# Direct Reactions and Decay Spectroscopy using the MSU High Resolution Array

**HiRA core collaboration**

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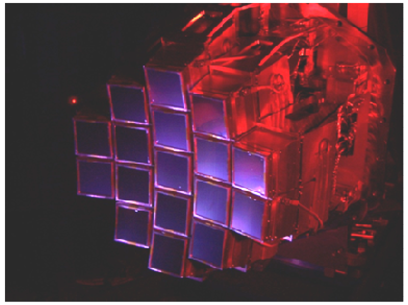
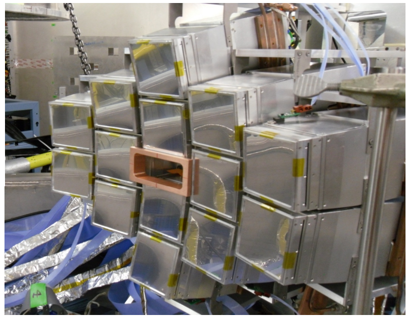
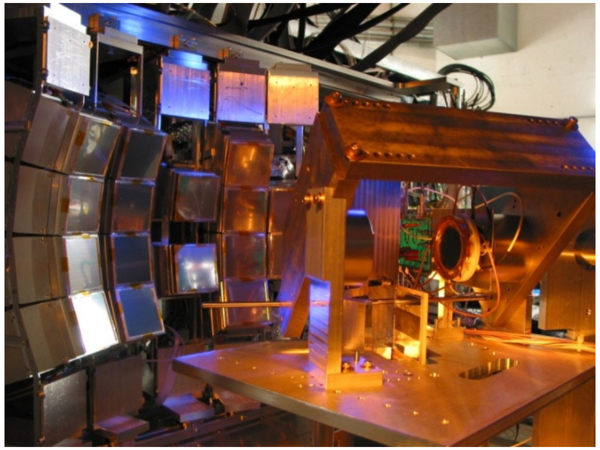
**INFN, Milan** **Arialdo Moroni**

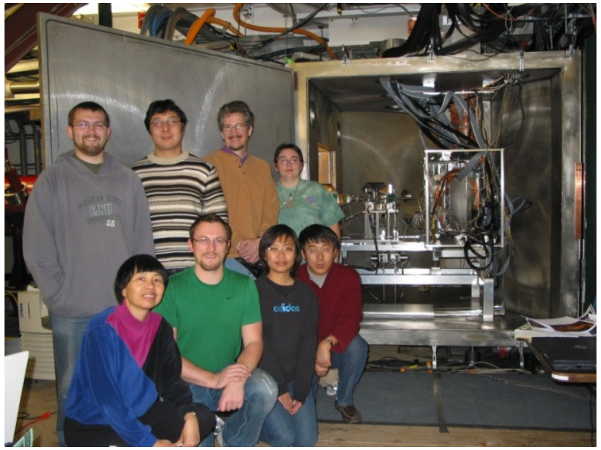
**Western Michigan University** **Mike Famiano**

