Verification of Recoil Separator Properties Through Reaction Measurements

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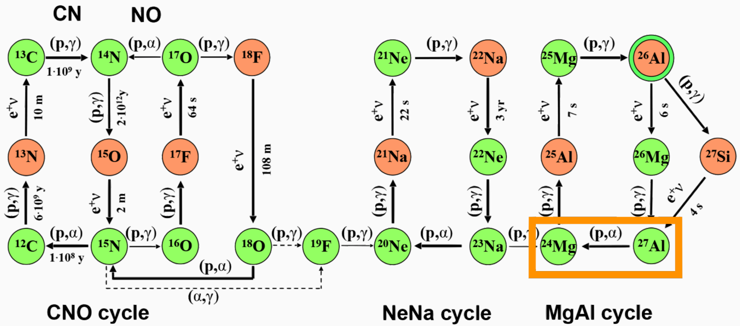
Introduction

Stellar energy production depends on the type of star and the current lifecycle stage

pp-Chains and CNO cycles dominate for stars similar to our sun

- Include radiative capture reactions: (p, γ) and (α, γ)

Can be grouped under "Hydrogen burning" processes


CN
NO
13C
14N
17O
18F
(p,γ)
(p,α)
1·10^9 y
e+ν
10 m
2·10^12 y
64 s
108 m
13N
15O
17F
6·10^9 y
2 m
12C
15N
16O
18O
19F
1·10^8 y
(α,γ)
CNO cycle
21Ne
22Na
21Na
22Ne
20Ne
23Na
22 s
3 yr
NeNa cycle
25Mg
26Al
25Al
26Mg
27Si
24Mg
27Al
7 s
6 s
4 s
MgAl cycle

Reactions of the form $A(a,\gamma)B$

Commonly studied by detecting the emitted γ

- Can have large background count rate, making detection difficult or impossible
- Limited by detector efficiency

Focus primarily on resonances

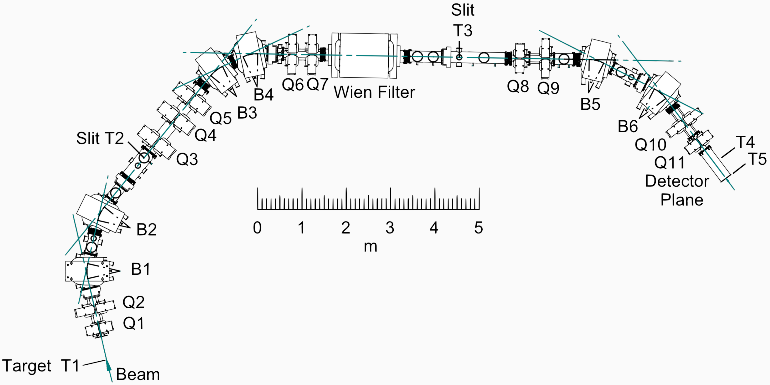
We can instead detect the heavy recoil particle using a high-efficiency detector to study complete cross sections

- Perform the reaction in inverse kinematics $a(A, B)\gamma$
- Heavy projectile impinges on light target, heavy recoil escapes the target
- Requires a stable H or He (commonly) target

Gain in efficiency of detector offset by complexities of distinguishing the few recoil particles from the high-intensity beam

Recoil Separation

St. George


Slit
T3
Q6 Q7
Wien Filter
Q8 Q9
B4
B3
Q5
Q4
Slit T2
Q3
B5
B6
Q10
Q11
T4
T5
Detector
Plane
0 1 2 3 4 5
m
B2
B1
Q2
Q1
Target T1
Beam

Magnetic and Electric Rigidities

Elements within St. George are tuned for the $B\rho$ and $E\rho$ of the recoil particle

$$B\rho = \frac{\sqrt{2mT}}{q} \qquad E\rho = \frac{2T}{q}$$

Design limits: $0.1 \leq B\rho \leq 0.45$ Tm and $E\rho \leq 5.7$ MV

We can uniquely identify particles by their mass, charge and energy:

