Verification of Recoil Separator Properties Through Reaction Measurements

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Introduction

Capture Reactions

Primary burning processes for energy production depend on the properties of the star

Hydrogen burning:

- low mass: *pp*-chains
- massive stars: CNO, NeNa, and MgAl cycles

Helium burning:

- Triple-α process and $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$

Additional He reactions:

- main sources of neutrons for *s*-process: $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ and $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ (AGB stars)
- reactions on ashes of cyclic H burning (e.g. $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}$)

Reactions: (p, γ) and (α, γ) (in general, $A(a, \gamma)B$)

- studied by detecting γ-ray produced

Detecting the γ can be difficult due to:

- large background count rates (move underground)
- low count rates (measure only resonances)
- limited detector efficiency

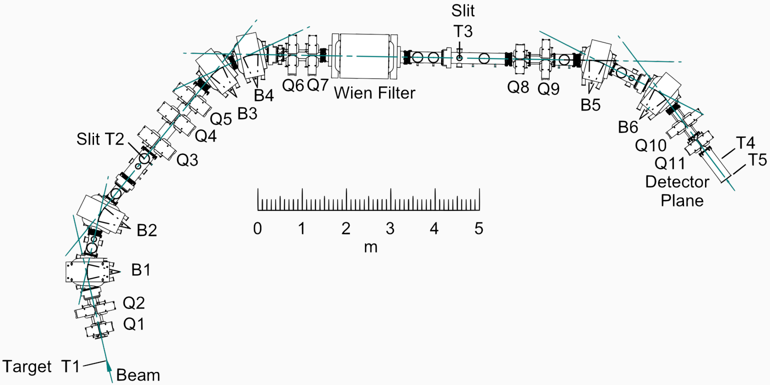
Perform reaction in inverse kinematics: $a(A, B)\gamma$

- heavy projectile impinges on light target (H or He)
- heavy recoil escapes the target
- detect with high-efficiency detector

Incident beam also passes through the light target, so we need to **stop the beam** from reaching our detector

Recoil Separation

St. George



Couder *et al.*, 2008

Particle Selection

Uniquely identify particles by charge, energy, mass, and momentum

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Magnetic Selection

$$B\rho = \frac{\sqrt{2mT}}{q} = \frac{p}{q}$$

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Wien Filter Selection

$$v = \frac{E\rho}{B\rho}$$

Recoils leave target with a range of momentum/energy values and angles due to kinematics of the reaction

$$p_{\mathrm{recoil}} = \sqrt{2m_A E_A} \pm p_\gamma \qquad \theta_{\mathrm{recoil,max}} = \arctan\left(\frac{p_\gamma}{\sqrt{2m_A E_A}}\right)$$

Recoils must be transported within defined parameter bounds

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

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

Importance of Acceptances

In an experiment, all produced recoils must be transported to the detector plane

Verifying the acceptance will:

- eliminate St. George as a potential source of uncertainty
- show the beam rejection properties are sufficient to measure the cross section

Once verified for enough $B\rho$ and $E\rho$ possibilities, separator has a **single tune** that is scaled to new values

Acceptance Measurements

Types of Acceptances

The goal is for 100 % of the particles to make it to the final detector plane

- “particles” are produced recoils or incident test beam
- measure with Faraday cups or particle detectors

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change the particle energy without interfering with other properties

Angular
change the deflection of the particle at the target location

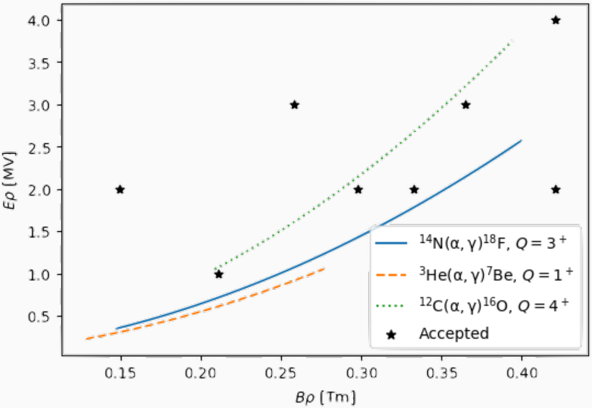
Joint
adjust both at the same time

Energy Acceptance

For a particle beam with a given $B\rho$ and $E\rho$:

