Radioactive Beams for Nuclear Spectroscopy and Nuclear Astrophysics

DREB 2007 Direct Reaction with Exotic Beams

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May 30, 2007

Today's Talk

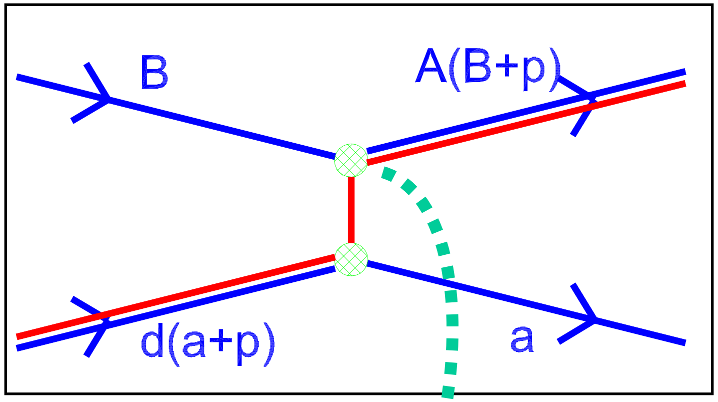
- **What we measure in transfer reactions**
- **ANCs** for nuclear astrophysics
  - recent results
- **Spectroscopic factors**
  - connections to nuclear astrophysics
- **Future directions**

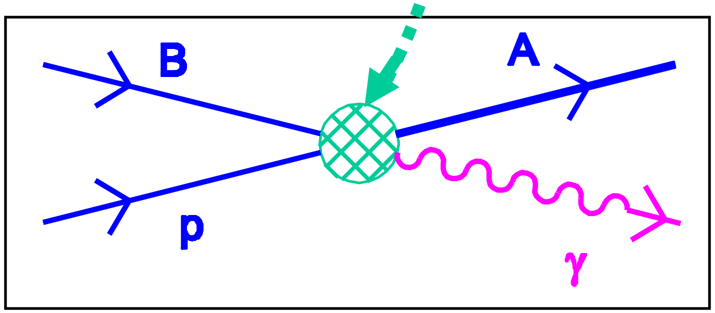
Extracting spectroscopic factors

Transfer reaction B+d→A+a

$$\frac{d\sigma}{d\Omega} = \sum S_{Bpl_A j_A} S_{apl_d j_d} \sigma^{DW}_{l_A j_A l_d j_d}$$

$$\frac{d\sigma}{d\Omega} = (C^A_{Bpl_A j_A})^2 (C^d_{apl_d j_d})^2 \frac{\sigma^{DW}_{l_A j_A l_d j_d}}{b^2_{Bpl_A j_A} b^2_{apl_d j_d}}$$





$$I^A_{Bp} \overset{r_{Bp}>R_N}{\approx} C^A_{Bp} \frac{W_{-\eta_A, l+\frac{1}{2}}(2\kappa_{Bp} r_{Bp})}{r_{Bp}}$$

Direct *p* capture

$$\sigma_{(p,\gamma)} \propto (C^A_{Bp})^2$$

Direct *n* capture

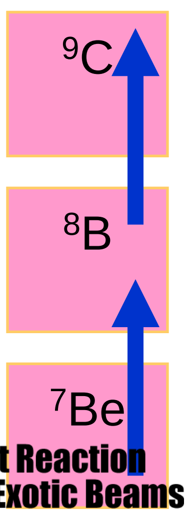
$$\sigma_{(n,\gamma)} =$$ more complicated!