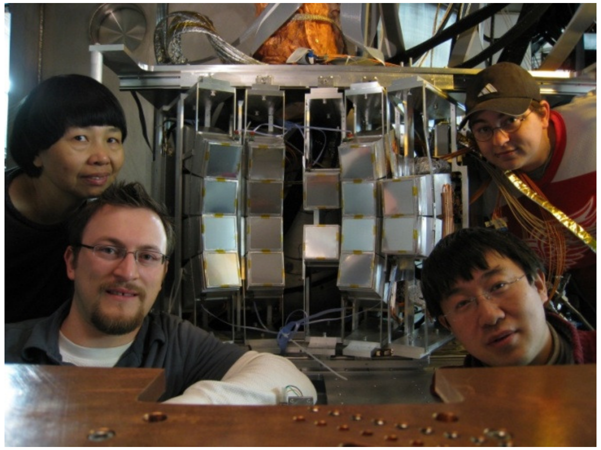
**ORNL** **Dan Shapira**







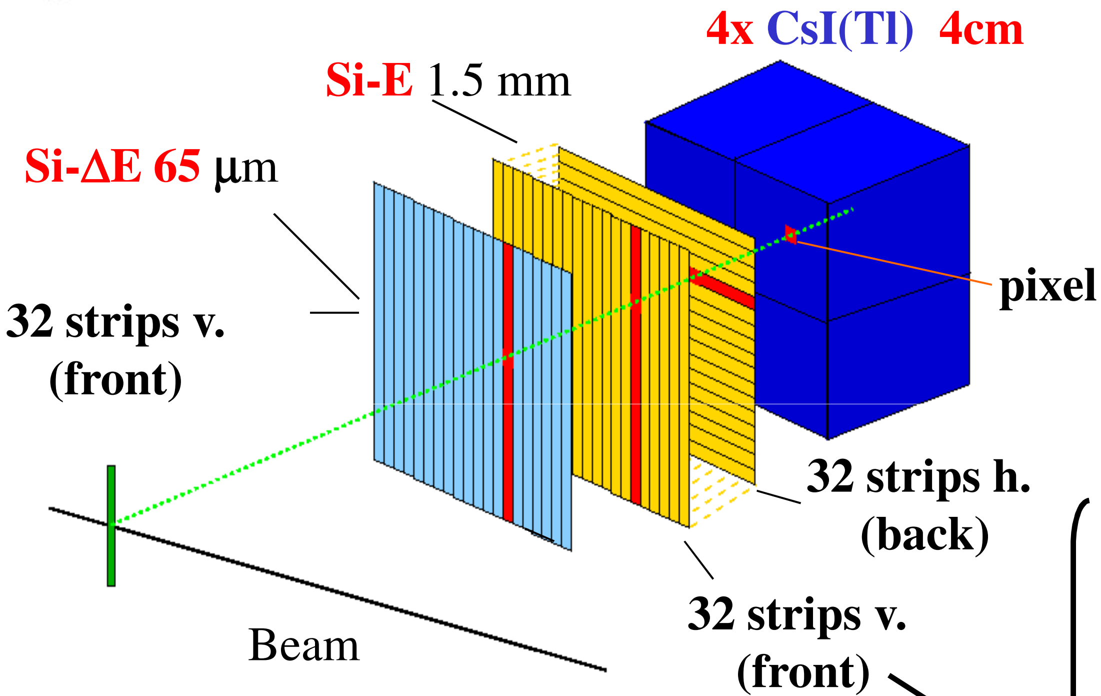


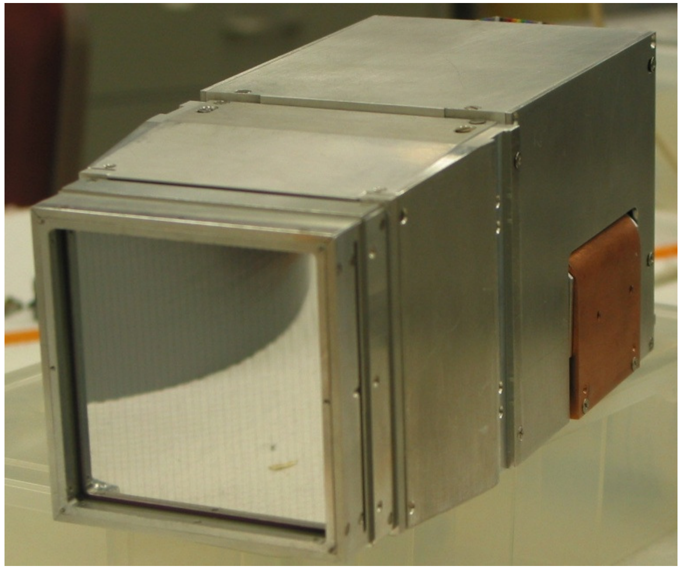


**Jenny Lee**
*RIKEN , Nishina Center*

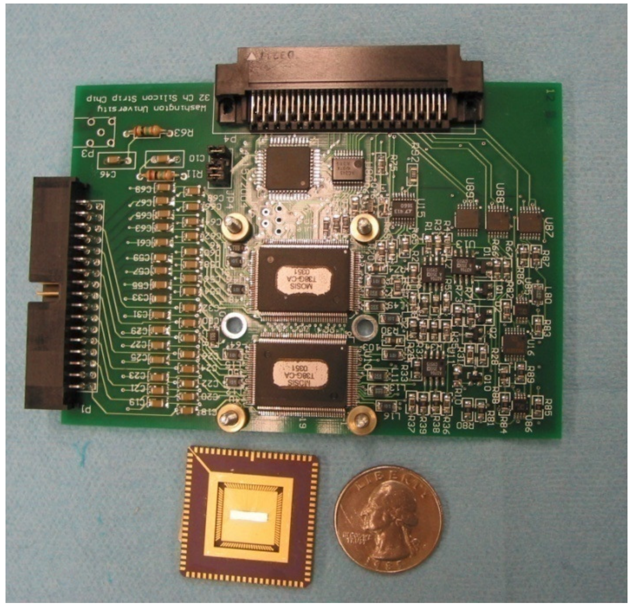
**DREB2012**
**March 26-29, 2012**

# HiRA
High Resolution Array



**1920 Channels → ASIC readout**
16 channels per chip



**up to 20 Telescopes**

**62.3 x 62.3 mm$^2$ active area**

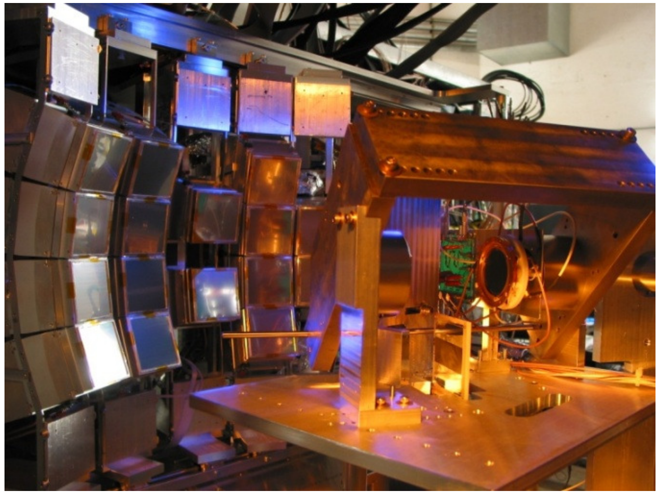
**strip pitch 2 mm**

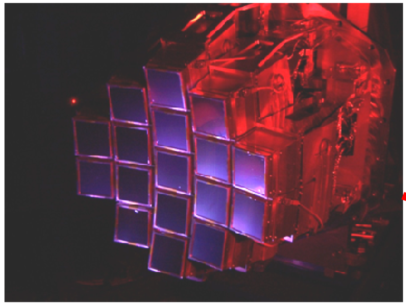
**1024 Pixels per telescope**

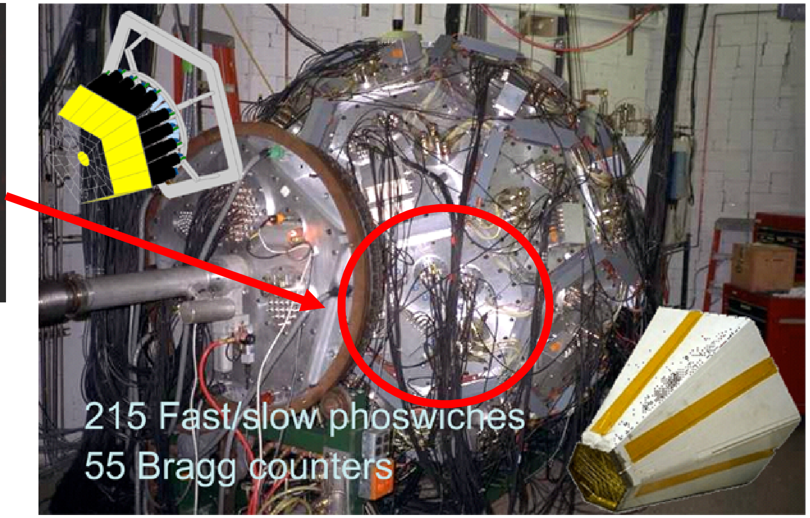
@ 35 cm from target => Δθ~0.16°

# HiRA Scientific Results (2005-2011)

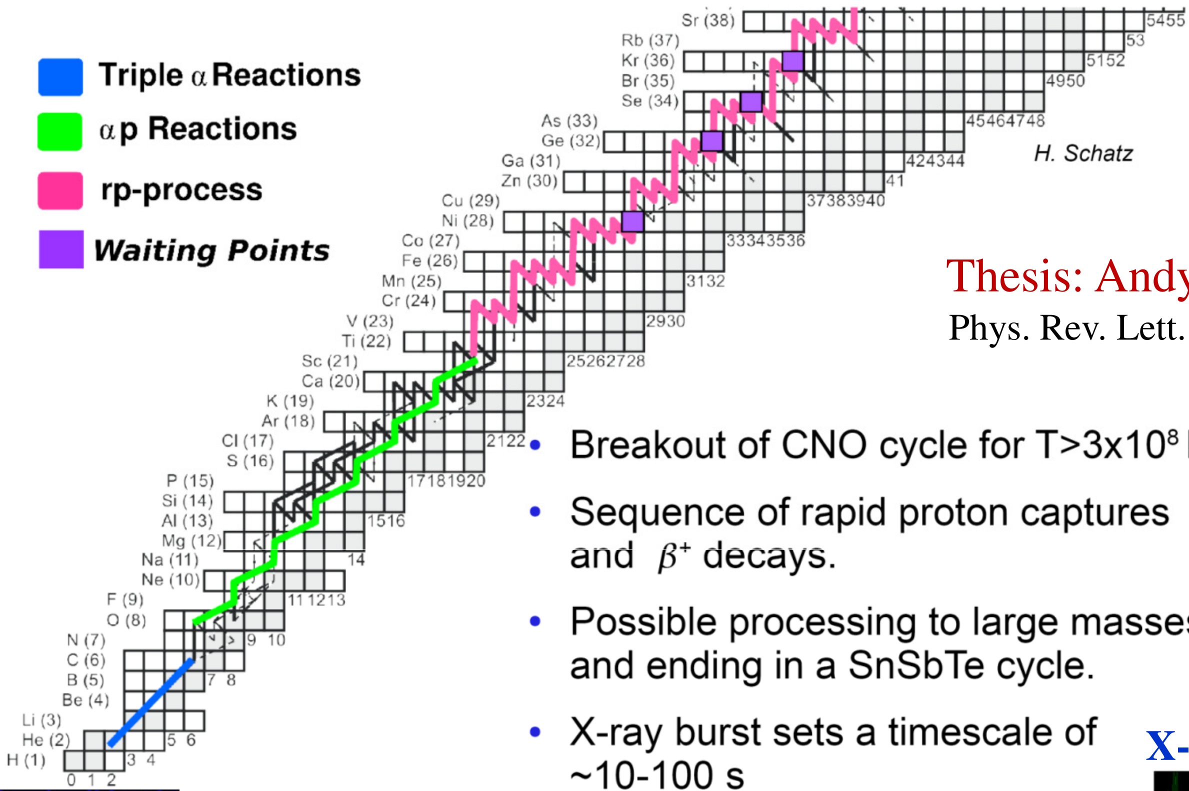
- Mass of *rp*-process waiting point nucleus $^{69}$Br (Andy Rogers)
- Transfer reactions: $^{34,46}$Ar(p,d), $^{56}$Ni(p,d), (d, $^{3}$He), $^{84}$Se(p,d) (Jenny Lee, Alisher Sanetullaev, Tilak Ghosh)
- Proton knockout reactions (Danel Bazin)
- Particle unbound state: 2 p decay in $^{10}$C & 4p+α decay in $^{9}$C.
  - (Bob Charity & Lee Sobotka)
- Spectra and two particle correlations (Micha Kilburn et al)







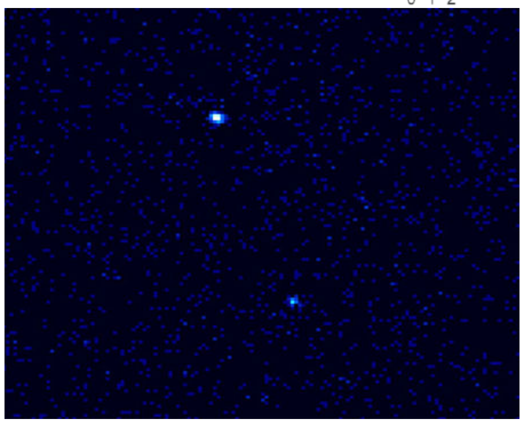
# First HiRA exp.: rp- process nucleo-synthesis




Thesis: Andy Roger (2009)

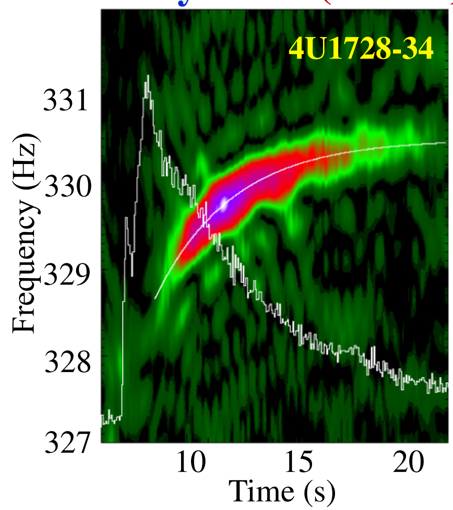
Phys. Rev. Lett. 106, 252503 (2011)

- Breakout of CNO cycle for $T>3\times10^8$ K
- Sequence of rapid proton captures and $\beta^+$ decays.
- Possible processing to large masses and ending in a SnSbTe cycle.
- X-ray burst sets a timescale of ~10-100 s



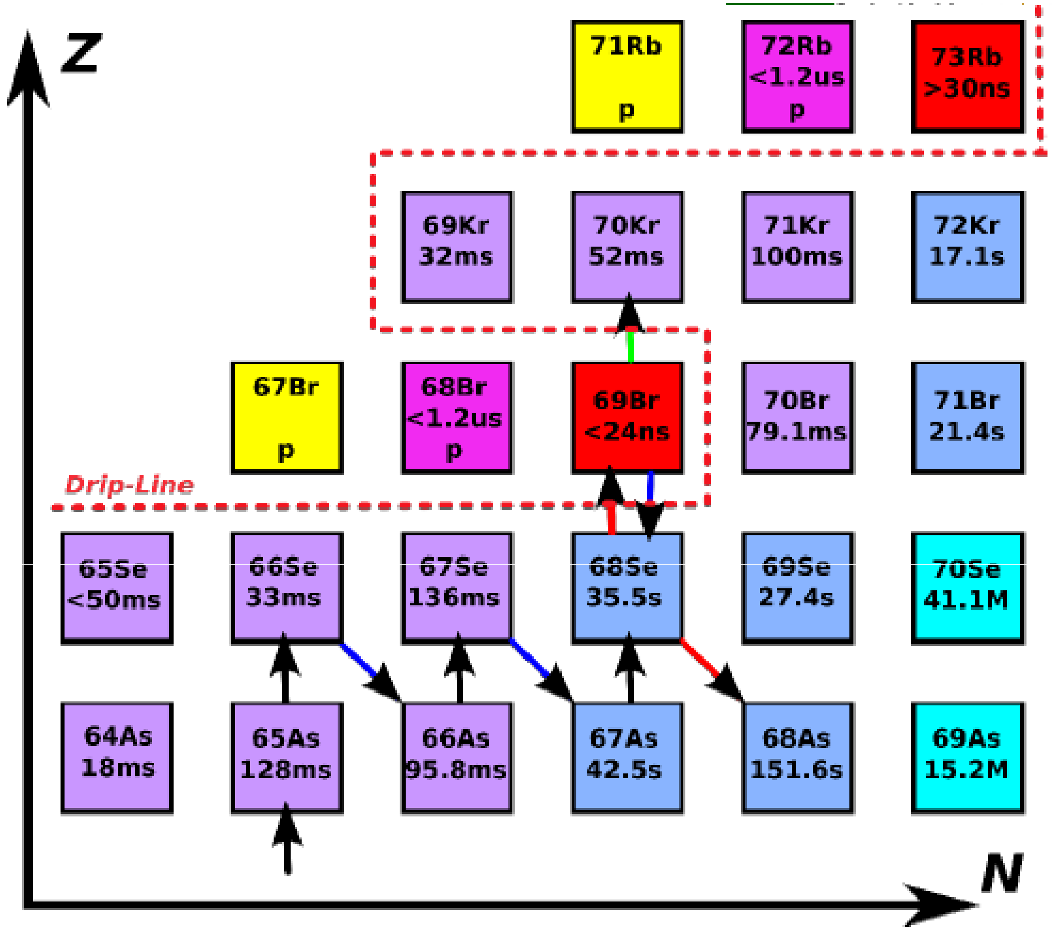
In a binary system including a neutron star, hydrogen accreted from companion star ignites and burns via rp process leading to X-ray burst.

X-ray burst (RXTE)



# $^{68}$Se waiting point

- $T_{1/2}$=35.5s and $^{69}$Br is unbound.
- Bypass of waiting point via sequential 2p-capture to $^{70}$Kr.
- $S_p$ determines proton-capture and ($\gamma$,p) processes.




$$N_{69} \approx N_p N_{68} e^{S_p/\tau} \qquad \frac{dN_{70}}{dt} \approx N_{69} \cdot \langle \sigma \nu \rangle$$

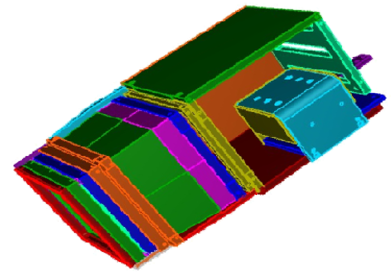
- Two proton capture through $^{69}$Br depends exponentially on proton separation energy $S_p$.

