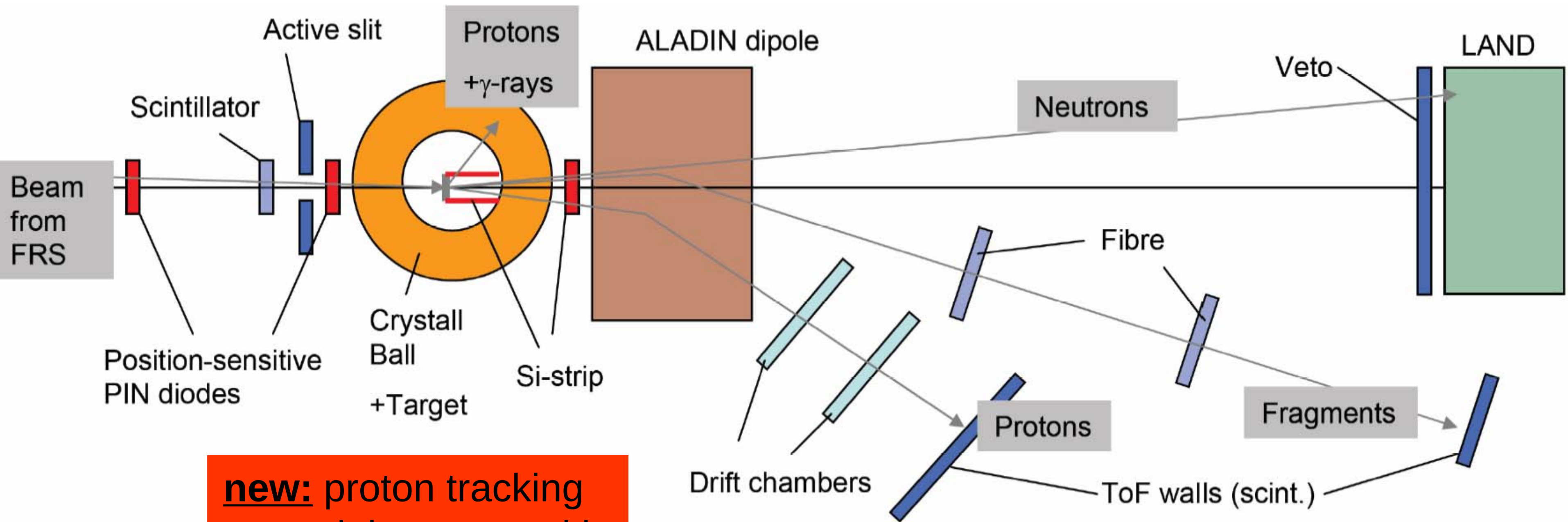


Examples:

- ^{92,93,98}Mo(γ,n) photo-dissociation cross section for p-process studies and comparison to (γ,n) experiments with real photons performed simultaneously at S-DANILAC (TU Darmstadt) and ELBE (FZ Rossendorf)

- ^{14}C(n,γ)^{15}C

New experimental setup in cave C



new: proton tracking around the target with Si-strip detectors

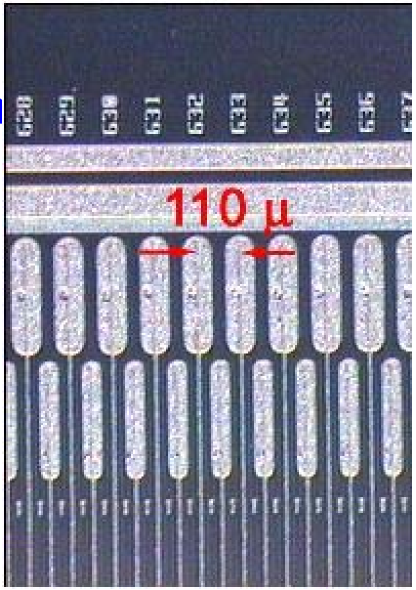
new: proton tracking

behind magnet with drift chambers

Technical achievements – µ Strip Silicon Detectors

µSSD sensors characteristics

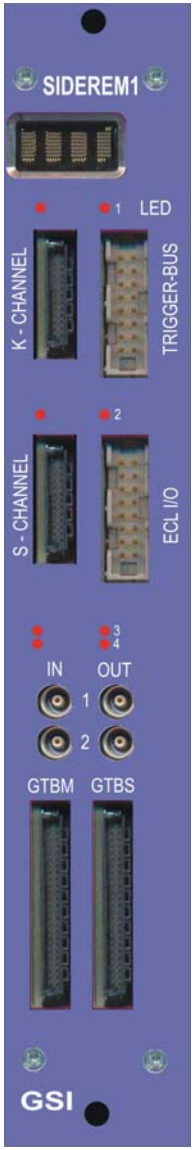
Dimensions	7.2 cm × 4.1 cm
Thickness	~300 µm
Strip pitch p-side	27.5 µm
Readout pitch p-side	110 µm
Num. of p-side readout strips	640
Strip pitch n-side	52 µm
Readout pitch n-side	104 µm
Num. of n-side readout strips	384