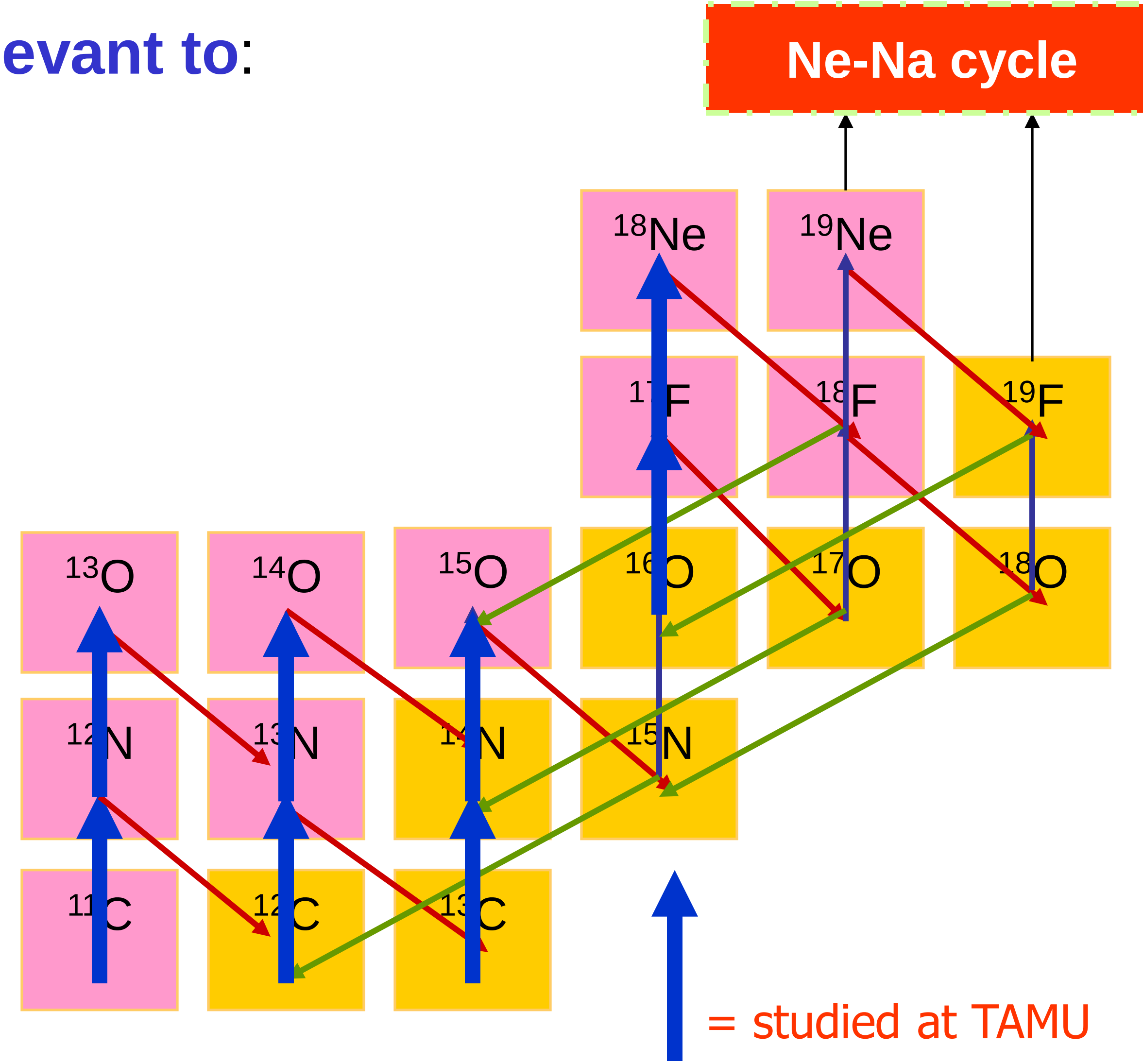
ANCs for **(p,γ)** rates

- **Proton transfer reactions**
  - stable and radioactive beams
- **Neutron transfer reactions + charge symmetry**
  - stable beams
- **Breakup reactions**
  - radioactive beams
- **Ancillary measurements**
  - elastic scattering for O.M. parameters
  - folding model O.M. parameters in the *p* shell

H burning, CNO & HCNO Cycles

Reactions studied relevant to:
***p-p* chain**
rapid α-p reactions
CNO cycle
HCNO cycle
Breakout from CNO cycle
Ne-Na cycle





ANCs (p) measured using stable beams

- ^{9}Be + p $\leftrightarrow$ ^{10}B* [^{9}Be(^{3}He,*d*)^{10}B;^{9}Be(^{10}B,^{9}Be)^{10}B] ^{9}Be(p,γ)^{10}B
- ^{12}C + p $\leftrightarrow$ ^{13}N [^{12}C(^{3}He,*d*)^{13}N] ^{12}C(p,γ)^{13}N
- ^{13}C + p $\leftrightarrow$ ^{14}N [^{13}C(^{3}He,*d*)^{14}N;^{13}C(^{14}N,^{13}C)^{14}N] ^{13}C(p,γ)^{14}N
- ^{14}N + p $\leftrightarrow$ ^{15}O [^{14}N(^{3}He,*d*)^{15}O] ^{14}N(p,γ)^{15}O
- ^{16}O + p $\leftrightarrow$ ^{17}F* [^{16}O(^{3}He,*d*)^{17}F] ^{16}O(p,γ)^{17}F
- ^{20}Ne + p $\leftrightarrow$ ^{21}Na* [^{20}Ne(^{3}He,*d*)^{21}Na] ^{20}Ne(p,γ)^{21}Na

beams $\approx$ 10 MeV/u

*** Test cases**

ANCs measured by our group with **radioactive** (rare isotope) **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)}