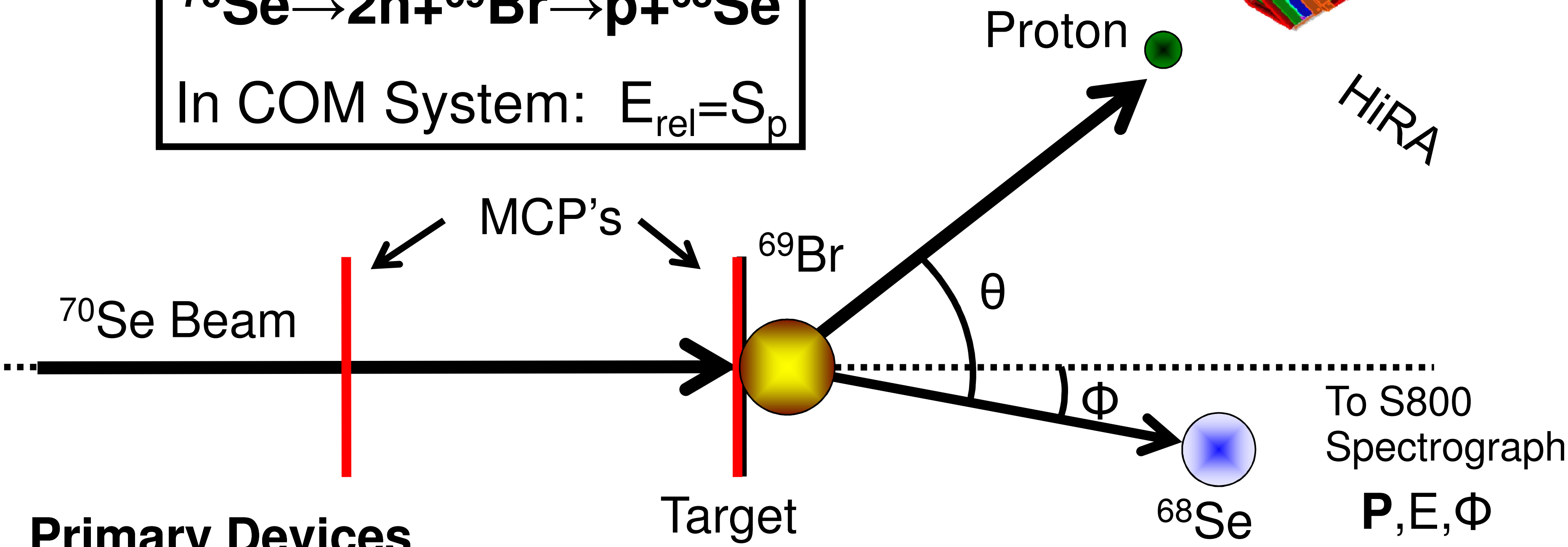
# Experimental Technique

## Direct Measurement of ground-state one-proton decay from $^{69}$Br

$^{70}Se \rightarrow 2n + ^{69}Br \rightarrow p + ^{68}Se$

In COM System: $E_{rel} = S_p$




**Primary Devices**

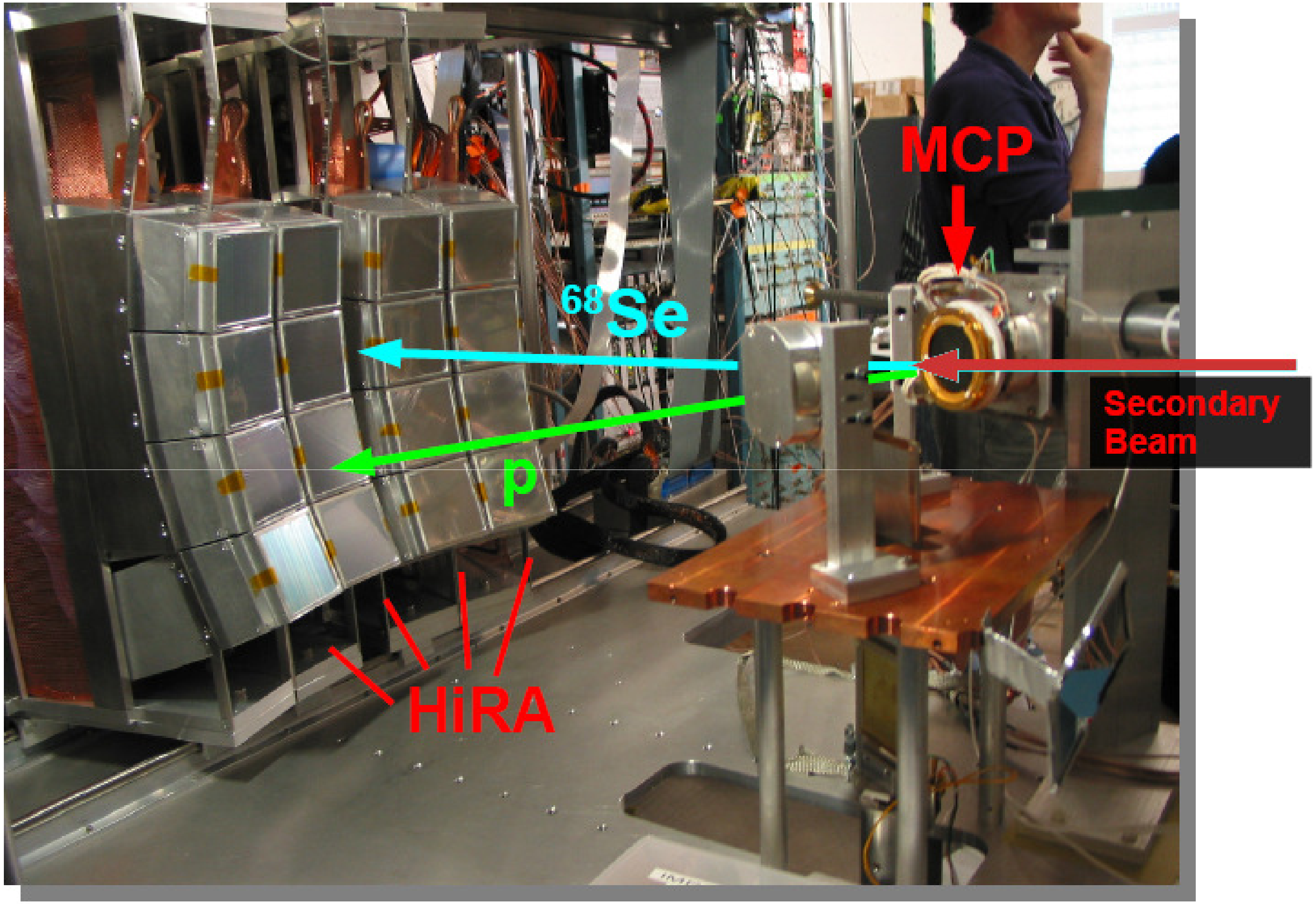
1. **High Resolution Array**
2. **S800 Spectrograph**
3. **Micro Channel Plates**

✓ **Complete Kinematics**

✓ **Invariant-mass method**
→ **Particle-decaying State**

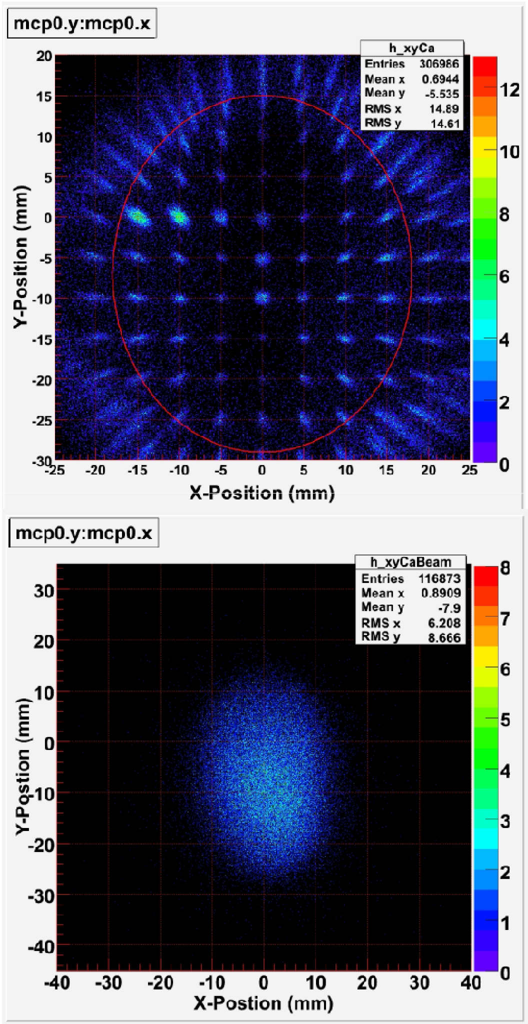
Andrew M. Rogers (2009 thesis)

# Experimental Setup



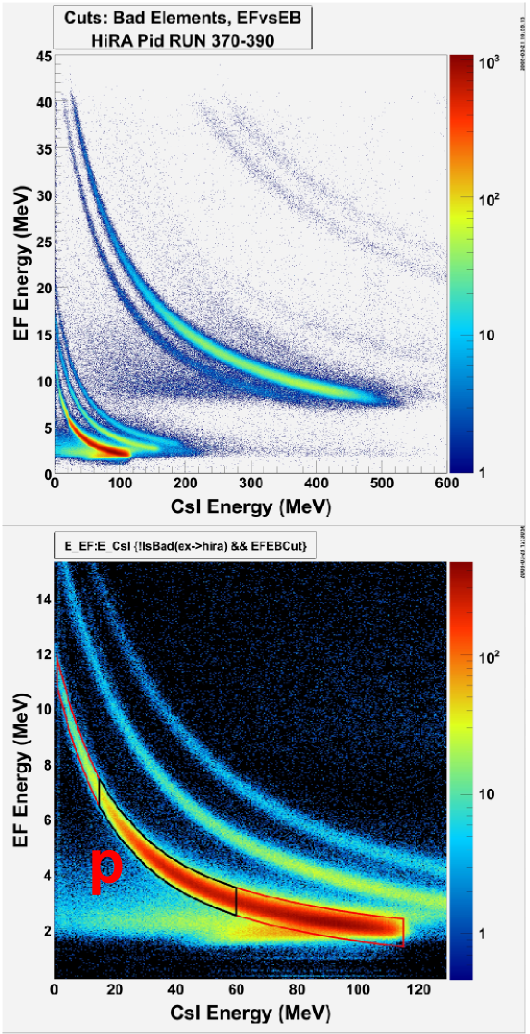

Separation energy is determined by calculating the decay energy $E_{rel}$ in the p+$^{68}$Se C.M. system, where: $S_p = - E_{rel}$