Magnetic Selection

$$\frac{m}{q} = \frac{B\rho}{2}\left(\frac{T}{q}\right)^{-1}$$

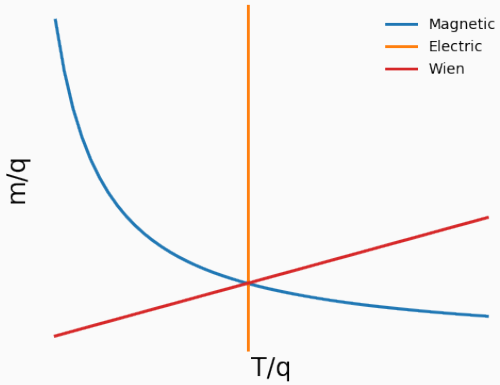
Electric Selection

$$\frac{T}{q} = \frac{E\rho}{2}$$

Wien Filter Selection

$$\frac{m}{q} = \frac{2}{v^2}\frac{T}{q}$$

Any two of the three possibilities may be combined to uniquely identify a particle



Angular and Energy Acceptance

Recoils can only be transported within defined parameter bounds

$$\Delta E/E = 7.5\,\% \qquad \Delta\theta = 40\,\mathrm{mrad}$$

These bounds must hold for all possible $E\rho$ and $B\rho$

Importance of Acceptances

Verifying the acceptances across a wide range of $B\rho$ and $E\rho$ is required in order to eliminate it as an unknown source of error

Ensures that all of the produced recoils for a given reaction reach the detector plane

- The produced recoils can be extremely rare (10^{-15} per beam particle)

Once acceptances have been verified for enough $B\rho$ and $E\rho$ possibilities, scaling the electromagnetic elements to other rigidity values should retain the acceptance properties

Commissioning

Types of Commissioning

Can divide commissioning between three possible cases:

Energy

change the particle energy without interfering with the other quantities

The goal is to get 100 % of the recoil particles to the final detector plane

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Angular

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Joint

adjust both at the same time

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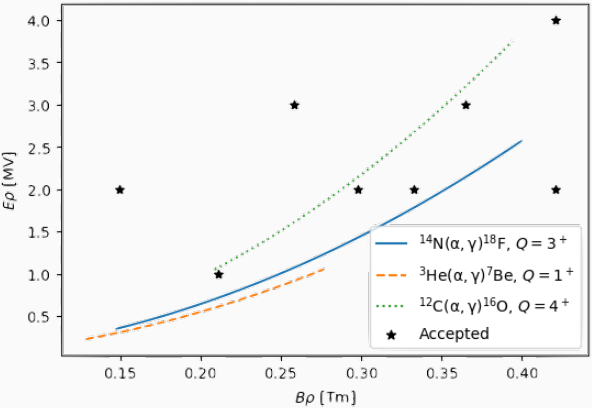
Energy Acceptance



Joint Acceptance

All experiments will have an angular and energy spread, so must confirm that the acceptances can be achieved at the same time

Can use a degrader foil to create an angular and energy spread at the same time

- New central energy based on energy loss
- Target material and thickness extremely important to understand well
- "Fuzziness" of beam spot may still make it difficult to tune