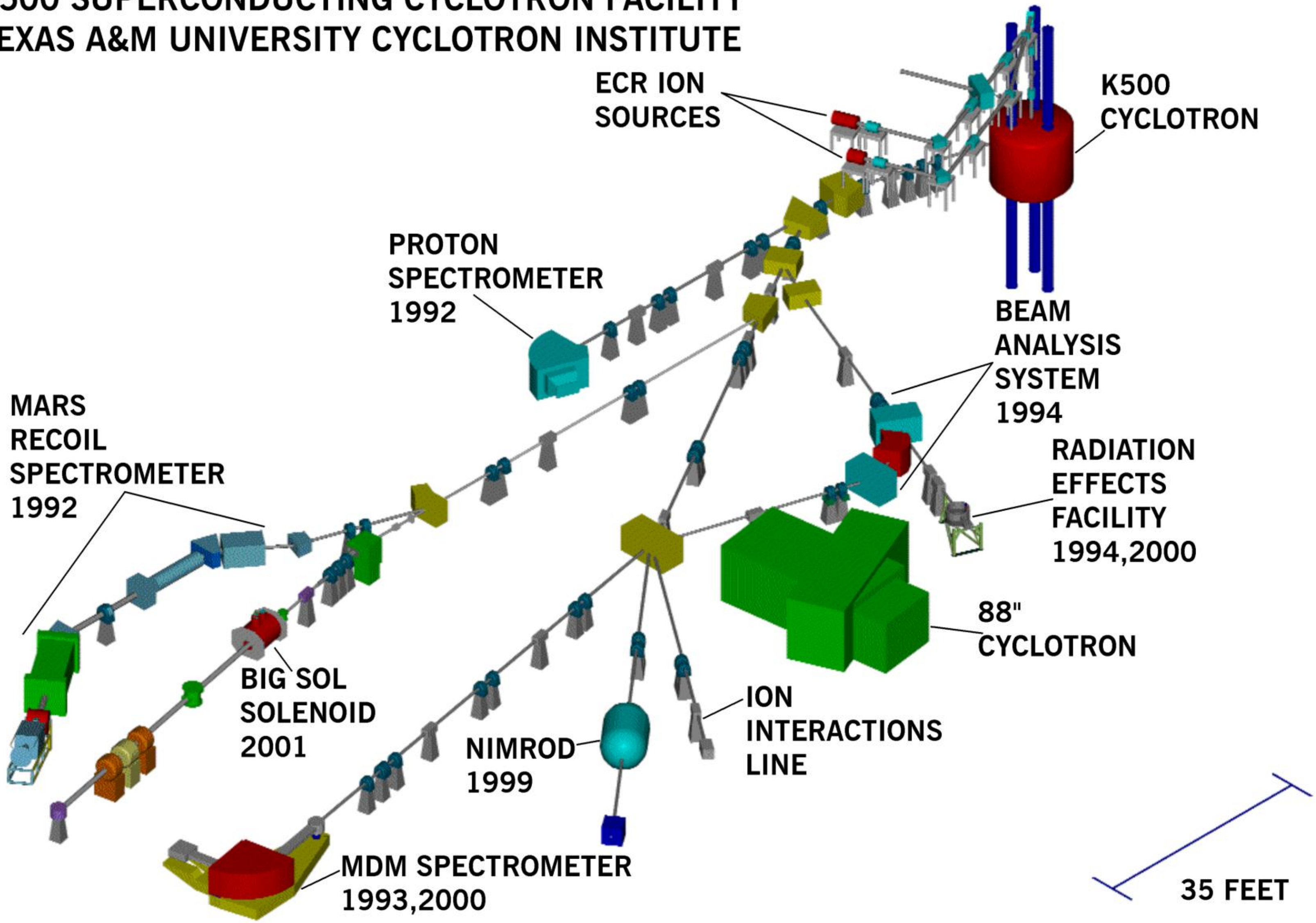
beams ≈ 10 - 12 MeV/u

ANCs (n) measured using stable beams [**Charge Symmetry**]

- **^{7}Li + n $\leftrightarrow$ ^{8}Li** [^{13}C(^{7}Li,^{8}Li)^{12}C] **^{7}Be(p,γ)^{8}B**
- **^{12}C + n $\leftrightarrow$ ^{13}C** [^{12}C(^{13}C,^{12}C)^{13}C]
- **^{22}Ne + n $\leftrightarrow$ ^{23}Ne** [^{13}C(^{22}Ne,^{23}Ne)^{12}C] **^{22}Mg(p,γ)^{23}Al**
- **^{16}O + n $\leftrightarrow$ ^{17}O** [^{13}C(^{16}O,^{17}O)^{12}C] **^{16}O(p,γ)^{17}F**
- **^{17}O + n $\leftrightarrow$ ^{18}O** [^{13}C(^{17}O,^{18}O)^{12}C] **^{17}F(p,γ)^{18}Ne**