# Detectors and Calibrations




**Beam Tracking**

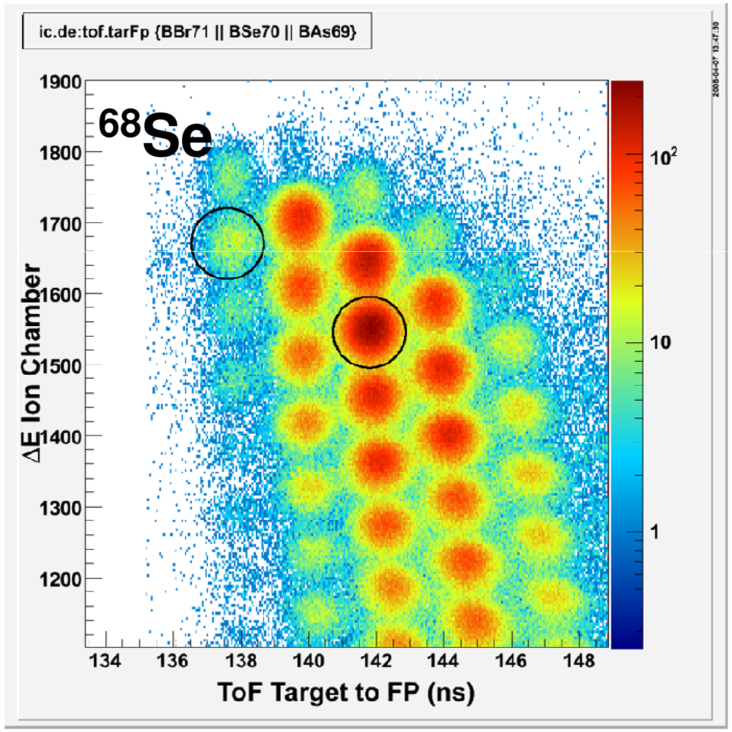
Beam Resolution ~ **1mm**




**Protons**

PID using ΔE-E
Si Resolution: **≈ 70 keV FMHM**
CsI Resolution: **≈ 800 keV**

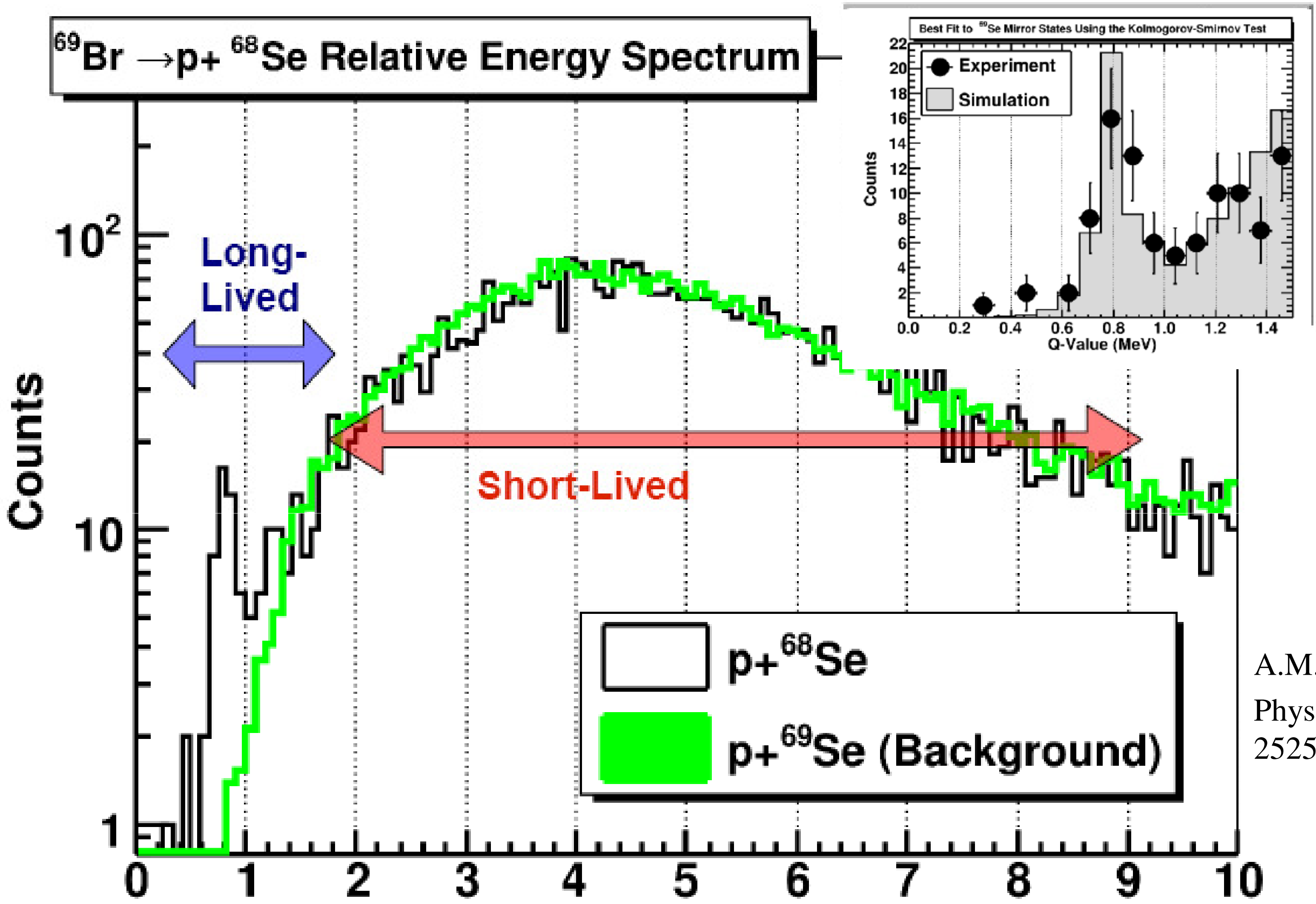
$^{70}Se \rightarrow 2n + {}^{69}Br \rightarrow p + {}^{68}Se$




**Heavy Products**

PID using ΔE-ToF method.
Good isotopic separation.
Measurement of E, **P**, and θ

# Decay spectrum in the p+$^{68}$Se system




A.M. Rogers et al., Phys. Rev. Lett. 106, 252503 (2011)

- The peak corresponds to the proton separation energy of $^{69}$**Br,** assuming the structure of its mirror, $^{69}$Se. **$S_p$=-785±27 keV**
- The large (negative) $S_p$ → rp-process probably terminates at $^{68}$Se

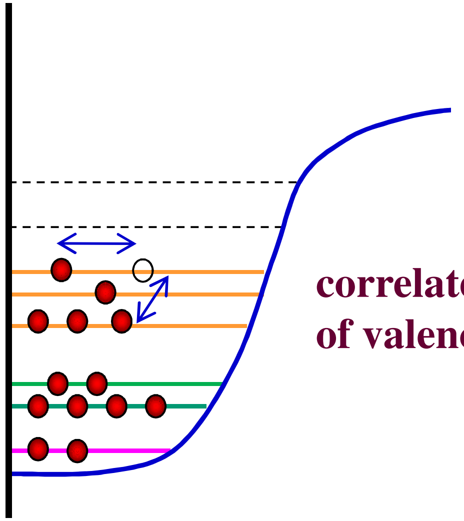
# Nuclear Structure Study with Transfer Reactions

**Transfer Reactions:**

✓ Determine masses and excitation energies from complete kinematics reactions

✓ Obtain spectroscopic information such as ℓ-values from angular distributions

✓ Extract Spectroscopic Factors → single-particle strengths & correlation effects



**correlated motions of valence nucleons**

***Establish a systematic way to extract consistent SF's using 50 year of transfer reaction data***

$$\left(\frac{d\sigma}{d\Omega}\right)_{EXP} = SF_{EXP}\left(\frac{d\sigma}{d\Omega}\right)_{Theo}$$

← **ADWA**

$$SF_{exp}/SF_{SM} < 1$$

**Some correlations missing in the interactions (shell model) ?**

**Large Basis Shell Model**

$$H = \sum_i \left(\frac{\vec{p}_i^{\,2}}{2m} + U(r_i)\right) + \sum_{i<j} V_{NN}(\vec{r}_i - \vec{r}_j) - \sum_i U(r_i)$$

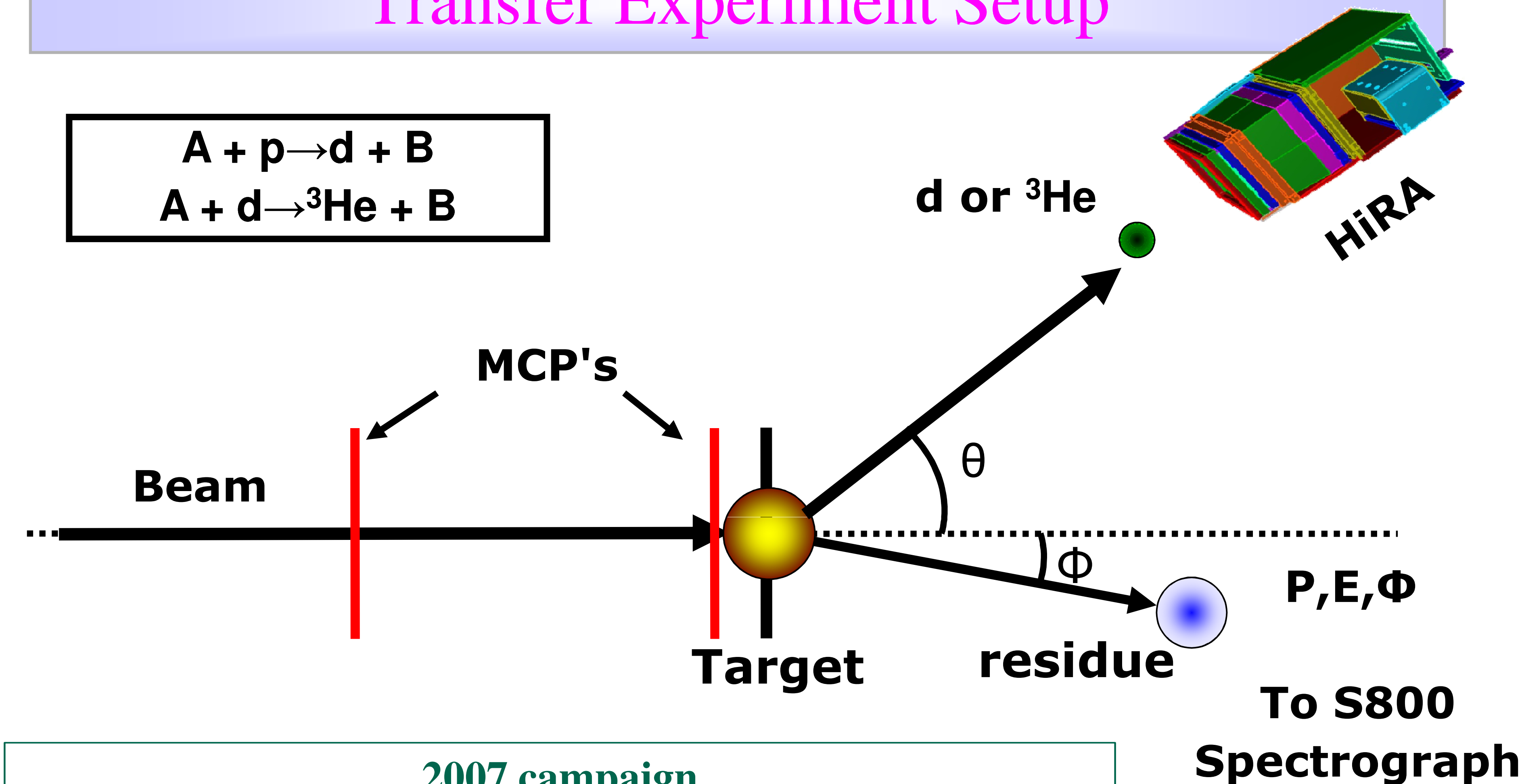
**Mean field** **Residual interactions**

***How much ? What is the Asymmetry Dependence of nucleon correlations?***

# Transfer Experiment Setup

$A + p \rightarrow d + B$

$A + d \rightarrow {}^{3}He + B$




**2007 campaign**

*$p({}^{34,36,46}Ar, d){}^{33,35,45}Ar$ ; $p({}^{56}Ni, d){}^{55}Ni$; E/A~35 MeV*