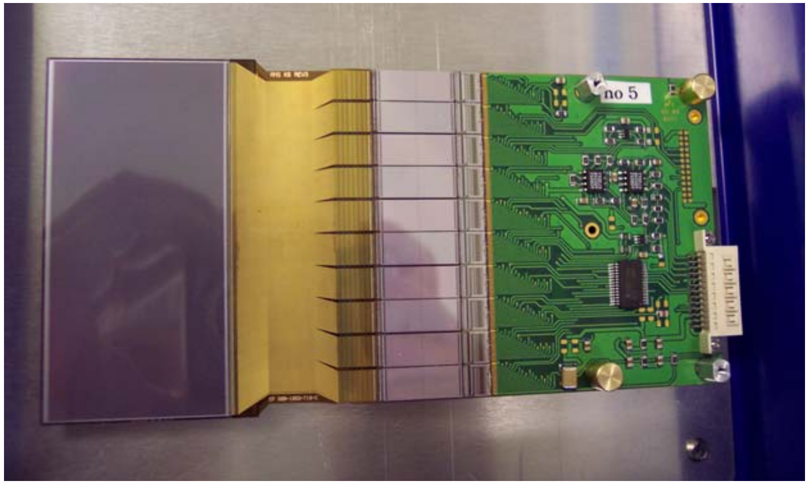


SIDEREM

SIlicon Strip
DEtector
REadout
Module

developed at
GSI ElEx





Developed together with AMS group at DPNC University of Geneva

µSSD used in a first CD experiment in 2006: ^{19}Mg(γ,2p)^{17}Ne

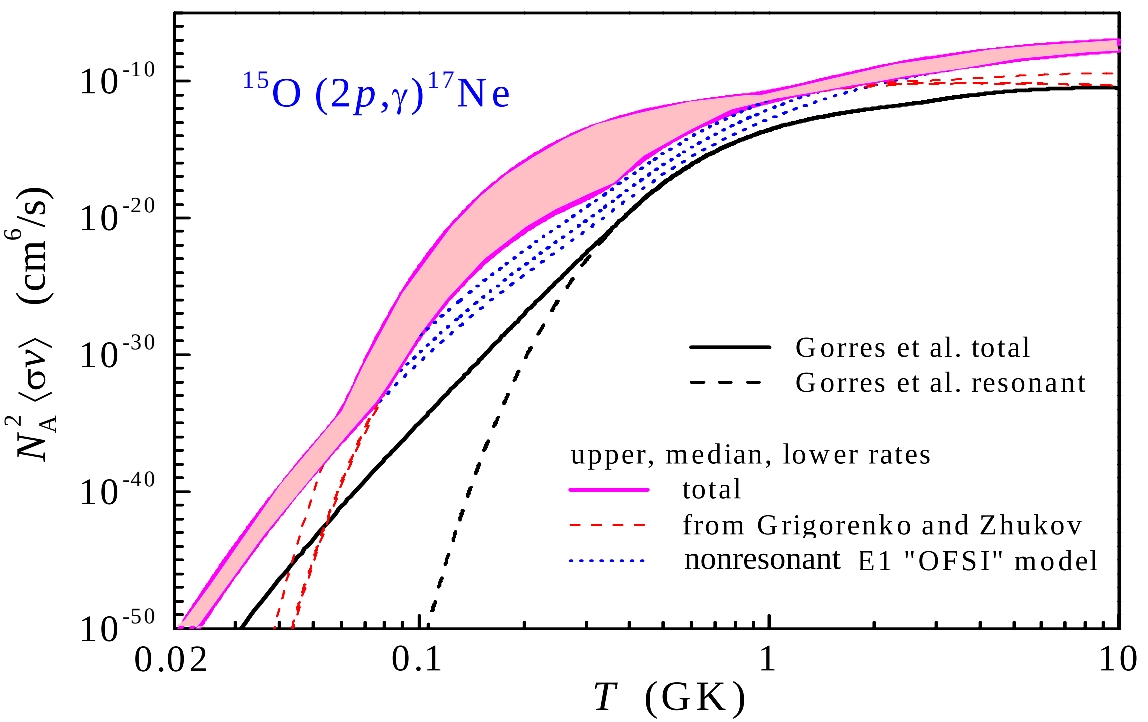
CD Experiments

$^{15}O(2p,\gamma)^{17}Ne$:

Possible breakout of the CNO cycle during rp-process

J.Görres, M.Wiescher, and F.-K.Thielemann, PRC 51 (1995) 392

CD measurement carried out at GSI in 2007: **$^{17}Ne(\gamma,2p)^{15}O$**

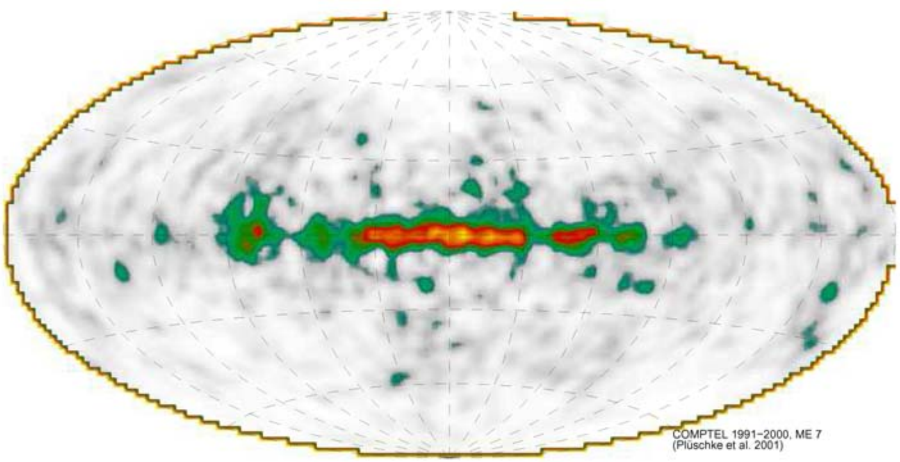


CD Experiments

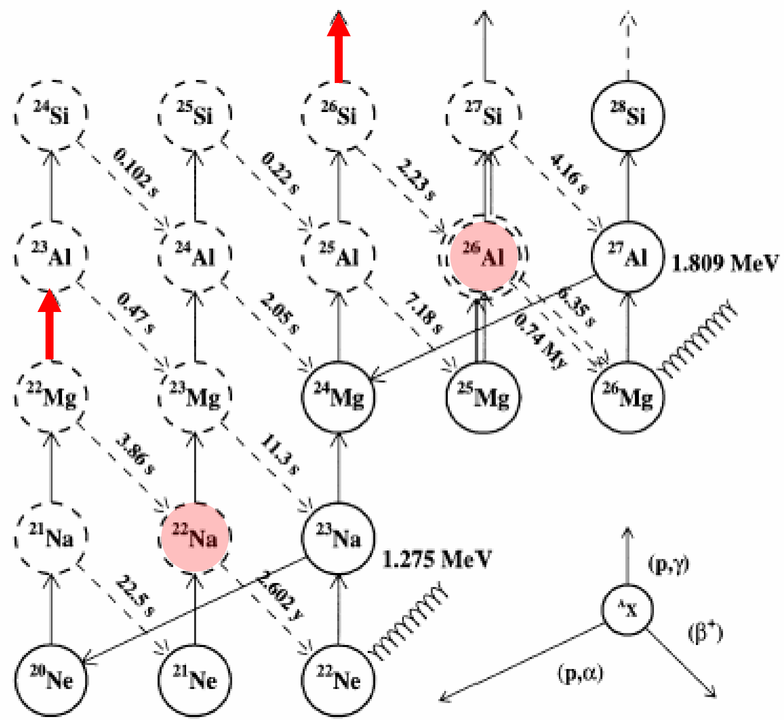
^{26}Si(p,γ)^{27}P and ^{22}Mg(p,γ)^{23}Al:
Possible bypass for production of long-lived radioactive nuclei ^{22}Na and ^{26}Al in hot hydrogen burning environments.

Ideal cases to be studied via CD because of low Q-value and isolated resonances.

Measurement carried out at GSI in 2007.