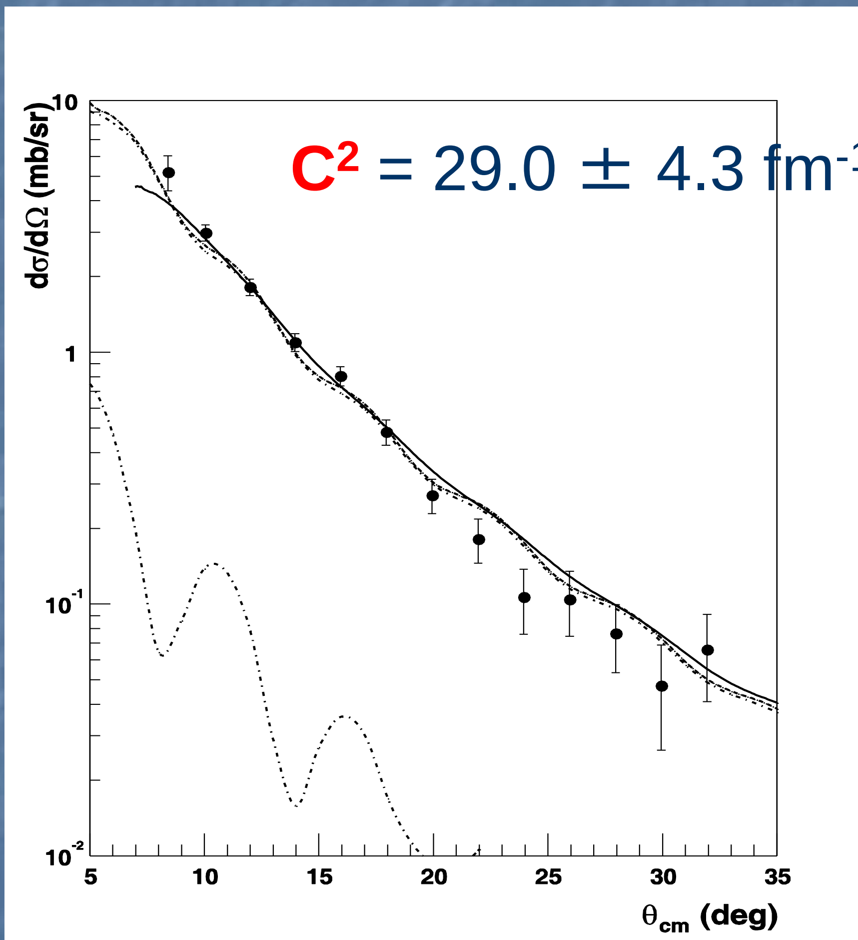
beams $\approx$ 10 MeV/u

K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY CYCLOTRON INSTITUTE



S Factor for ^{13}N(p,γ)^{14}O

^{14}N(^{13}N,^{13}C)^{14}O

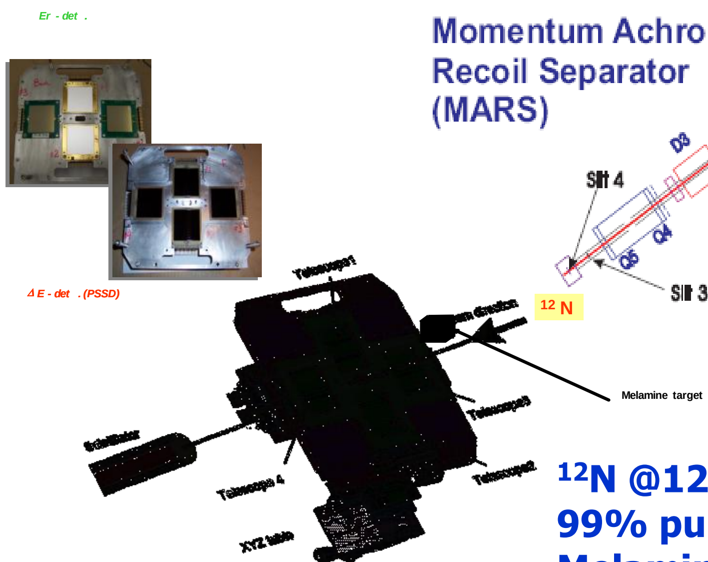


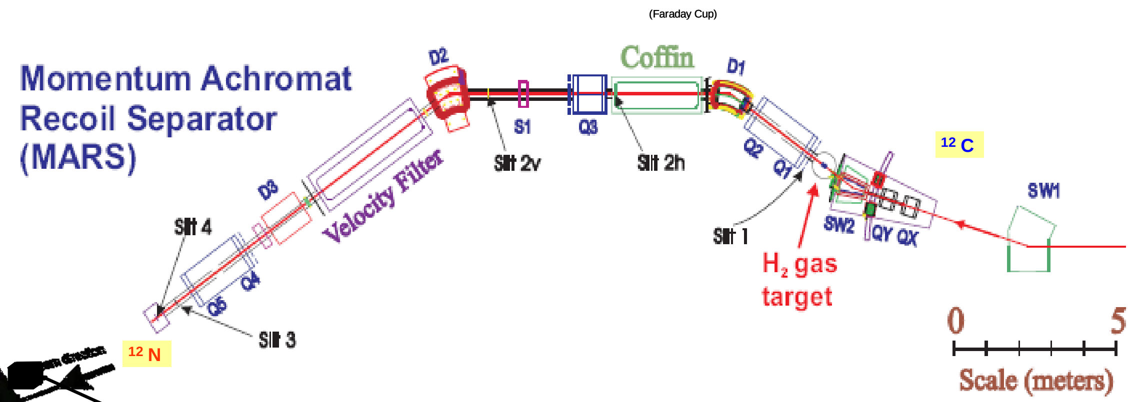
DWBA by FRESCO

Use R-matrix with resonant and DC pieces to get S factor

Find S(0) about 7 keVb with constructive int.