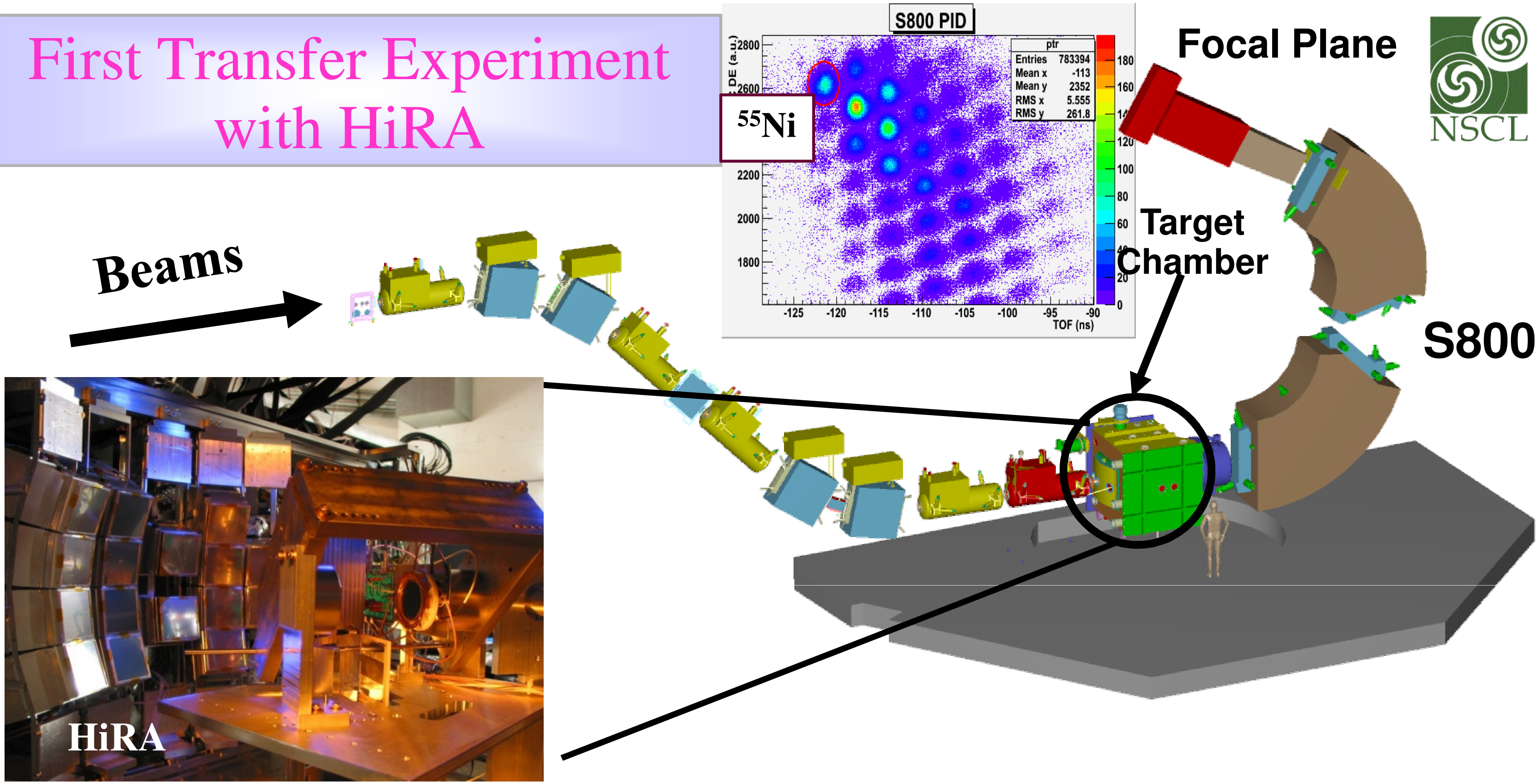
**2010 campaign**

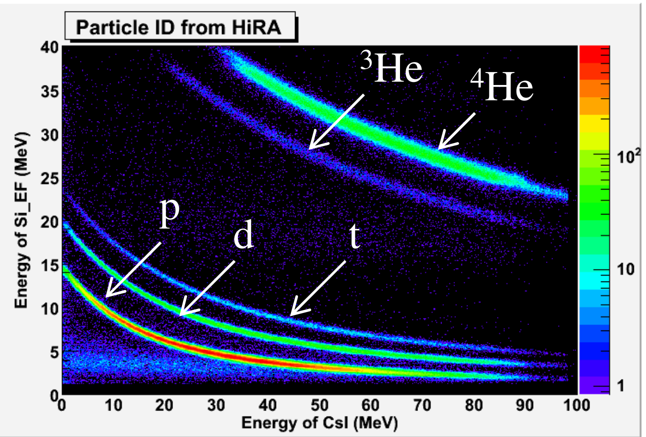
*$p({}^{86}Kr, d){}^{85}Kr$; $p({}^{84}Se, d){}^{83}Se$; E/A~40MeV*

*$p({}^{56}Ni, d){}^{55}Ni$; $p({}^{56}Ni, d){}^{55}Ni$; $d({}^{56}Ni, {}^{3}He){}^{55}Co$; E/A~80MeV*

NSCL

# First Transfer Experiment with HiRA




***HiRA: Excellent Isotopes Identification***

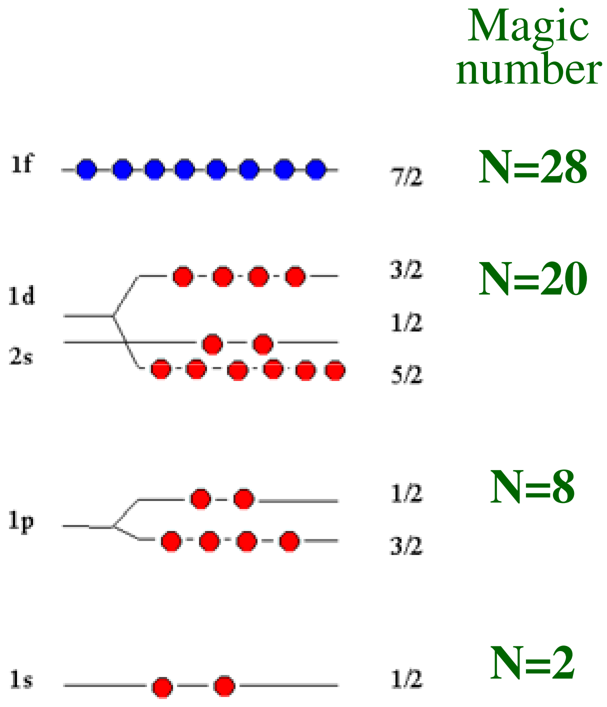
***2007 campaign***

*$p(^{34,36,46}Ar, d)^{33,35,45}Ar$; E/A~35 (Jenny Lee 2010)*

*$p(^{56}Ni, d)^{55}Ni$; E/A~37 MeV; (Alisher Santullanev, 2011)*

# Nuclear Structure Study with (p,d) reactions

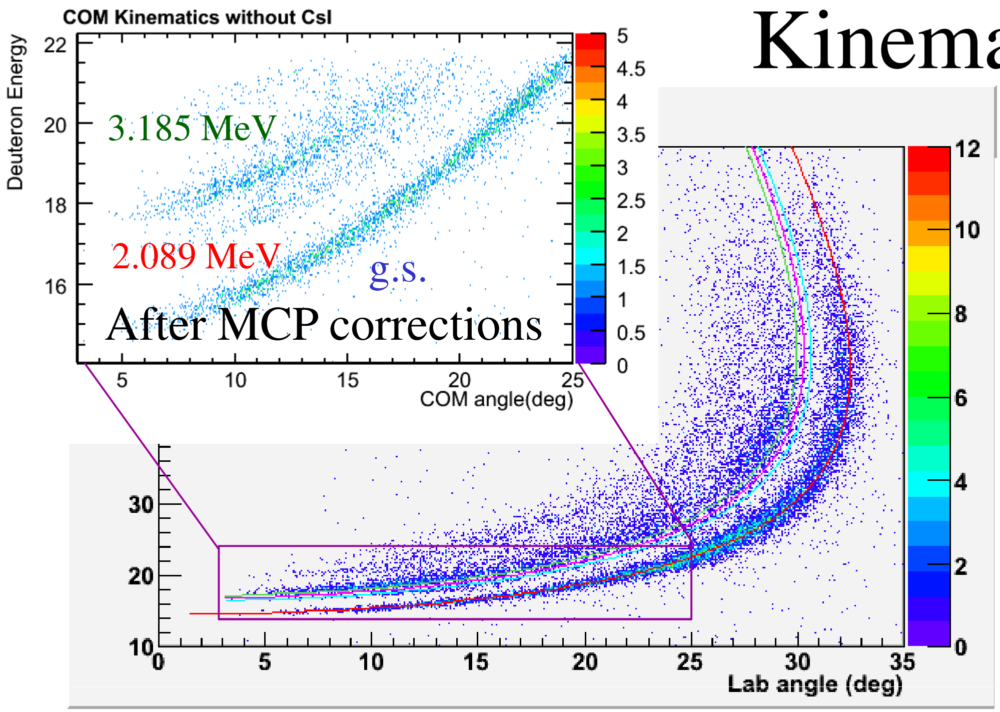
*(Alisher Santullanev, 2011)*

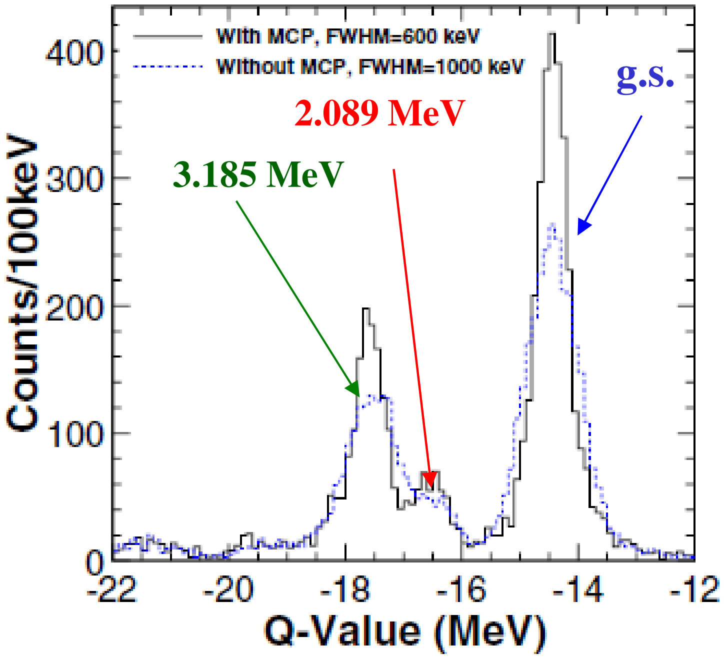



## Single Particle States in $^{56}$Ni

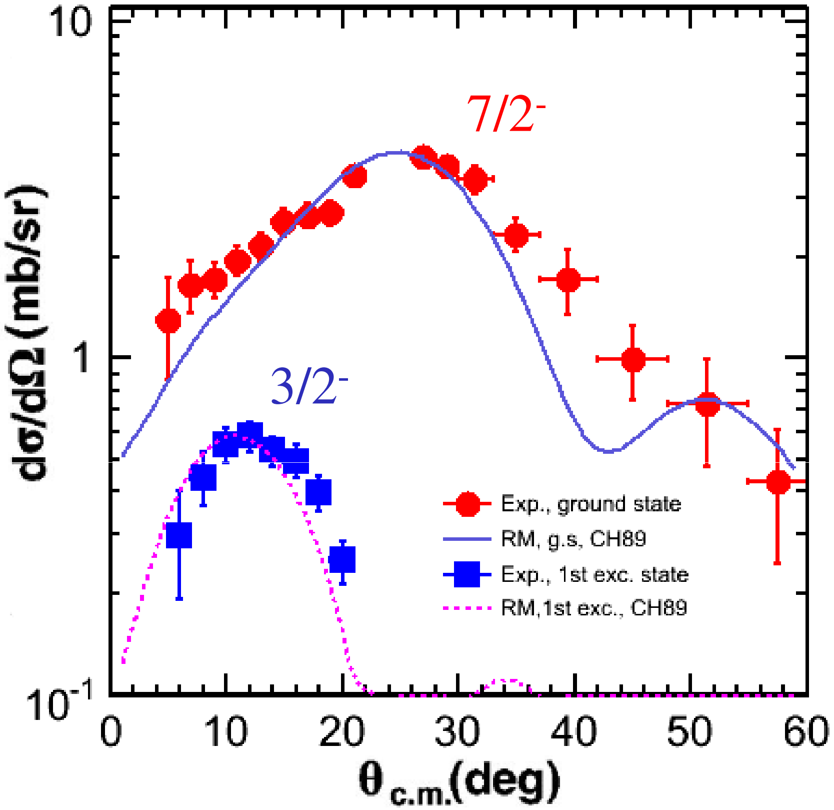
- $^{56}$Ni is the end product in many astrophysical models.
- First double magic nucleus that is unstable !
- How good is $^{56}$Ni a double magic nucleus ?
- $^{55}$Ni → No spectroscopic information about the first excited state at 2.09 MeV.