COMPTEL observation

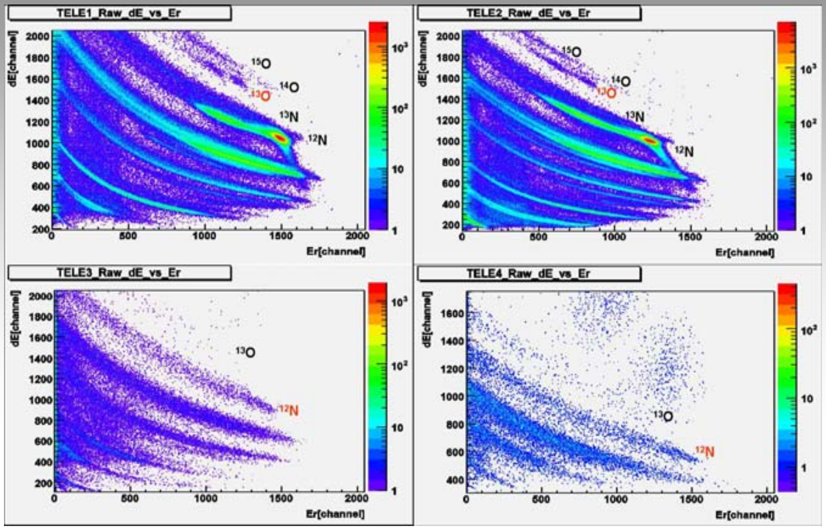


ANC's measured by the Texas A & M group with radioactive beams

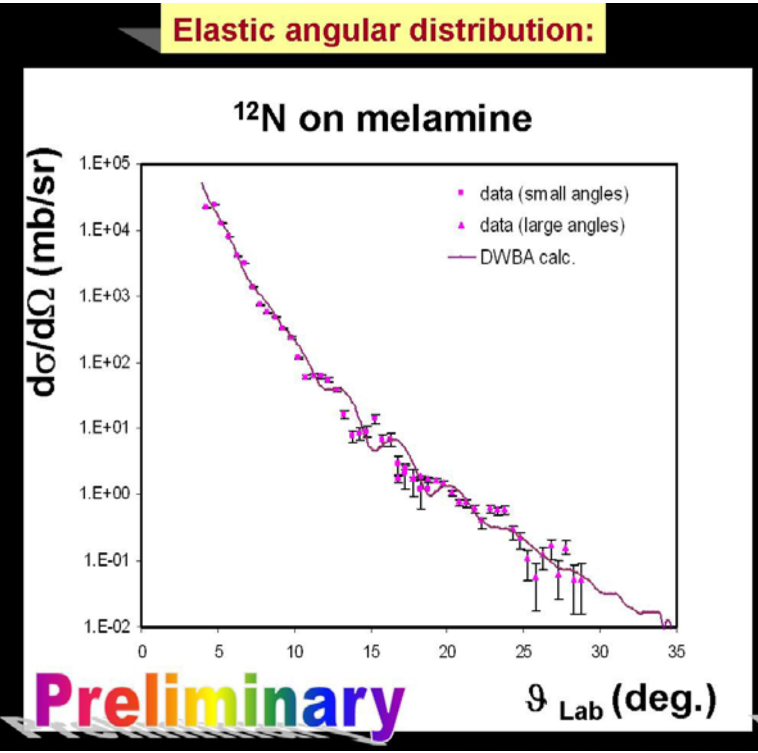
- $^{7}Be + p \leftrightarrow {}^{8}B$ [$^{10}B(^{7}Be,^{8}B)^{9}Be$] $^{7}Be(p,\gamma)^{8}B$
  [$^{14}N(^{7}Be,^{8}B)^{13}C$]
- $^{11}C + p \leftrightarrow {}^{12}N$ [$^{14}N(^{11}C,^{12}N)^{13}C$] $^{11}C(p,\gamma)^{12}N$
- $^{12}N + p \leftrightarrow {}^{13}O$ [$^{14}N(^{12}N,^{13}O)^{13}C$] $^{12}N(p,\gamma)^{13}O$
- $^{13}N + p \leftrightarrow {}^{14}O$ [$^{14}N(^{13}N,^{14}O)^{13}C$] $^{13}N(p,\gamma)^{14}O$
- $^{17}F + p \leftrightarrow {}^{18}Ne$ [$^{14}N(^{17}F,^{18}Ne)^{13}C$] $^{17}F(p,\gamma)^{18}Ne$
  {ORNL (TAMU collaborator)}