Cross sections for **(p,γ)** from ***p*-transfer reactions** with RNB from MARS

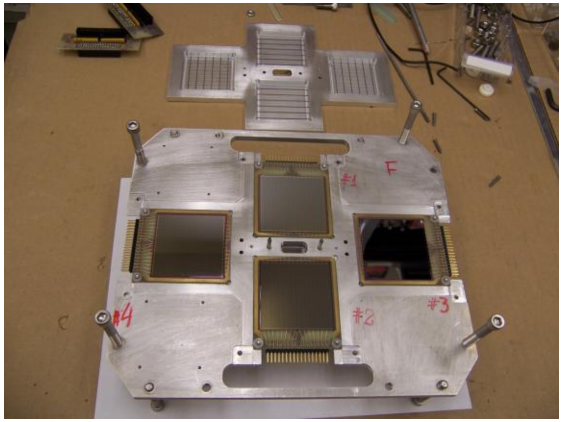


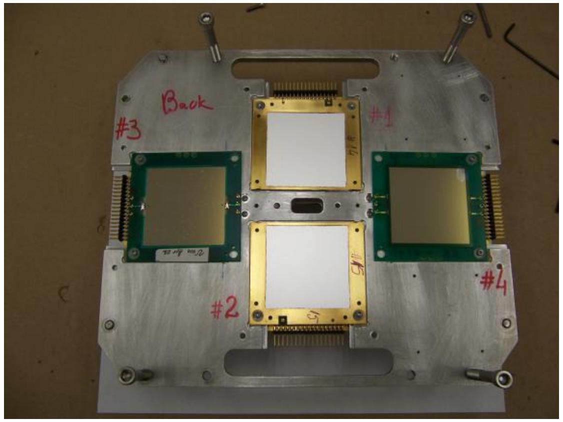


^{12}N @12 MeV/u
99% pure, 4 mm dia
Melamine target

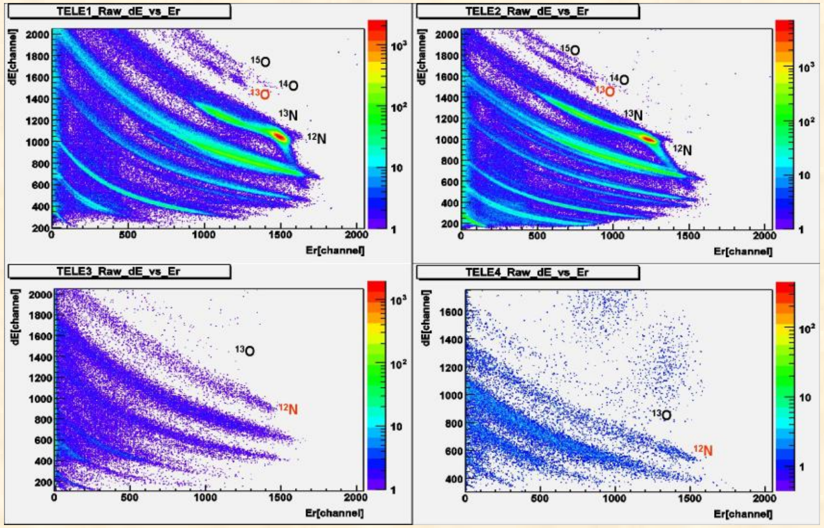
^{12}C @23 MeV/u
H_2 cryotarget

Extended telescope system:
ΔE – PSD 65, 110 μm
E – 500 μm

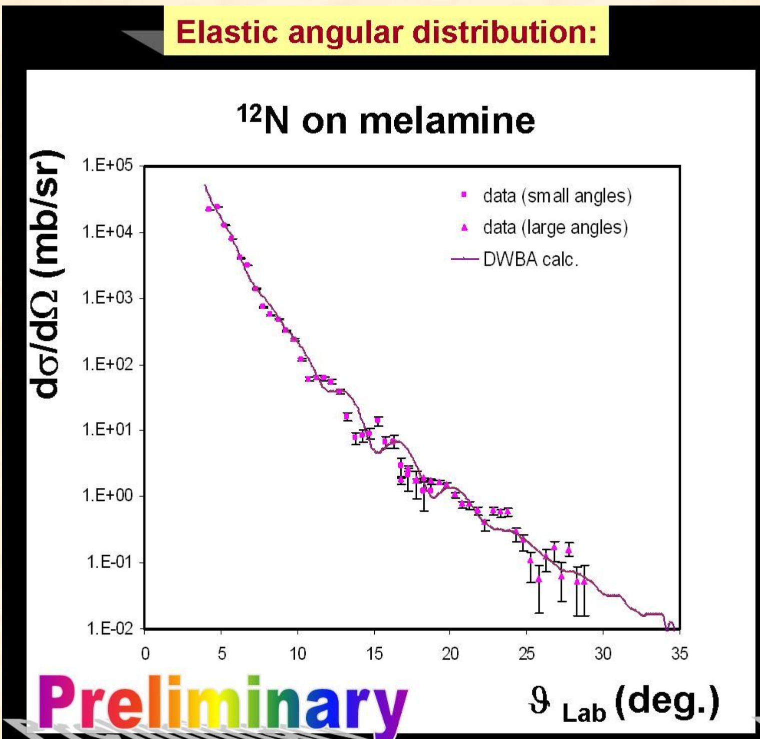


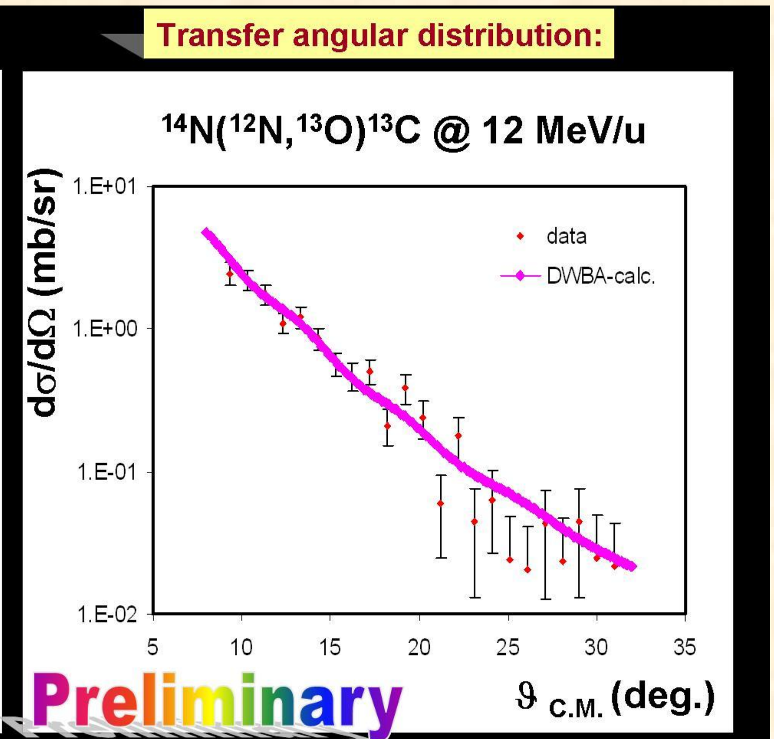


^{12}N @12 MeV on $N_6C_3H_6$ – May 2006



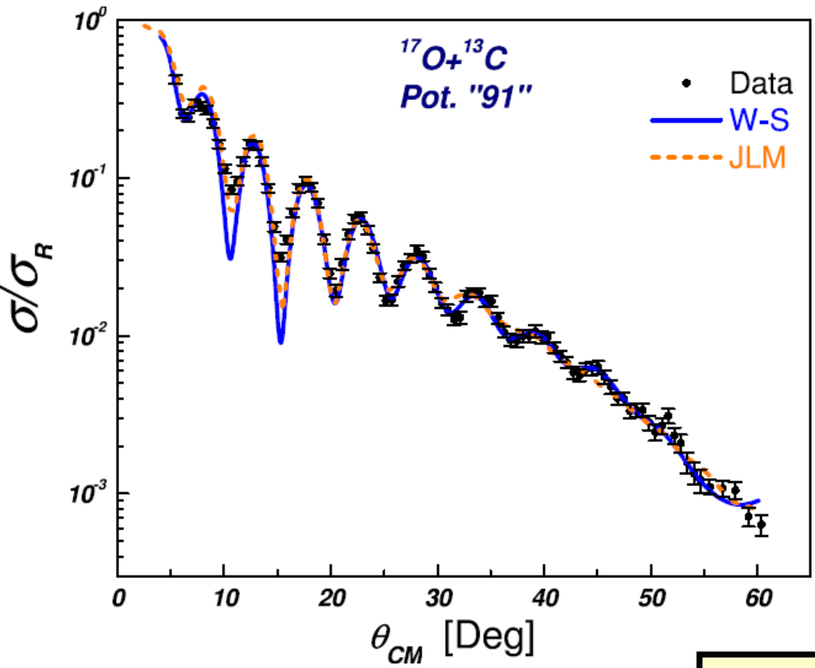
- ^{12}C @ 23 MeV/A - 150 pnA
- ^{12}N @12 MeV/A - 10^5 pps