# Kinematics and Q-Value




***p(*** $^{56}$***Ni, d)*** $^{55}$***Ni; E/A~37 MeV***




| | SF(ex) | SF(SM) |
|---|---|---|
| g.s. | 7.0±0.7 | 6.78 |
| 2.09 MeV (unknown) | 0.13±0.01 | 0.18 |

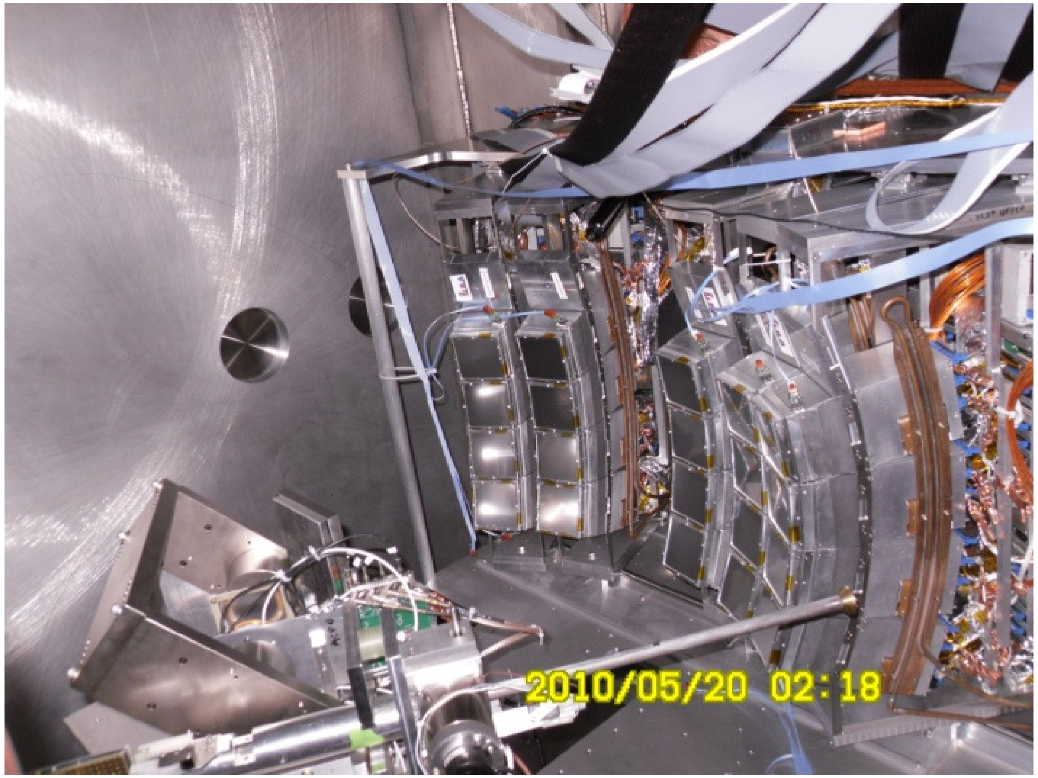
**Evolution of Neutron hole states in N=50 closed shells**

Rutgers +VECC+ MSU

**E/A=45 MeV**

$^{86}$**Kr + p → d +** $^{85}$**Kr**

$^{84}$**Se+ p → d +** $^{83}$**Se**




**Comparison of Spectroscopic Factors from (p,d) and Knockout**

VECC + MSU collaboration

**E/A=37 MeV**

$^{56}$**Ni + p→d +** $^{55}$**Ni**

**E/A=80 MeV**

$^{56}$**Ni + p→d +** $^{55}$**Ni**

**Comparison of proton and neutron spectroscopic factors in** $^{56}$**Ni**

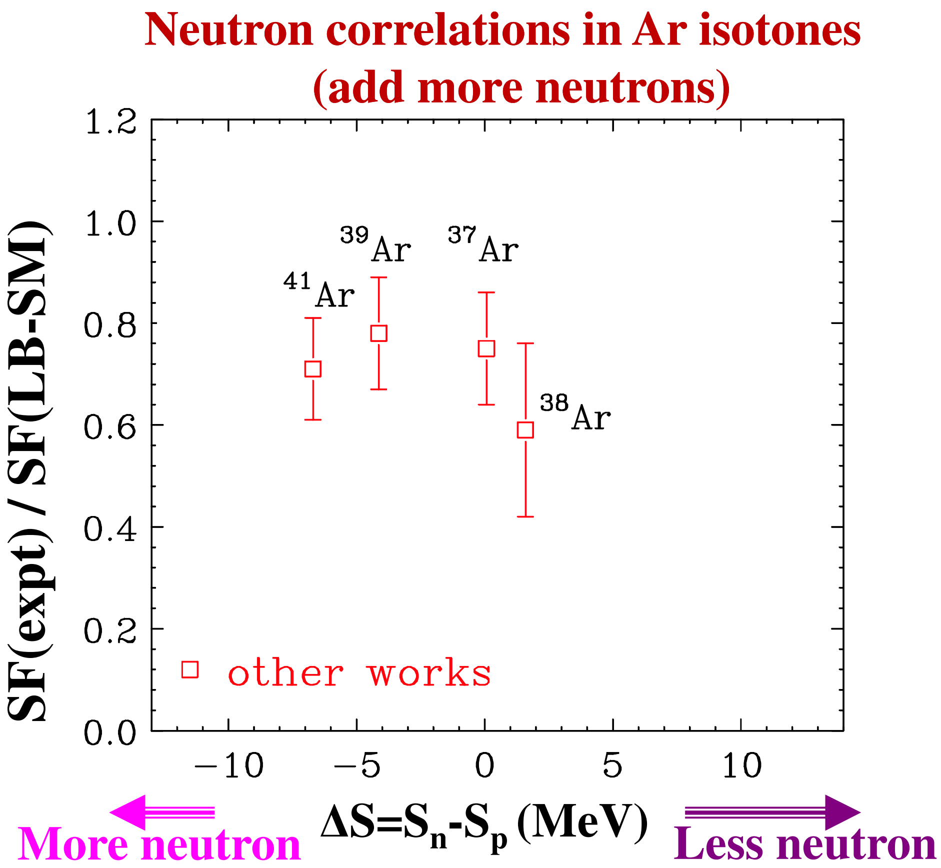
VECC + MSU collaboration

**E/A=80 MeV**

$^{56}$**Ni + p→d +** $^{55}$**Ni**

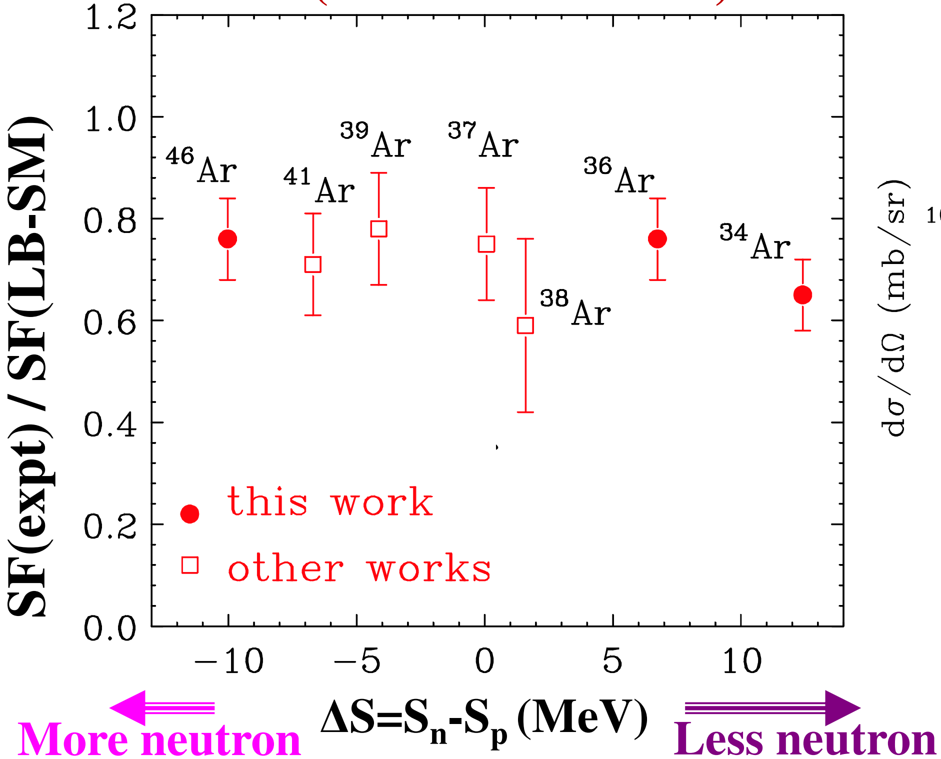
$^{56}$**Ni+ d→**$^{3}$**He +** $^{55}$**Co**

# Asymmetry Dependence of Shell Occupancies ?



# Asymmetry Dependence of Shell Occupancies ?

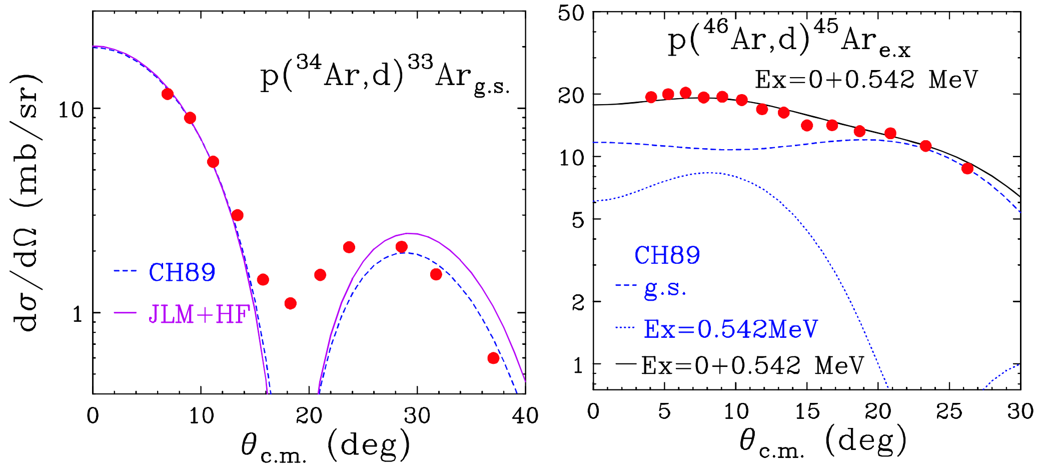
**Neutron correlations in Ar isotones (add more neutrons)**