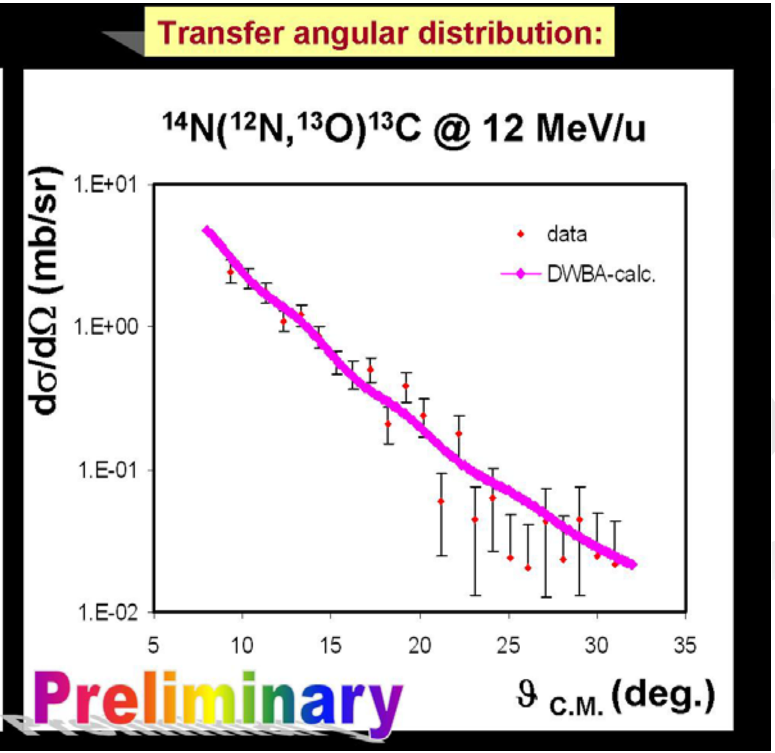
beam energies 10 - 12 A MeV

^{12}N @12 MeV on $N_6C_3H_6$ – May 2006



- ^{12}C @ 23 A MeV - 150 pnA
- ^{12}N @12 A MeV - 10^5 pps



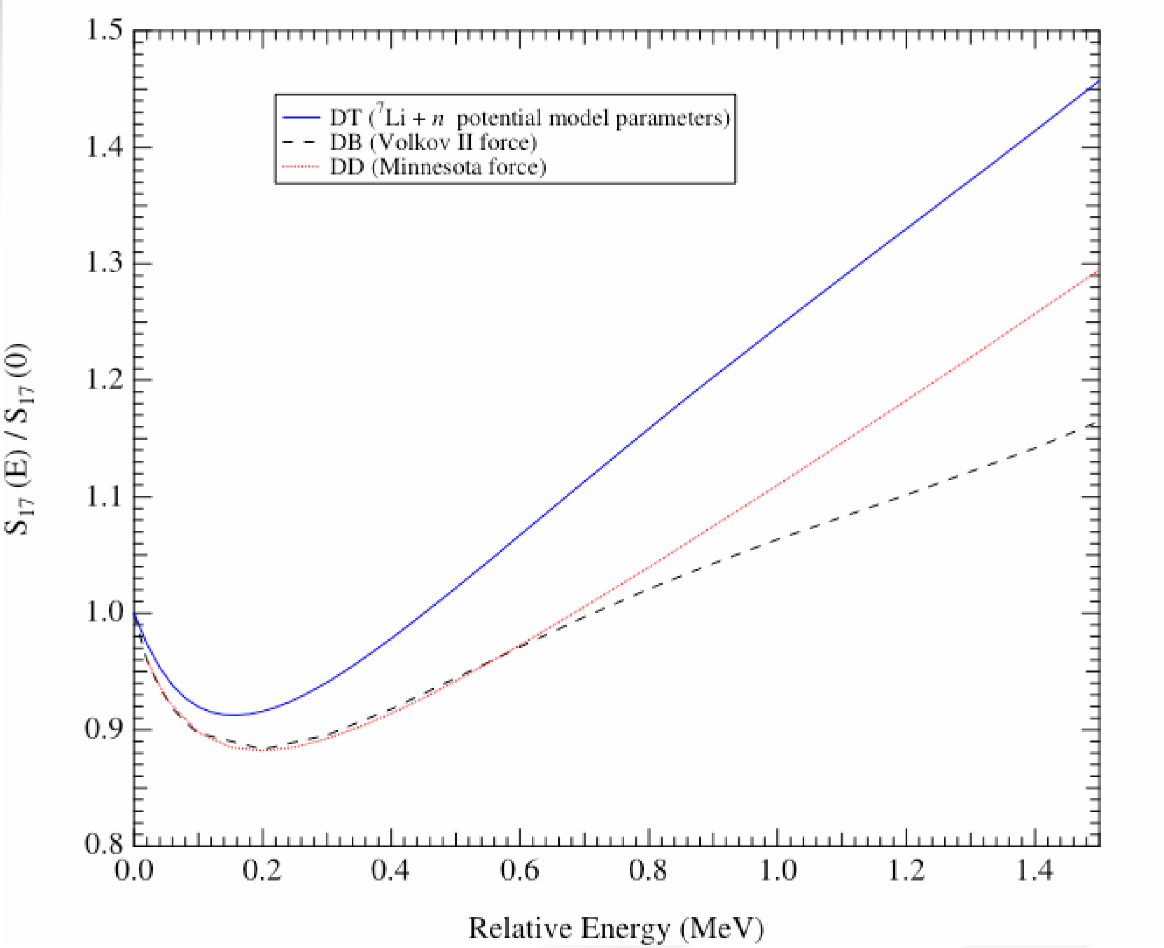


$C^2 \sim 3.3\ fm^{-1}$

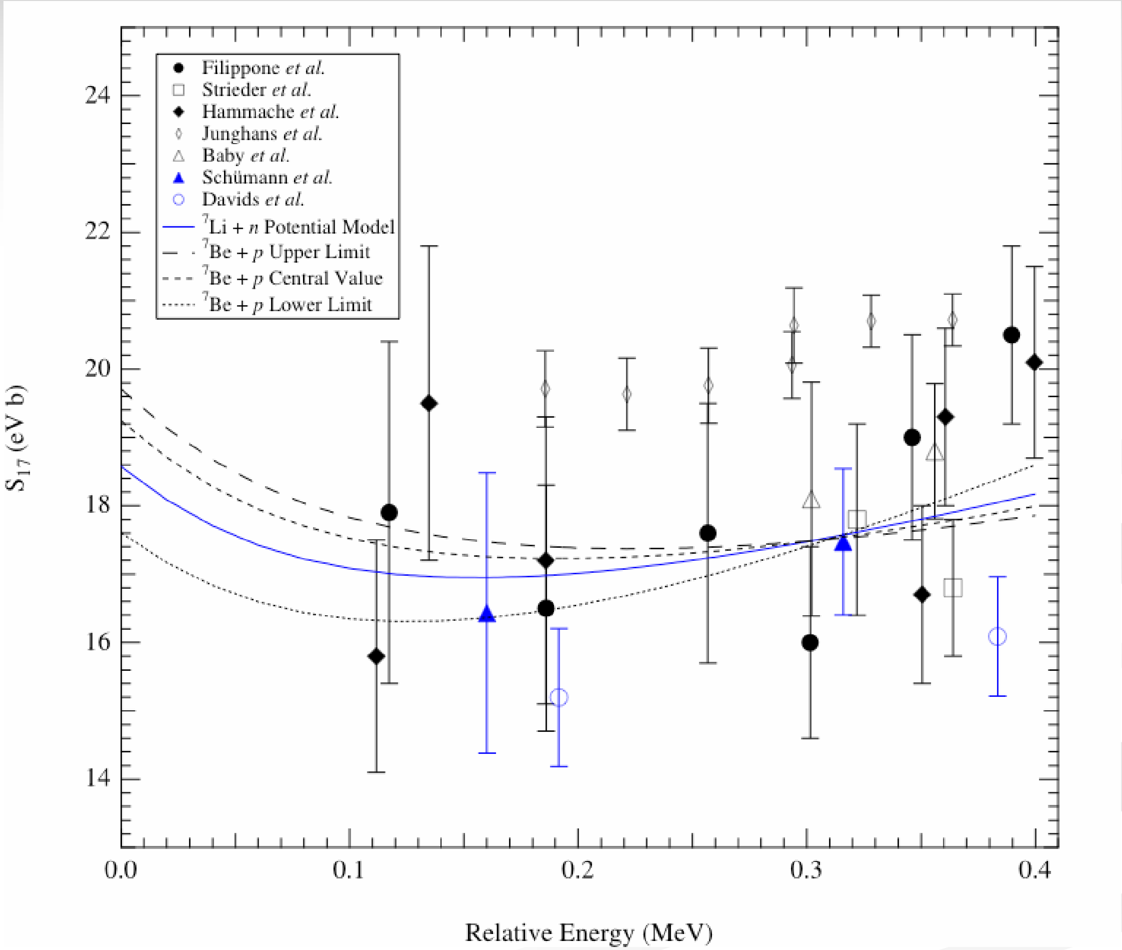
$^7Be(p,\gamma)^8B$ Reaction: Remaining Uncertainties