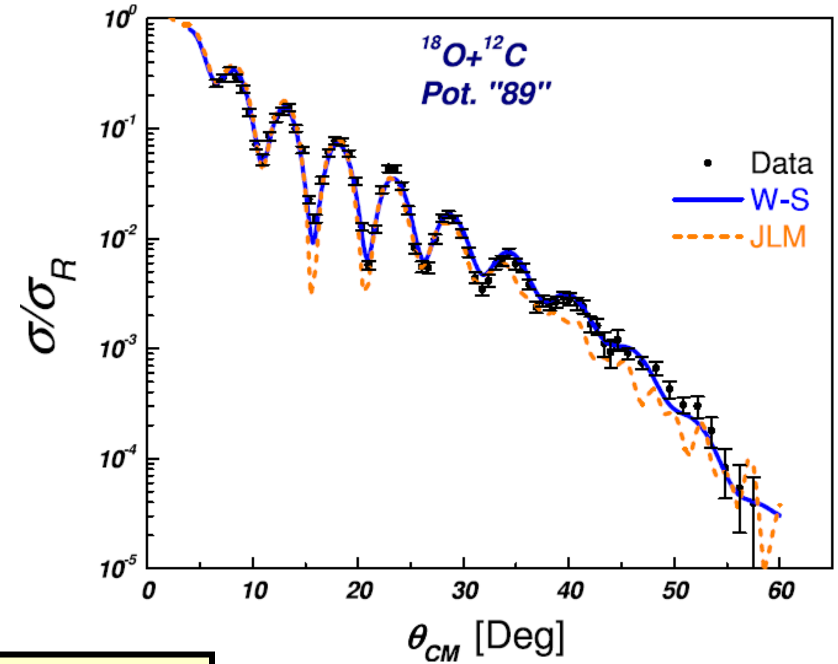




$C^2 \sim 3.3\ fm^{-1}$

$^{13}C(^{17}O,^{18}O)^{12}C$





Wood-Saxon & double folding both work!

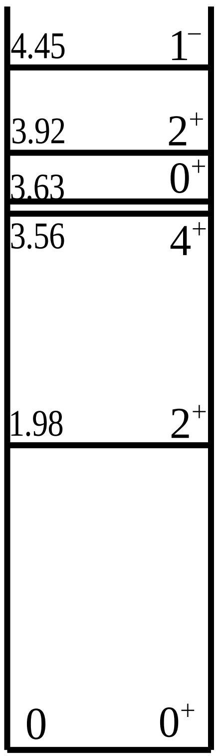
V [MeV]	r_V [fm]	a_V [fm]	W [MeV]	r_W [fm]	a_W [fm]	$\chi 2$
91.8	0.90	0.86	26.9	1.10	0.71	4.4
200	0.70	0.95	22.0	1.16	0.65	4.9
396.3	0.57	0.95	25.2	1..18	0.62	4.9

V [MeV]	r_V [fm]	a_V [fm]	W [MeV]	r_W [fm]	a_W [fm]	$\chi 2$
89.1	0.88	0.90	26.2	1.16	0.70	5.0
189.8	0.69	0.96	27.2	1.16	0.69	8.6
218.0	0.86	1.42	22.0	1.36	0..97	14.0