J. Lee et al., Phys. Rev. Lett 104, 112701 (2010)

***p($^{34,36,46}$Ar,d) at 33 MeV/u***

Thesis: J. Lee, 2010

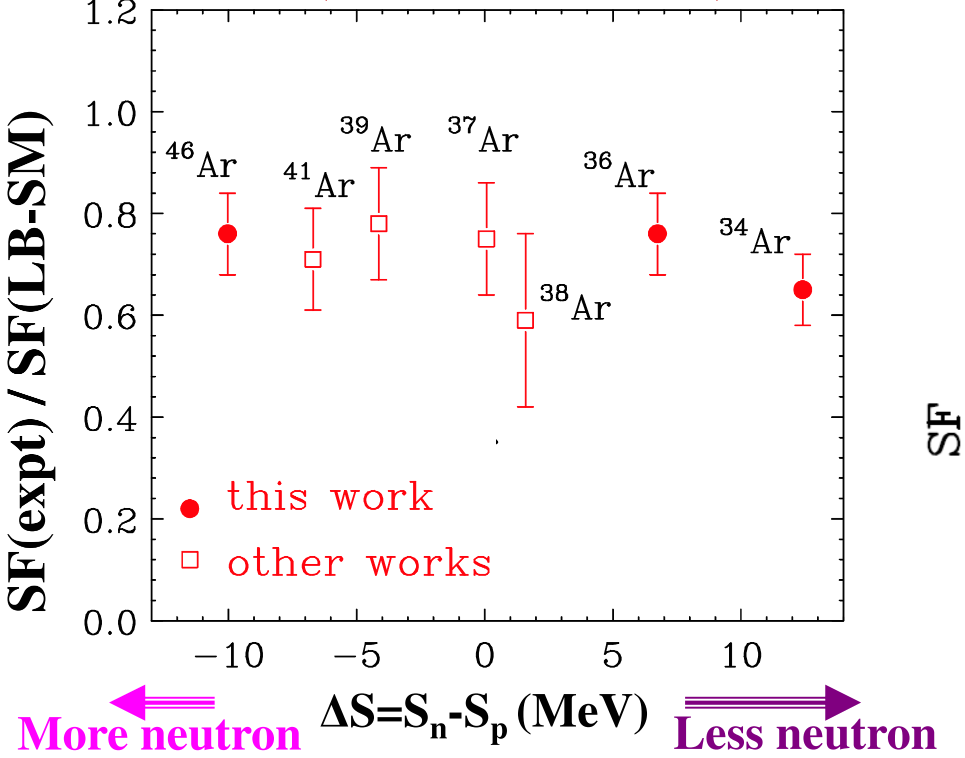



**Transfer Reactions:**

**Weak Asymmetry dependence of nucleon correlations**

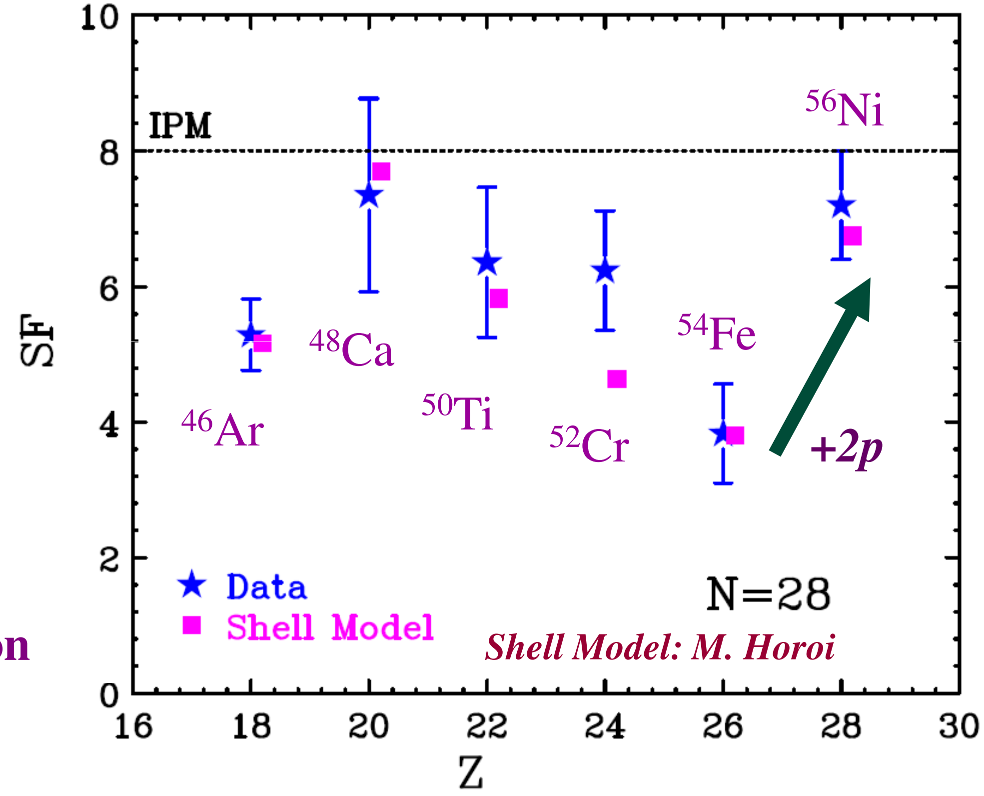
# Asymmetry Dependence of Shell Occupancies ?

**Neutron correlations in Ar isotones (add more neutrons)**




J. Lee et al., Phys. Rev. Lett 104, 112701 (2010)

**Neutron correlations in N=28 isotones (add more protons)**

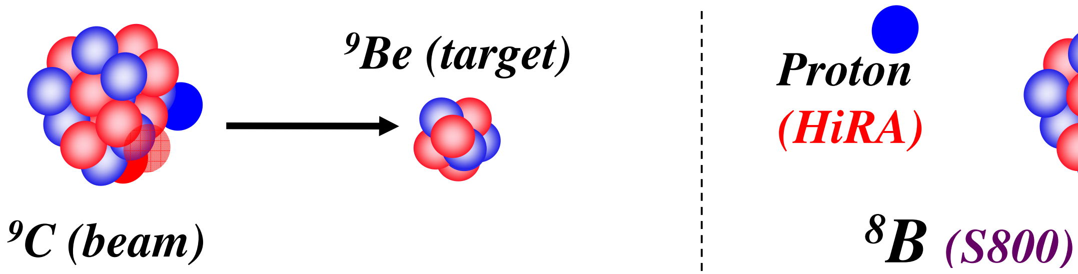


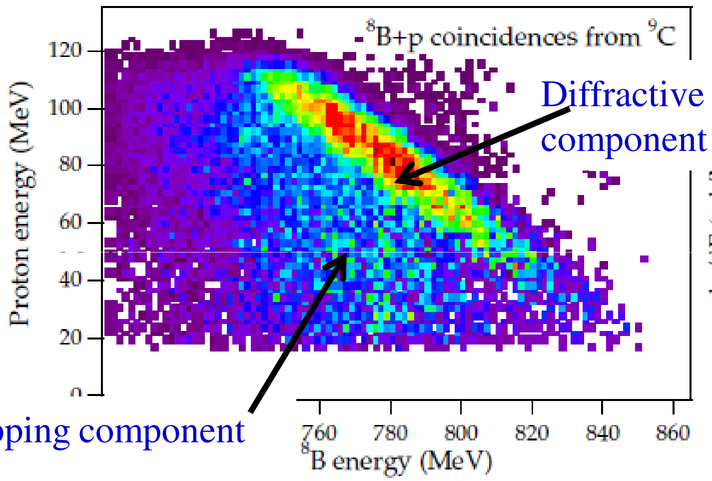

**HiRA Data: p($^{46}$Ar,d), p($^{56}$Ni,d)**

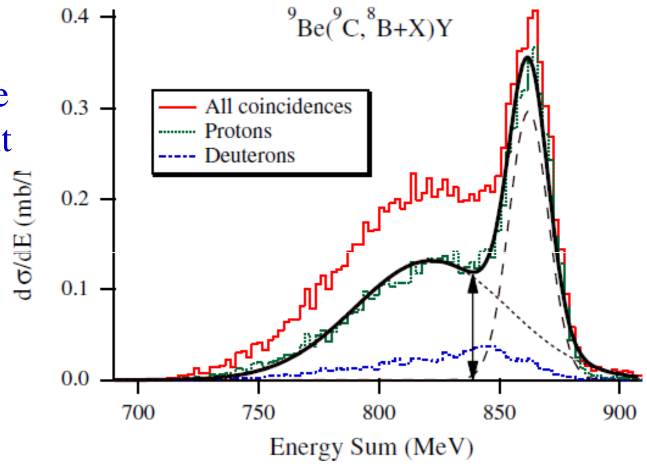
**Transfer Reactions:**
**Weak Asymmetry dependence of nucleon correlations**

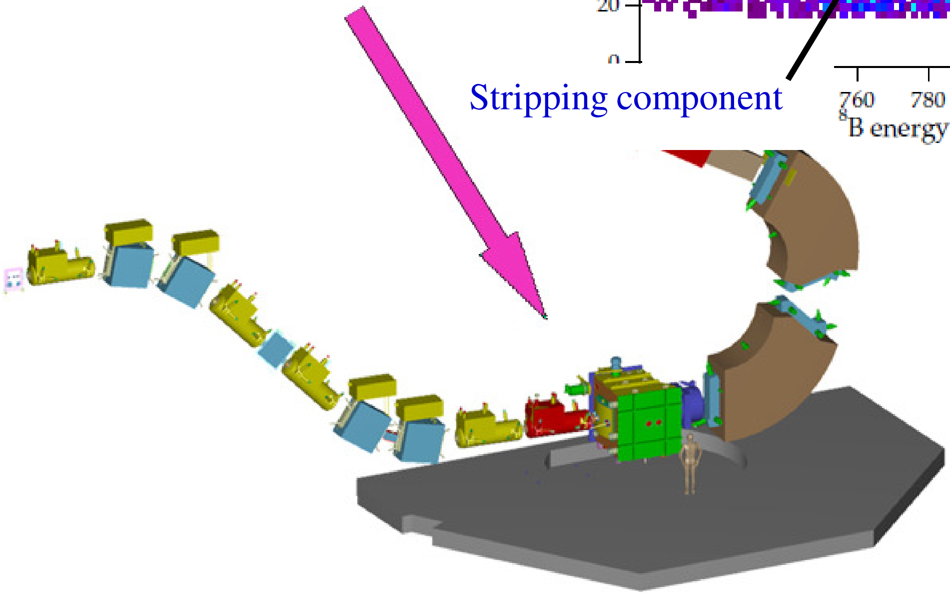
***Effects of Neutron-Proton pairing Correlations ?***

# Reaction Mechanism of Knockout Reactions



| Proj. | $\%_{diff}$ [a] | $\%_{diff}$ [b] |
|---|---|---|
| $^{9}$C | 25(2) | 26.8 |
| $^{8}$B | 38(3) | 37.1 |

**Results agree with Eikonal model**
**→ Loosely-bound nucleon systems**

D. Bazin et al, Phys. Rev. Lett. 102, 232501 (2009)

# Overview of $^{8}C$ and $^{6}Be$ decays

1. The excitation of an unbound species can be reconstructed from the relative energy of the decay fragments.

$$^{8}C \rightarrow \alpha+p+p+p+p$$

$$E^*(^{8}C) = E_{TKE}(\alpha+4p) - Q_{decay}$$

2. If $^{8}C$ decays via $^{8}C \rightarrow [^{6}Be] + 2p \rightarrow [\alpha+2p] + 2p$

   there will be **two** protons from the first step and **two** from the second.