Reaction Measurements

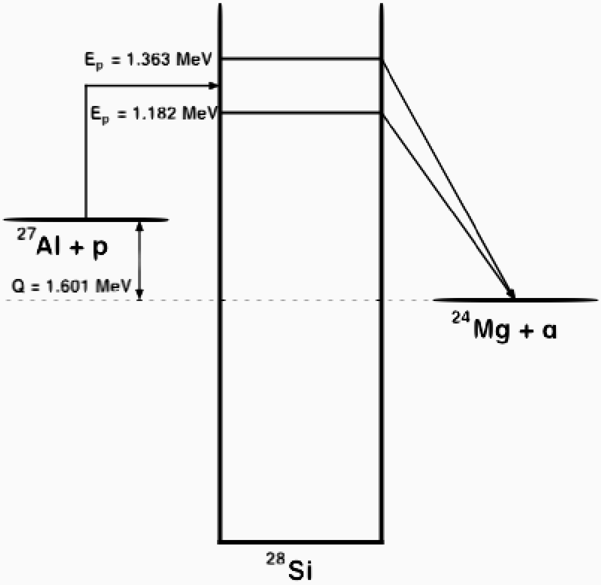
Justification for Reaction Measurements

Joint acceptance measurements are costly to cover all of the possibilities

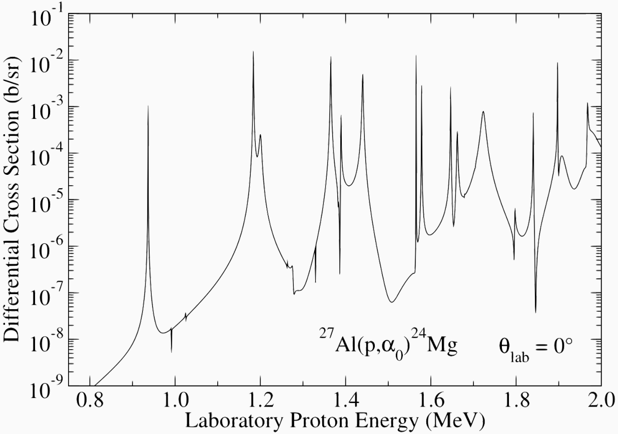
Reactions can be used to “bootstrap” the process

- Reactions have a known cross section, angular and energy spread, etc.
- If all of the expected produced recoils reach the detector, the separator is performing optimally

The $^{27}\mathrm{Al}(\mathrm{p},\alpha)^{24}\mathrm{Mg}$ Reaction



The $^{27}\mathrm{Al}(\mathrm{p},\alpha)^{24}\mathrm{Mg}$ Reaction



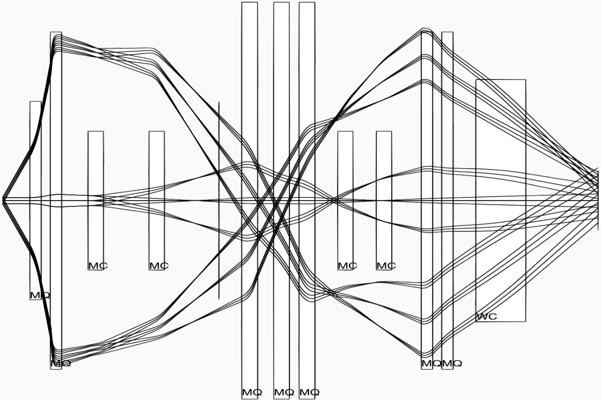
Alternate Tune

Since the last segment of St. George has not been fully commissioned (full angular acceptance not yet verified), we can use the focal plane after the Wien filter to perform cross section measurements

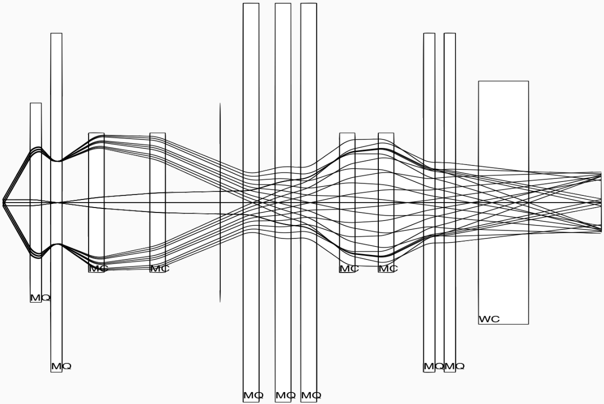
For (p, α) reactions, the beam suppression is sufficient to reject the high-intensity incident beam

The beam spot at this focal plane needs to be adjusted to direct the reaction products to the detector

Alternate Tune



Alternate Tune



Angular Acceptance Measurement

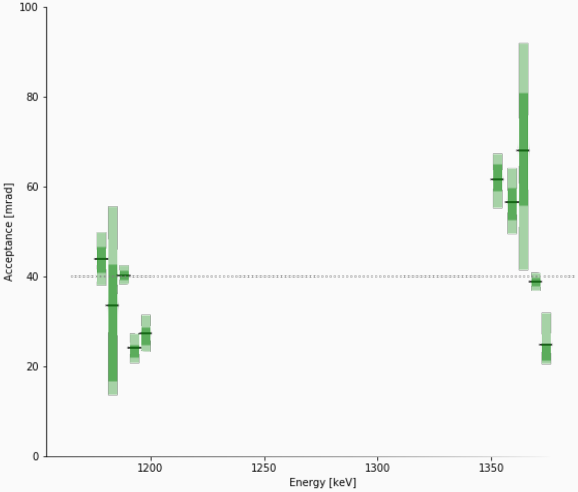
Since $^{27}\mathrm{Al}(\mathrm{p},\alpha)^{24}\mathrm{Mg}$ emits the α particles within a large cone, we can measure the acceptance of those that pass into St. George