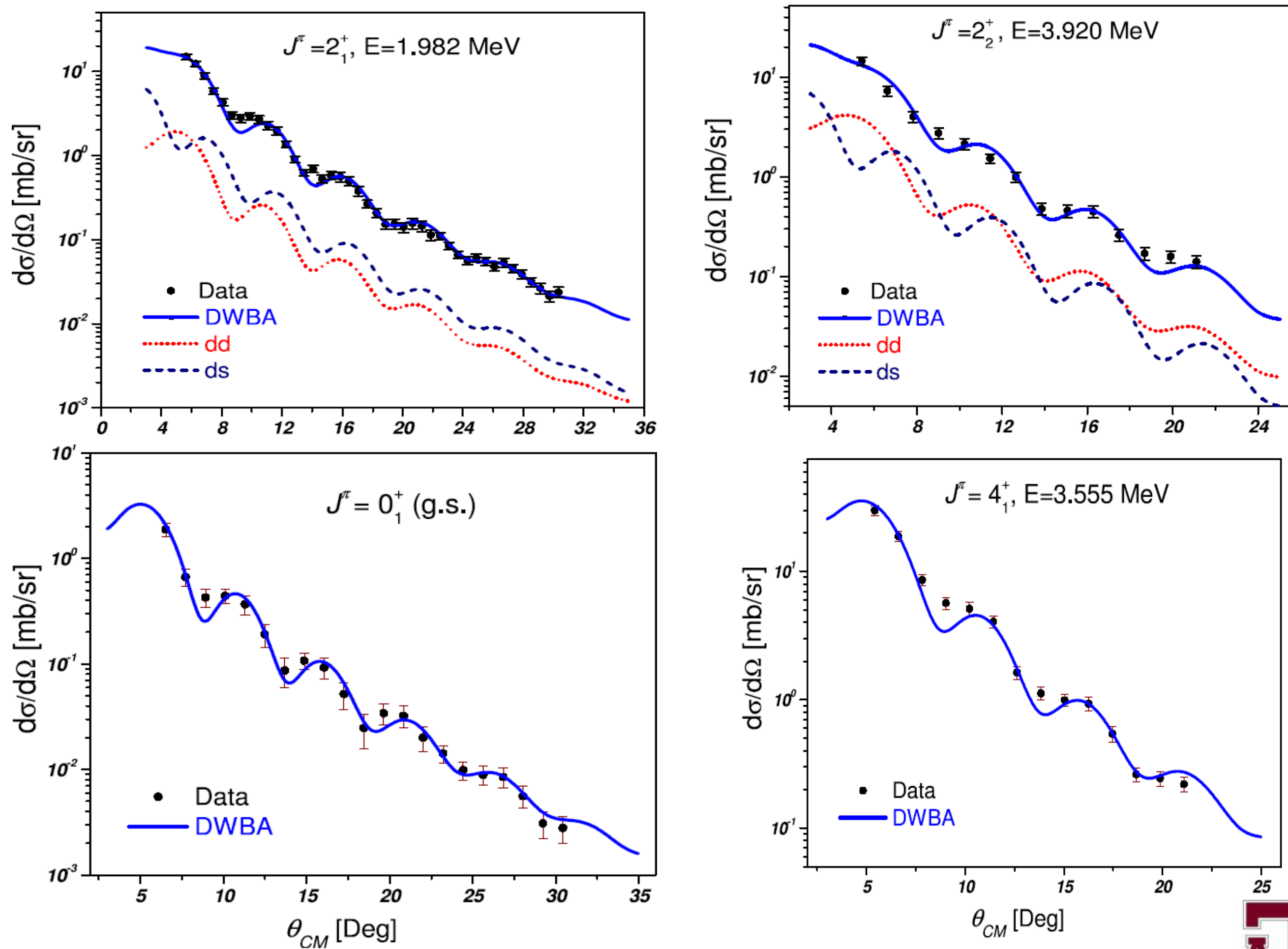
$^{13}C(^{17}O,^{18}O)^{12}C$

- ANCs for first 4 states in ^{18}O
- 2_2^+ state dominates (p,γ) rate

$$\frac{d\sigma}{d\Omega}=\frac{\left(C^{^{13}C}_{^{12}C,\frac{1}{2}}\right)^2}{b^2_{^{12}C,\frac{1}{2}}}\left[\left(C^{^{18}O}_{^{17}O,\frac{5}{2}}\right)^2\frac{\sigma^{DW}_{\frac{5}{2},\frac{5}{2}}}{b^2_{^{17}O,\frac{5}{2}}}+\left(C^{^{18}O}_{^{17}O,\frac{1}{2}}\right)^2\frac{\sigma^{DW}_{\frac{5}{2},\frac{1}{2}}}{b^2_{^{17}O,\frac{1}{2}}}\right]$$



^{18}O



$^{17}F(p,\gamma)^{18}Ne$

Charge symmetry:

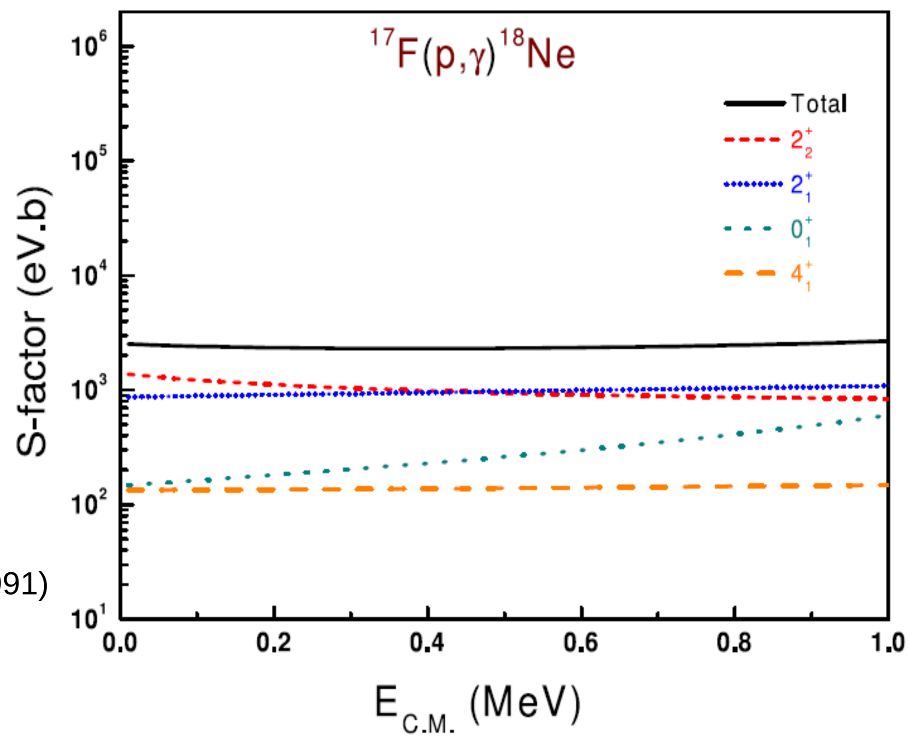
$$\frac{C_{\ell j}^2}{b_{\ell j}^2}\left({}^{18}\mathrm{O}\right) = \frac{C_{\ell j}^2}{b_{\ell j}^2}\left({}^{18}\mathrm{Ne}\right)$$

$$S_{1-17}(0) = 2.5 \pm 0.4 \text{ keV b}$$

Predictions:

$\approx$ $S_{1-17}(0) = 2.9 \pm 0.4$ keV b * PRC 43, 2012(1991)

$<$ $S_{1-17}(0) = 3.5$ keV b * NPA 730 (2004) 316



J^π	Proton Orbital	^{18}O B.E. [MeV]	^{18}O $C_{\ell j}^2$ [fm^{-1}]	^{18}Ne B.E. [MeV]	^{18}Ne $C_{\ell j}^2$ [fm^{-1}]
0_1^+	$d_{5/2}$	8.04	7.33 ± 0.73	3.92	10.76 ± 0.97
2_1^+	$d_{5/2}$	6.06	2.06 ± 0.21	2.04	2.17 ± 0.24
	$s_{1/2}$		6.55 ± 0.69		14.29 ± 1.71
4_1^+	$d_{5/2}$	4.48	1.05 ± 0.11	0.54	2.17 ± 0.22
2_2^+	$d_{5/2}$	4.12	0.49 ± 0.06	0.31	2.69 ± 0.32
	$s_{1/2}$		4.47 ± 0.54		127 ± 17