- High energy solar ν flux directly proportional to rate of this reaction
- Cyburt, Davids, and Jennings examined theoretical and experimental situation in 2004
- Must extrapolate measurements at accessible energies to very low, experimentally inaccessible energies
- Extrapolation is model-dependent
- Even below 400 keV, GCM cluster model of Descouvemont and potential model based on $^7Li + n$ scattering lengths of Davids & Typel differ by 7%

Extrapolation



The Data



Filippone et al.
Strieder et al.
Hammache et al.
Junghans et al.
Baby et al.
Schümann et al.
Davids et al.
^{7}Li + n Potential Model
^{7}Be + p Upper Limit
^{7}Be + p Central Value
^{7}Be + p Lower Limit
S_{17} (eV b)
Relative Energy (MeV)
0.0
0.1
0.2
0.3
0.4
14
16
18
20
22
24

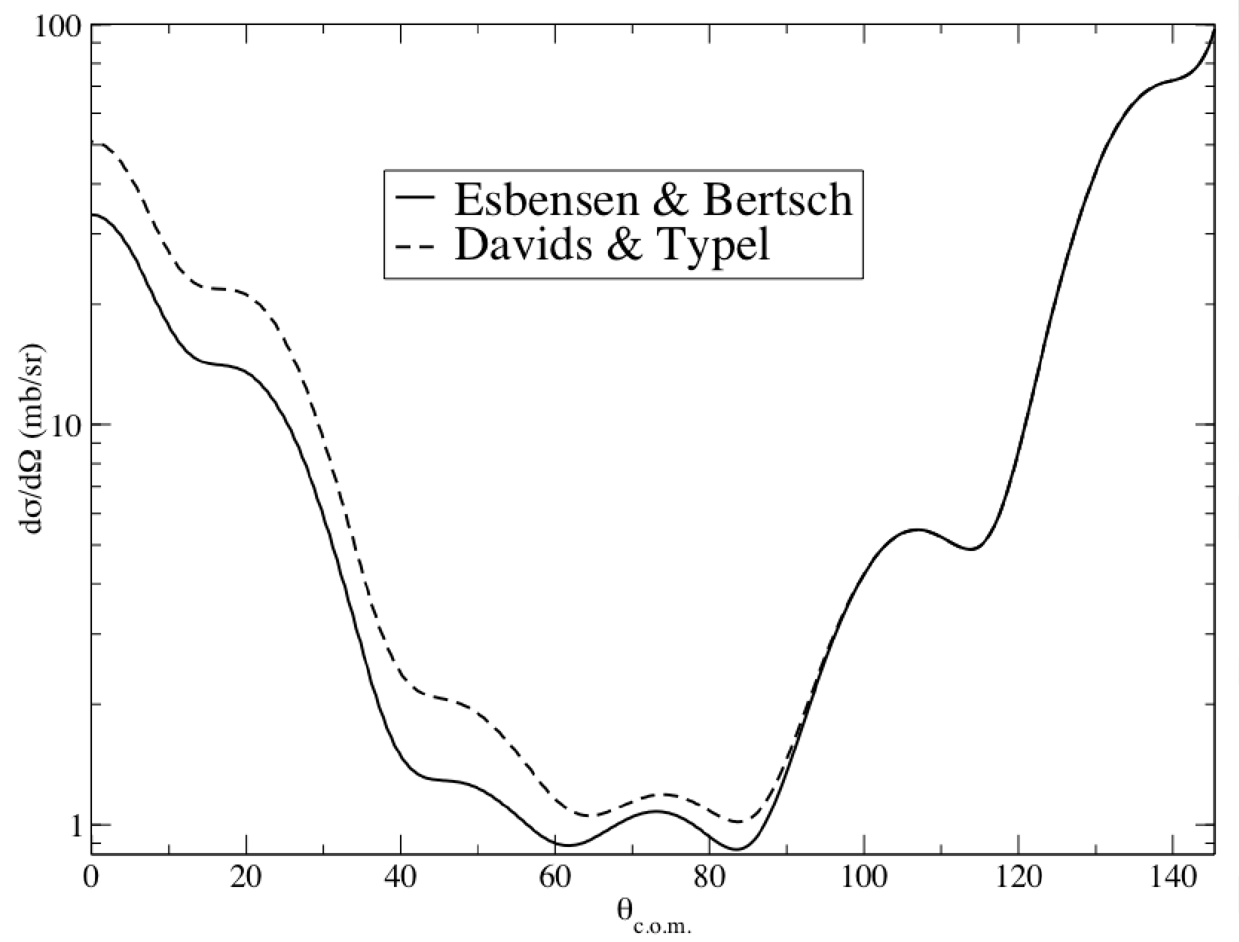
Mirror Asymptotic Normalization Coefficients