- Tune the test beam to a given energy, and tune St. George for that energy
- Verify 100 % transmission, adjust the tune if necessary
- Adjust the beam energy within the energy acceptance bounds and measure transmission
- Adjust the tune if necessary to have 100 % transmission for all possible energy changes within the acceptance bounds

Energy acceptance results in a single tune for St. George



Adapted from Meisel, **Moran**, *et al.*, 2017

Angular Acceptance

For a particle beam with a given $B\rho$ and $E\rho$:

- Tune the test beam to a given energy, and tune St. George for that energy
- Verify 100 % transmission, adjust the tune if necessary
- "Deflect" the beam at the target location within the acceptance bounds (horizontally and vertically)
- Adjust the tune if necessary to have 100 % transmission for all possible angular changes within the acceptance bounds

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

- target properties matched to test beam selection
- limited by diagnostic equipment (can't use a detector due to high-intensity beam)
- energy and angular distribution make it more difficult to refine the tune if we don't have 100 % transmission

Reaction Measurements

Use the known kinematics of the reaction to gradual move toward a full acceptance solution

- known cross section, angular and energy distribution, etc.
- tune so that 100 % of the produced particles captured by detector (can check with incident beam as well)
- St. George then has *at least* the acceptance necessary for the reaction

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

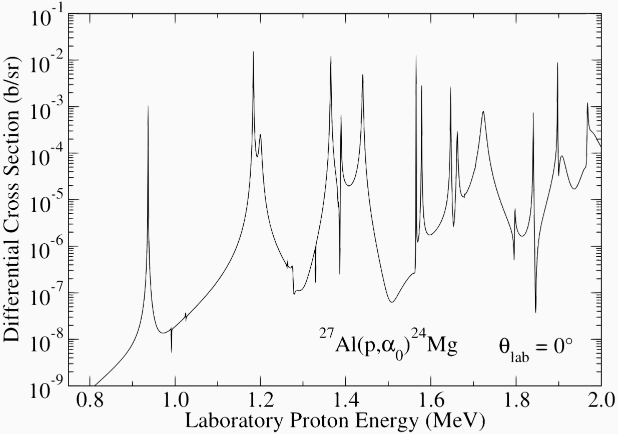
Focus on two isolated resonances:

- high energy: $E_\mathrm{p} = 1.36$ MeV → $E_\alpha = 2.77$ MeV
- low energy: $E_\mathrm{p} = 1.18$ MeV → $E_\alpha = 2.59$ MeV
- both are $2+$ resonances with isotropic angular distribution

For both reactions, kinematics and target effects give $\Delta E/E = 3\,\%$

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

Cross section is well-known, reducing it as an uncertainty in the measurements



Courtesy of R. J. deBoer, 2017

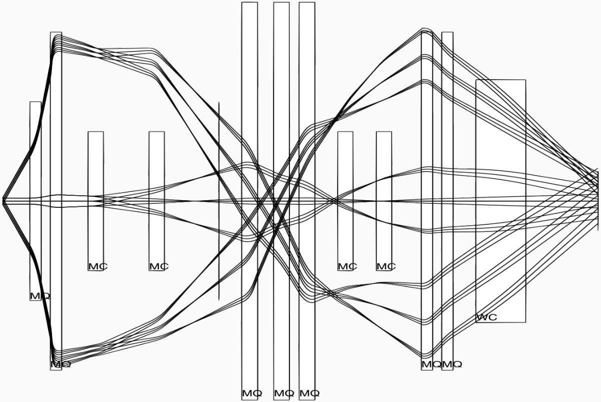
Alternate Tune

Due to limits of previous work at the time, we have to move our detector system up to the Wien filter focal plane

- can replicate this work once angular acceptance measurements extended to last section of St. George
- beam suppression is sufficient to reject the incident proton beam before the detector
- “canonical” St. George tune cannot be used

Alternate Tune

Determined expected field strengths using `COSY` and verified with direct particle transport before the experiment