Future direction:
extension to
(n,γ) direct capture

Test case: $^{14}C(n,\gamma)^{15}C$

- **ANC** from breakup of $^{15}C \rightarrow {}^{14}C + n$
- Compare to $^{13}C(^{14}C,^{15}C)^{12}C$ at TAMU
- Determine **spectroscopic factor**
  - $d(^{14}C,p)^{15}C$ in inverse kinematics – 12 MeV/A
  - compare to $^{14}C(d,p)^{15}C$ from Rez – 24 MeV
  - higher energy $^{14}C(d,p)^{15}C$ with K150 beam
- Use **ANC** to fix exterior part of cross section
- With **ANC**, determine $^{14}C(n,\gamma)^{15}C$ direct capture
- Compare **spectroscopic factor** to expectations
- Use **spectroscopic factors** for s-wave d.c.

TAMU Upgrade Project

- Further develop **RIB** capability

- Produce accelerated **RIB**'s at intermediate energies

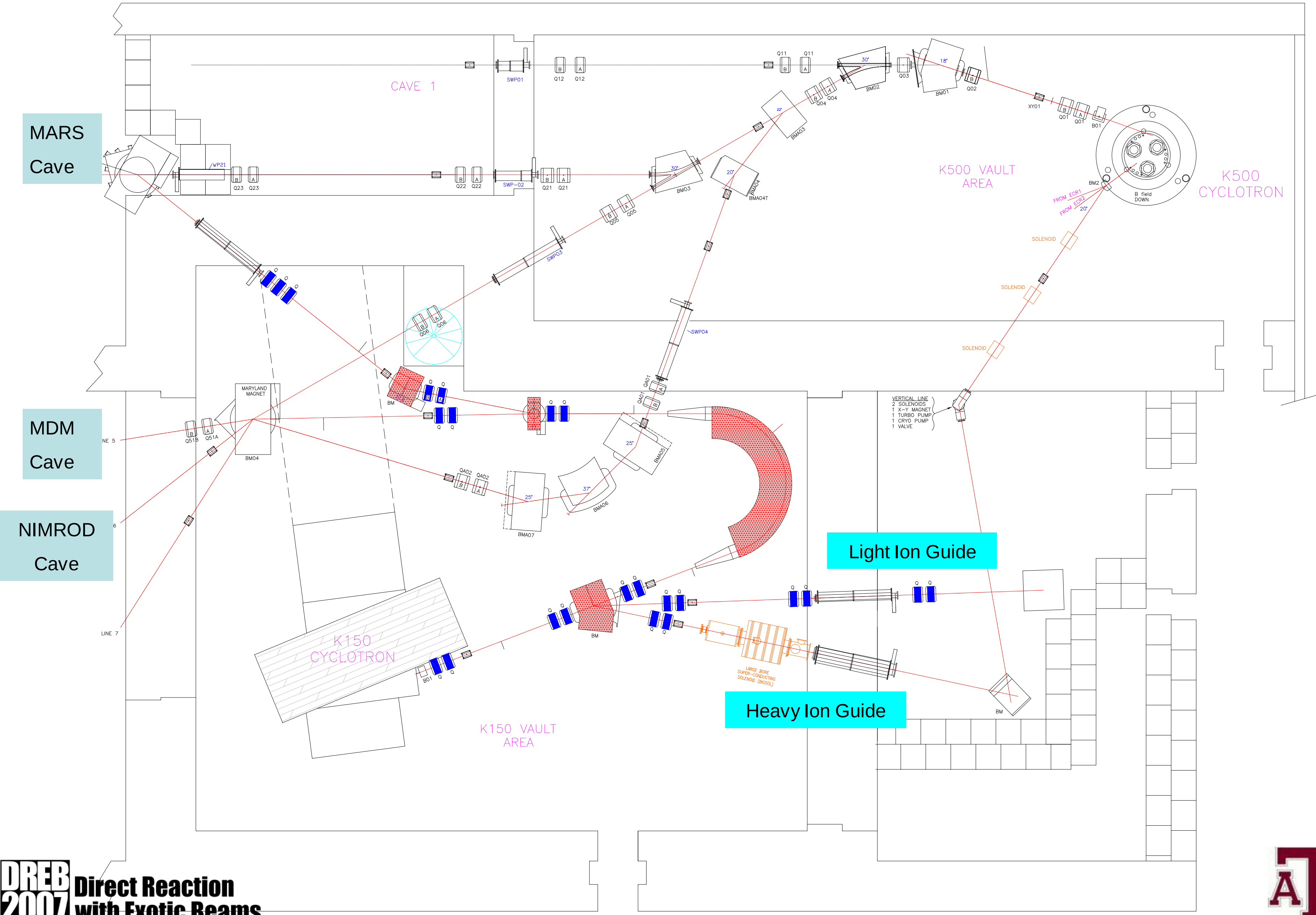
TAMU Upgrade Project

- **Stage I**
  - commission K150(88”) cyclotron
  - ECR source injection
  - commission beam lines to existing apparatus

- **Stage II**
  - isotope production stations completed
  - production of rare isotopes

- **Stage III**
  - K500 acceleration of rare isotope beams

Facility with K150 Beam Lines



DREB 2007 Direct Reaction with Exotic Beams

A&M

Collaborators

- **TAMU:** T. Al-Abdullah, A. Azhari, H. Clark, C. Gagliardi, C. Fu, Y.-W. Lui, G. Tabacaru, X. Tang, L. Trache, A. Zhanov (Mukhamedzhanov)
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