- Target cup restricts us to $\approx$ 40 mrad

Tuning the beginning of the separator to transport the particles to the Wien filter focal plane is an alternative to a full angular acceptance measurement

Ability to fine-tune and have confidence in the properties of the separator are required

Acceptance Measurements



Future Directions

Acceptances:

- $\Delta E/E \geq 7.5\,\%$
- $\Delta\theta = 40$ mrad (to WF)
- $\Delta E/E = 3\,\%$ and $\Delta\theta = 40$ mrad (to WF)

St. George can be used to study an additional class of reactions

Separation properties and beam currents are suitable for low-energy and off-resonance cross section measurements

Final commissioning work for the remainder of St. George

New supersonic jet gas target HIPPO to be commissioned

- Includes offset Si detector for continuous current measurements

First (α, γ) reactions performed

95 % Contributions

ACCEPTANCE BOUNDS WITH HELD VARIABLES, 95 %

Held	**241**	**234**	**260**†	**255**	**248**	**288**	**282**	**277**	**270**†	**264**
E_p [MeV]	1.178	1.183	1.188	1.193	1.198	1.353	1.359	1.364	1.369	1.374
δE	49.4	7.5	101.1	75.8	93.0	64.1	39.6	13.2	102.4	50.9
δt	101.8	95.3	101.3	99.8	99.6	102.7	101.0	97.9	99.0	107.6
δi	86.6	97.3	26.8	51.1	66.3	77.7	93.9	93.6	26.5	102.0
$\delta\Delta$	95.4	98.2	101.4	80.4	82.9	98.7	104.2	95.8	103.5	75.8
δE, δt	47.4	7.2	96.7	73.4	93.4	63.8	39.6	13.2	101.4	50.2
δE, δi	12.0	1.7	23.0	18.1	55.5	20.1	12.5	3.0	24.0	42.7
δE, $\delta\Delta$	46.8	7.6	100.3	72.0	73.8	60.4	38.0	12.9	103.5	20.6
δt, δi	88.0	97.2	13.4	50.1	64.6	78.2	96.8	96.9	15.2	94.7
δt, $\delta\Delta$	98.5	98.3	98.2	86.7	83.5	99.4	102.0	98.8	99.8	75.9
δi, $\delta\Delta$	87.7	95.9	26.6	29.7	29.1	76.9	93.4	93.5	25.6	72.9
δE, δt, δi	11.1	1.0	8.1	18.6	54.0	17.8	11.5	1.5	8.3	43.5
δE, δt, $\delta\Delta$	47.4	7.2	96.8	70.1	76.0	59.9	39.0	12.9	99.4	20.4
δE, δi, $\delta\Delta$	7.9	1.6	21.4	8.4	5.0	8.4	7.4	2.7	22.4	4.6
δt, δi, $\delta\Delta$	86.2	98.6	13.1	29.6	27.0	78.2	94.2	96.5	14.5	68.0
All	5.4	1.0	4.0	2.8	3.8	6.6	5.2	0.9	3.7	1.3

†: Denotes runs at resonance energy

Initial Test Reactions

Table 1

Inverse (α, γ) reactions of astrophysical interest

Beam	Recoil	Beam E_{lab} (MeV)	E_{cm} (MeV)	Recoil E_{lab} (MeV)	Recoil Q [14]	Recoil abund. (%)	Half angle (mrad)	E range $\pm\%$	Mom. p (MeV/c)	$B\rho$ (T m)
^{16}O	^{20}Ne	5.8	1.16	4.64	5	42	14.2	2.8	415.7	0.277
		12.5	2.5	10.02	6	40	11.8	2.4	610.9	0.340
^{18}O	^{22}Ne	1.94	0.35	1.59	3	38	39.2	7.8	177.1	0.284
		3.3	0.60	2.70	4	42	30.9	6.2	332.6	0.277
^{34}S	^{38}Ar	10.0	1.05	8.95	8	32	10.4	2.1	795.7	0.332
		38.0	4.00	34.00	12	32	7.2	1.4	1551.0	0.431
^{36}Ar	^{40}Ca	12.5	1.25	11.25	9	31	9.1	1.8	915.3	0.339
		40.0	4.00	36.00	13	30	6.7	1.3	1638.0	0.420