   **How to prove experimentally ?**

   → Evidence of $^{6}Be$ decay from $\alpha$+2p in detected $\alpha$+p+p+p+p event

   $$E^*(^{6}Be) = E_{TKE}(\alpha+2p) - Q_{decay}$$

   → Reference data needed:

   $$^{6}Be \rightarrow \alpha+p+p$$

## Continuum Decay Spectroscopy

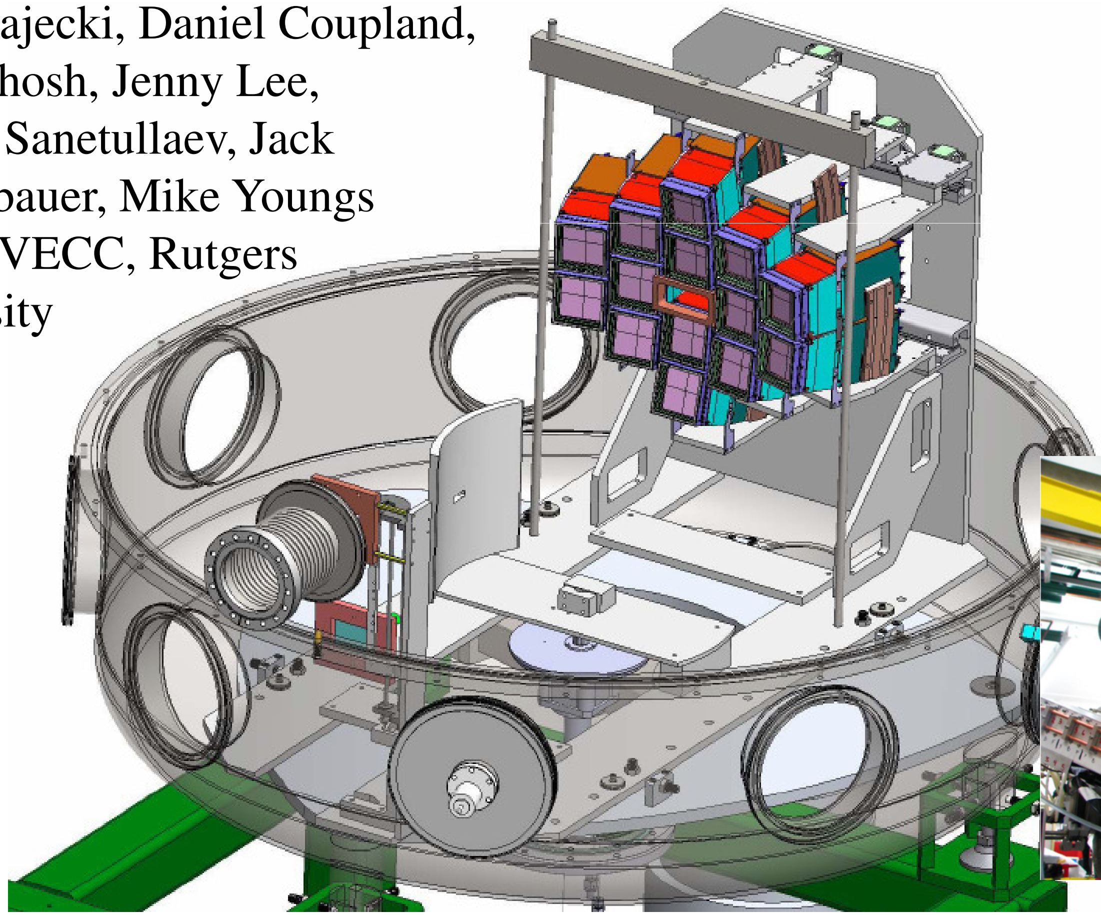
**$^{16}$O (150 MeV/u) ➔ $^{7}$Be (70 MeV/u) ➔ $^{6}$Be ➔ $\alpha$+p+p**

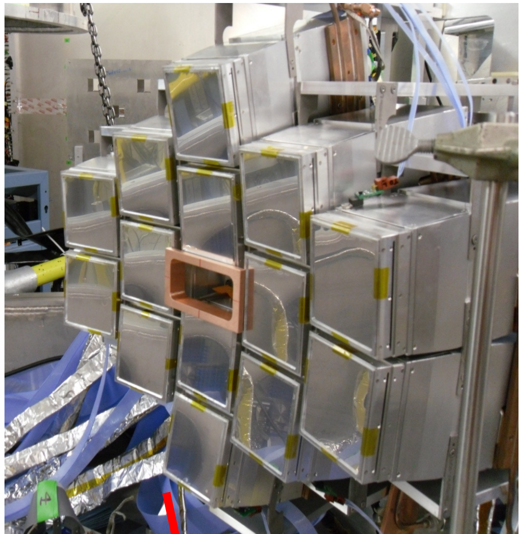
**$^{16}$O (150 MeV/u) ➔ $^{9}$C (70 MeV/u) ➔ $^{8}$C ➔ $\alpha$+ p+p + p+p**

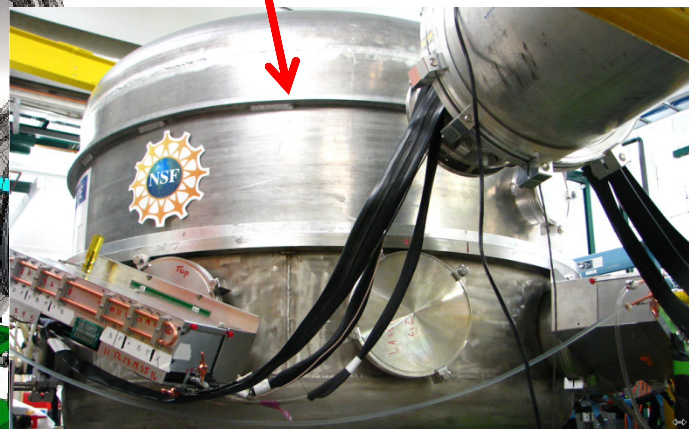
January 2010

**WU:** R. J. Charity, L. G. Sobotka, J. Elson, R. Shane

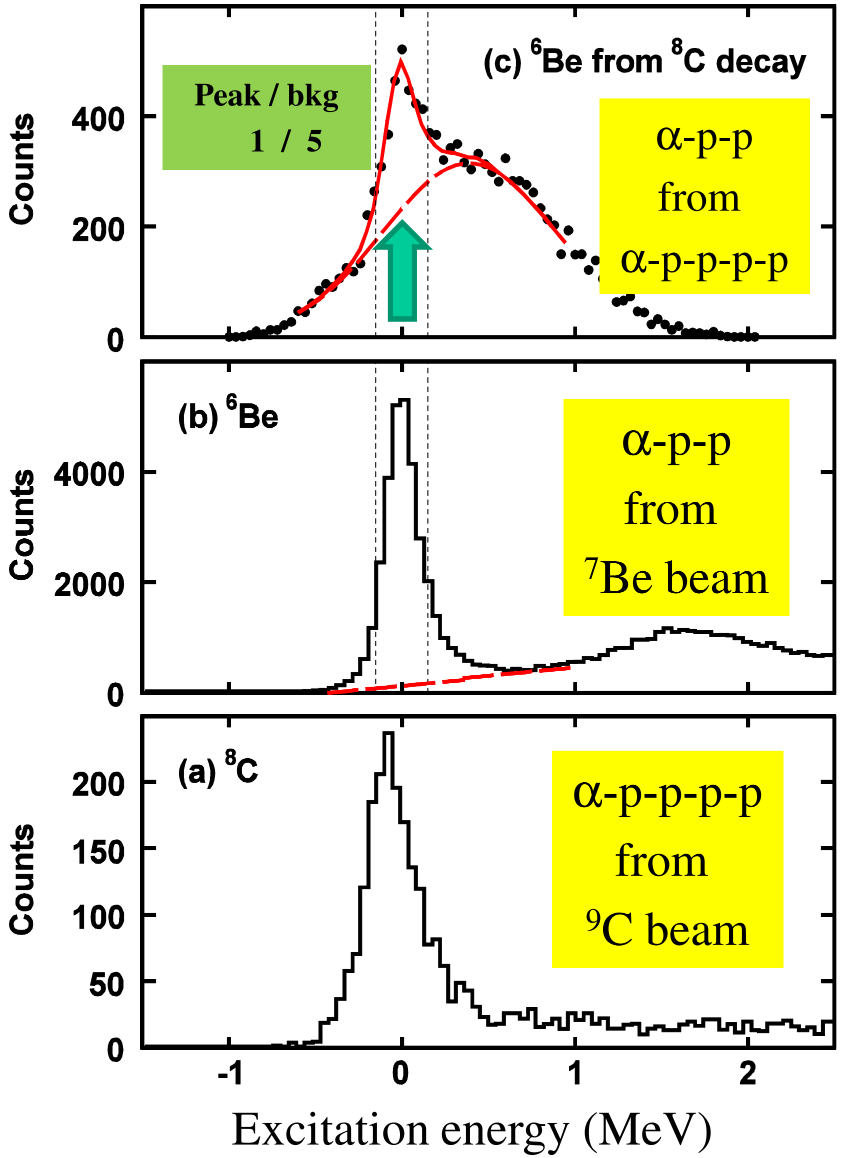
**NSCL:** Bill Lynch, Betty Tsang, Zibi Chajecki, Daniel Coupland, Tilak Ghosh, Jenny Lee, Alisher Sanetullaev, Jack Winkelbauer, Mike Youngs
WMU, VECC, Rutgers University

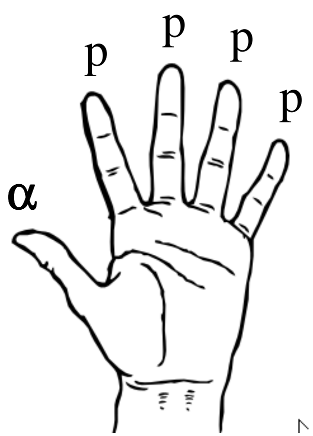






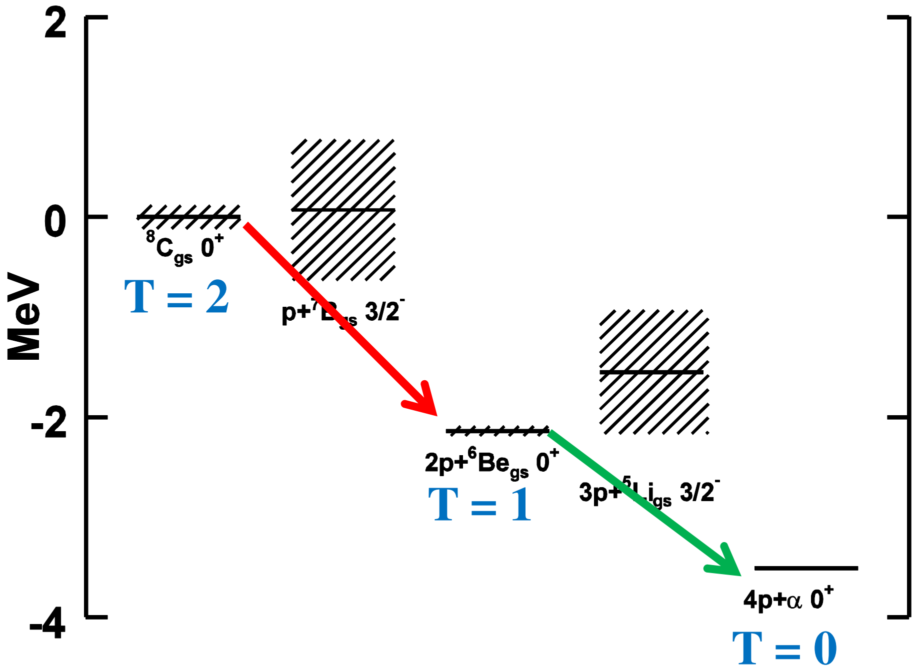
$^{8}C \rightarrow [^{6}Be] + 2p \rightarrow [\alpha + 2p] + 2p$




**6 ways** to choose **two protons** from **a set of four protons** :
$6 = 4!/(2!2!)$.

**$^{8}C$ decay –1 out of 6.**




**$^{6}Be$ is the intermediate, i.e.**
**$^{8}C \rightarrow [^{6}Be] + 2p \rightarrow [\alpha + 2p] + 2p$**

# Physics with HiRA Summary – Present and Future (Highly configurable)

- Mass of rp-process waiting point nucleus $^{69}$Br (Andy Rogers) – $^{73}$Rb
- Transfer reactions: (J. Lee, Alisher Sanetullaev, Tilak Ghosh)
  - $^{34,46}$Ar(p,d) at E/A=70 MeV; (d,p) to investigate particle states
- Proton knockout reactions (D. Bazin) – 1p & 2p knockout from $^{28}$Mg
- Particle unbound state. 2 p decay in $^{10}$C & 4p+α decay in $^{8}$C. (Bob Charity & Lee Sobotka) – $^{8}$B, $^{12}$N, $^{16}$F
- Spectra and two particle correlations (Micha Kilburn et al)