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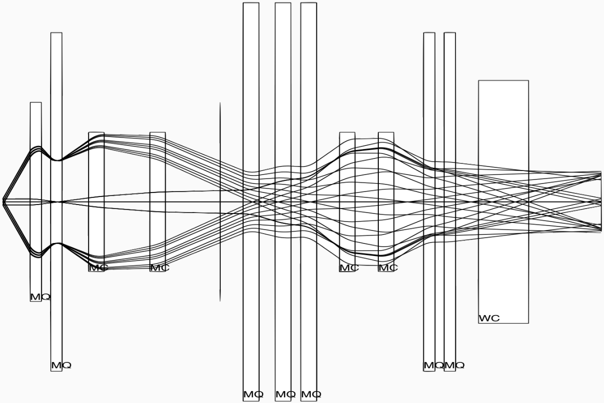


The reaction $^{27}\mathrm{Al}(\mathrm{p},\alpha)^{24}\mathrm{Mg}$ emits the α particles within an isotropic angular distribution

- target cup aperture limits entrance to $\approx$ 40 mrad acceptance
- we will attempt to transport all α particles (based on the cross section) to the detector

This is an alternate to a full acceptance measurement with St. George (limited energy acceptance, subset of separator)

- built upon previous acceptance measurements
- direct He beam used to verify acceptance before experiment at resonance energies

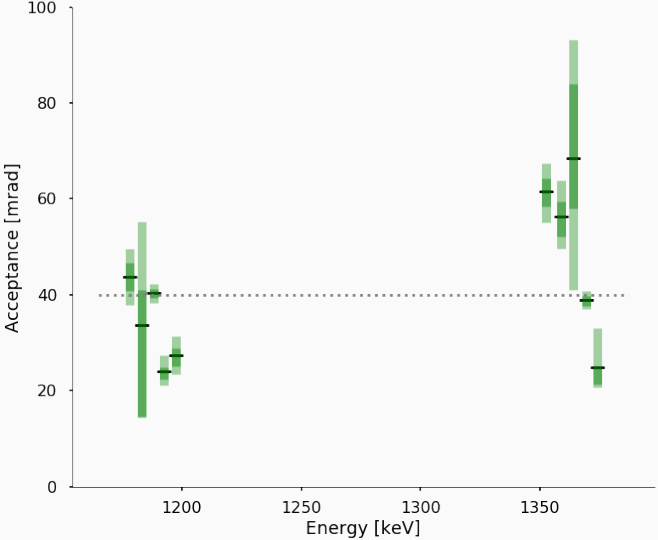
Acceptance

We can relate the yield at our detector to what we expect from the cross section to determine our angular acceptance

$$\theta = \arccos\left(1 - 2\frac{Y_{\text{experiment}}}{Y_{\text{theory}}}\right)$$

This assumes a "symmetric" acceptance (constant opening angle for acceptance cone)

Acceptance Measurements



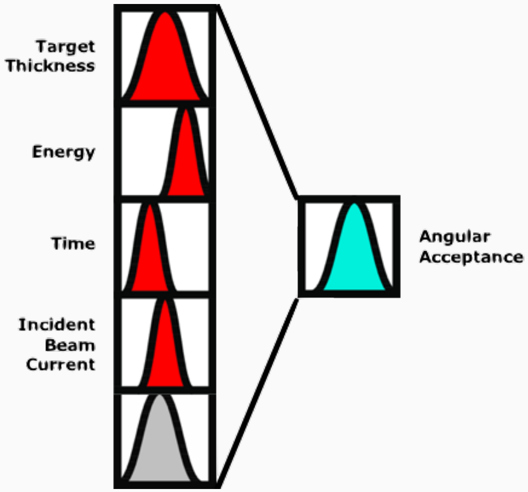
Acceptance Uncertainty

We can attribute the uncertainty at each measurement to the underlying variables within our control: energy, current, time, and target thickness

- E_{res} and higher: dominated by current uncertainty
- energies lower than E_{res}: dominated by energy uncertainty
- final irreducible uncertainty (cross section, counting statistics, etc.) cannot be avoided