- Timofeyuk, Johnson, and Mukhamedzhanov have shown that charge symmetry implies a relation between the ANC's of 1-nucleon overlap integrals in light mirror nuclei
- Charge symmetry implies relation between widths of narrow proton resonances and ANC's of analog neutron bound states

TRIUMF Experiment (2006)

- Measure ANC's of the valence neutron in ^{8}Li via the elastic scattering/transfer reaction $^{7}Li(^{8}Li,^{7}Li)^{8}Li$ at 11 MeV
- Interference between elastic scattering and neutron transfer produces characteristic oscillations in differential cross section
- Amplitudes of maxima and minima yield ANC

Calculations by Sam Wright

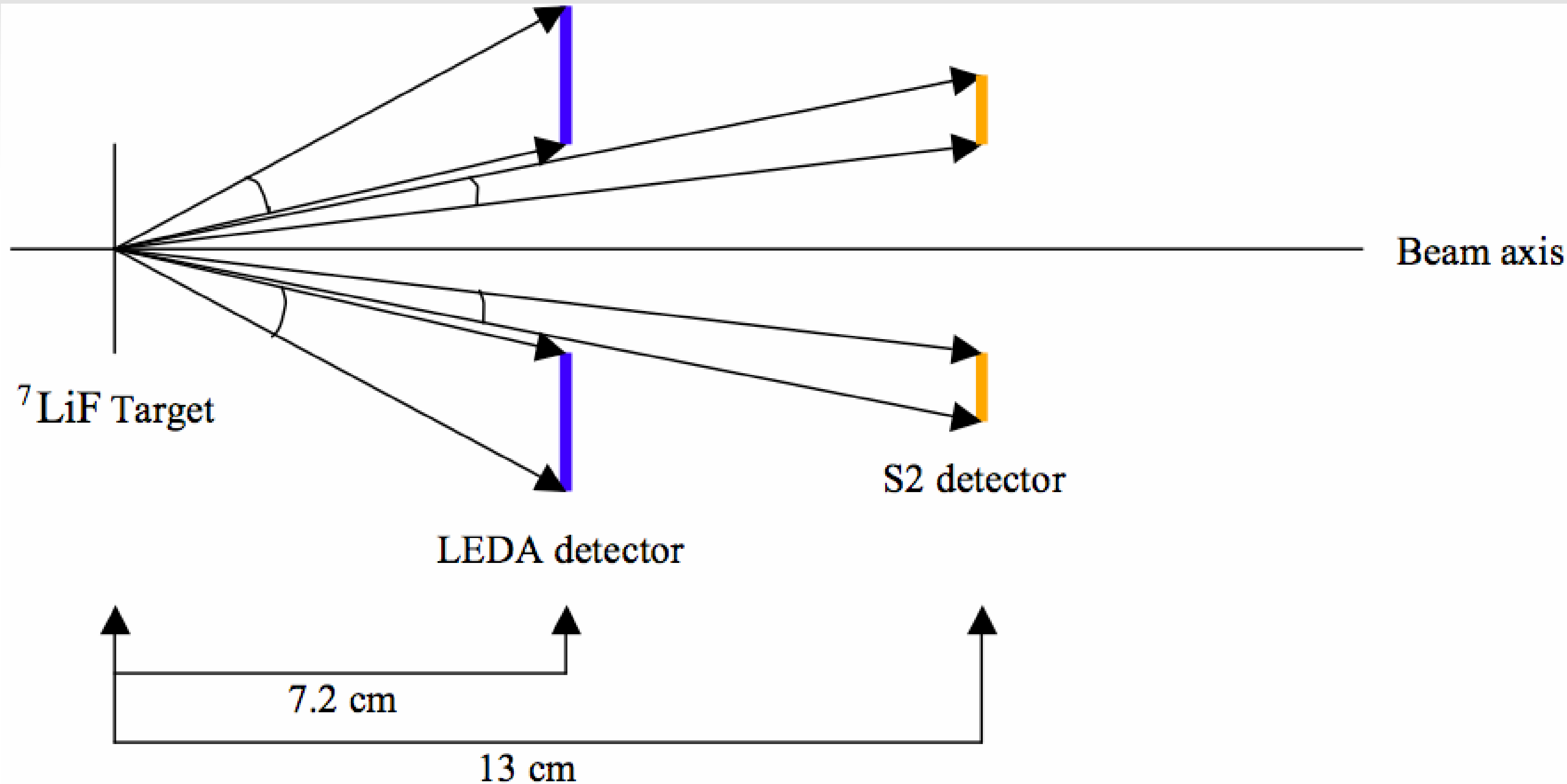


$^{7}Li(^{8}Li,^{7}Li)^{8}Li$

Advantages of the Method

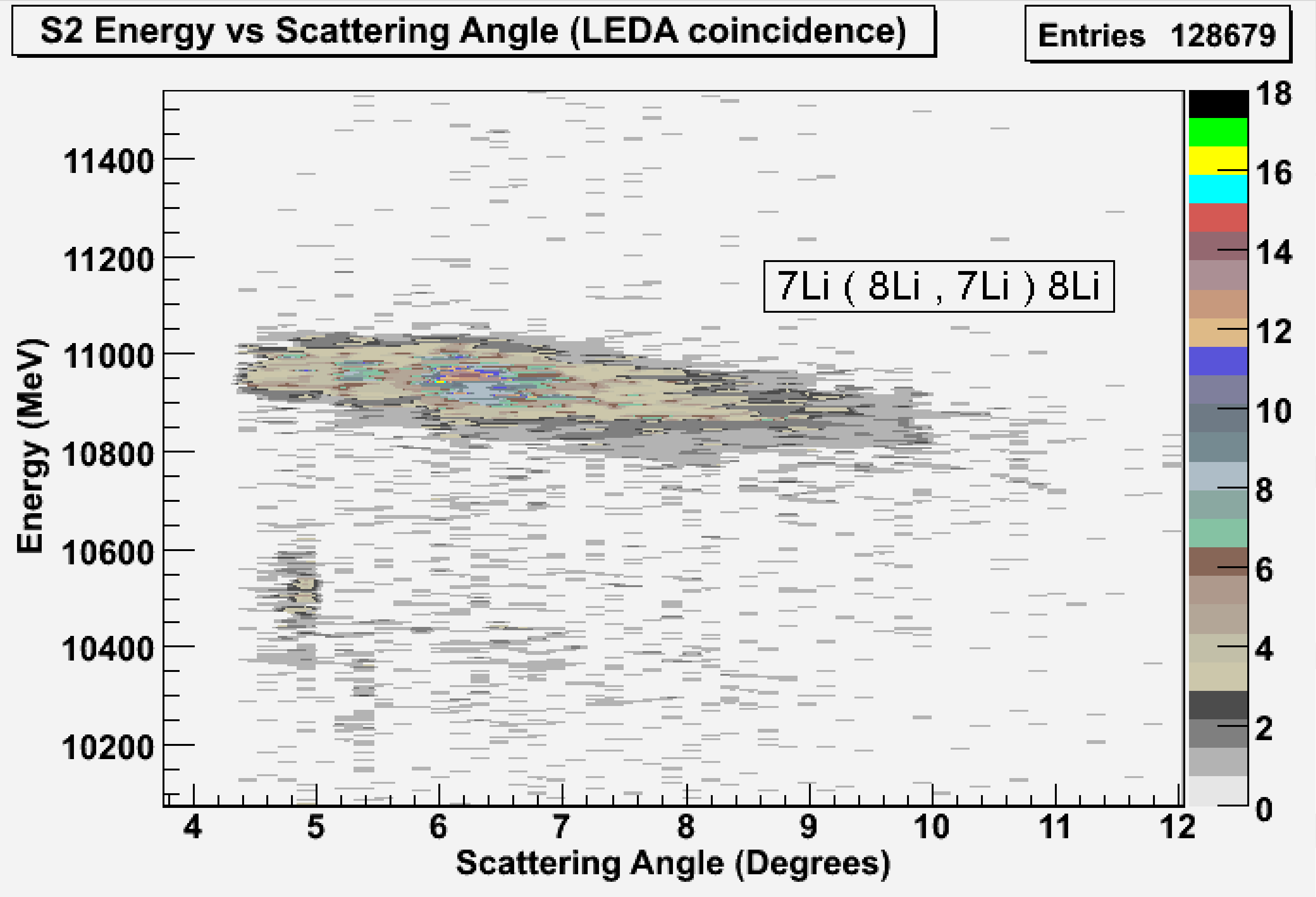
- Identical initial and final states => single vertex is involved
- Statistical precision greater (compared with distinct initial and final states)
- Single optical model potential needed
- Elastic scattering measured simultaneously
- Absolute normalization of cross section enters only as a higher-order effect in ANC determination

Experimental Setup



^{8}Li beam intensities of 2-4 × 10^7 s^{-1}

^{8}Li ANC via $^{7}Li(^{8}Li,^{7}Li)^{8}Li$



TRIUMF/Simon Fraser University Collaboration (Howell)

Summary

- Direct (p,γ) and/or (p,α) reaction rate measurements with radioactive beams performed at Oak Ridge, TRIUMF
- Direct radioactive beam studies of half lives, neutron emission probabilities at NSCL
- Indirect RIB reaction studies for asymptotic normalization coefficients, excitation energies, spins, and parities at GSI, Oak Ridge, NSCL, RIKEN, Texas A & M, TRIUMF