Attribution is done through a hybrid Monte Carlo/Bayesian approach, where we adjust our priors and observe the change in the outcome

Uncertainty Decomposition



Future Directions

St. George has been shown to have the following acceptances:

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

Preliminary beam reduction measurements on the order of 10^{12}

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

The Future of St. George

- St. George can be used for a restricted subset of experiments
- Ability to fine-tune the separator and verify its properties over a range of $B\rho$ and $E\rho$ values essential for future experiments
- Diagnostic equipment and procedures developed to be applied to future separators (SECAR)
- Final parts of the St. George system (HIPPO supersonic jet gas target, full detector system, additional diagnostics, etc) will unlock the full range of experimental work

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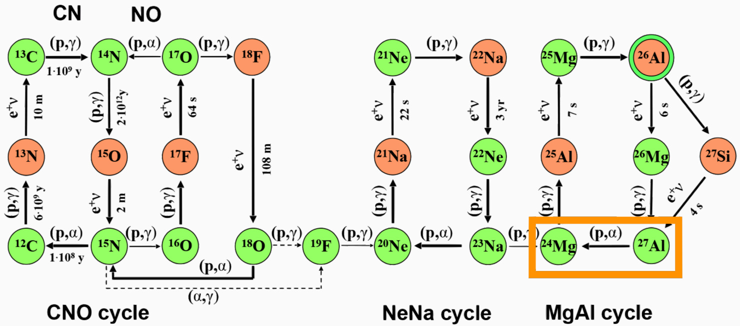
Hydrogen Burning



Magnetic and Electric Rigidities

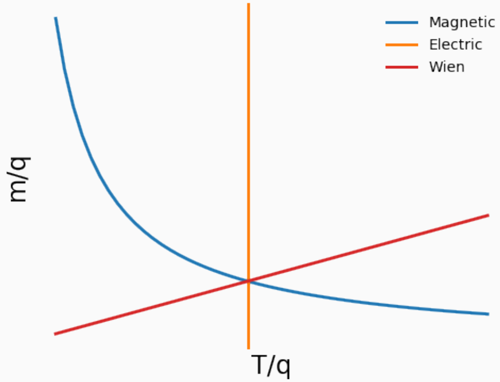
Elements within St. George are tuned for the $B\rho$ and $E\rho$ of the recoil particle

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

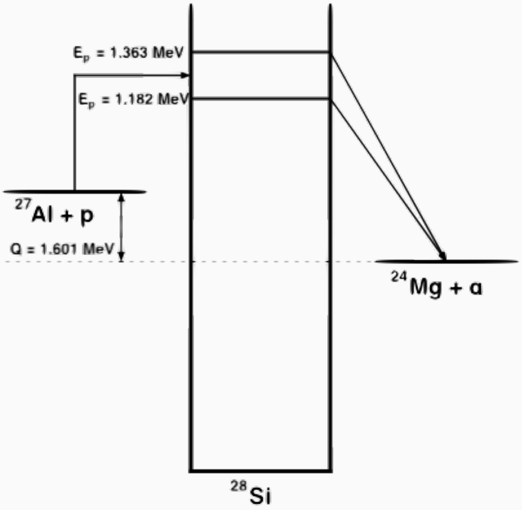
Design limits: $0.1 \leq B\rho \leq 0.45$ Tm and $E\rho \leq 5.7$ MV

Particle Selection

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



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



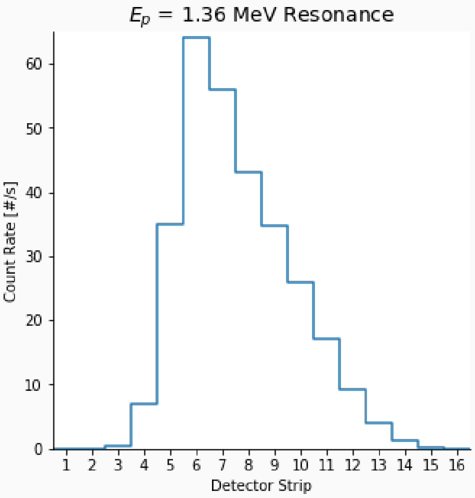
95 % Contributions

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

Detector Spectrum



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