Verification of Recoil Separator Properties Through Reaction Measurements

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November 9, 2018

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Introduction

Primary burning processes for energy production depend on the properties of the star (mass, temperature, enrichment, life cycle stage, etc.)

Hydrogen burning:

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

Helium burning:

- Triple-α process
- $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ determines C/O ratio
- primary sources of neutrons for *s*-process are $^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$ and $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ (AGB stars)
- breakout reactions from cyclic H burning (e.g. $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}$)

Radiative Capture

Reactions like (p,γ) and (α,γ)

Detecting the γ can be difficult due to:

- large background count rates
- low count rates
- HPGe detector efficiency

Studied focused primarily on resonances to reduce the effect of these problems

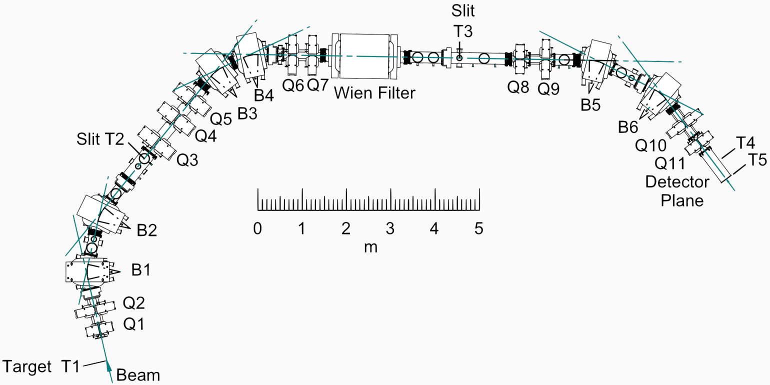
We can instead detect the heavy recoil particle

- perform the reaction in inverse kinematics $a(A, B)\gamma$
- heavy projectile impinges on light target, heavy recoil escapes the target
- produced recoil leaves the target and detected by high-efficiency detector

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

Recoil Separation

St. George



Couder *et al.*, 2008

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

selects a single momentum: $p = q \cdot B\rho$

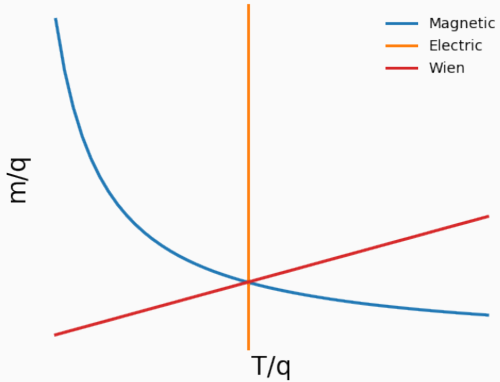
Electric Selection

selects a single energy: $T = q/2 \cdot E\rho$

Wien Filter Selection

selects a single velocity: $v = E/B$

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



Recoils can only 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

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

Ensures that all of the produced recoils and none of the incident beam particles for a given reaction reach the detector plane

- produced recoils can be extremely rare (1 for every 10^{15} beam particles)

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

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

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Angular
change the deflection of the particle at the target location

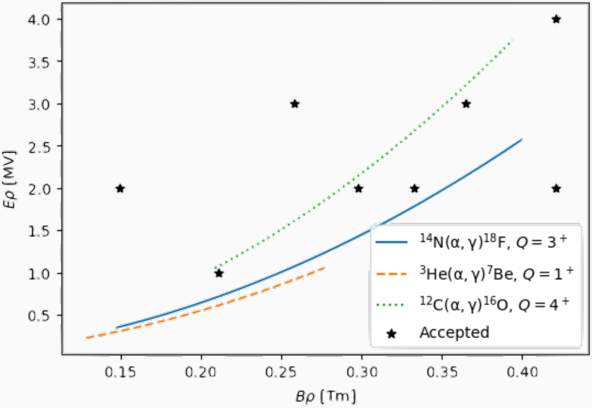
Joint
adjust both at the same time

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 completed for a subset of $B\rho$ and $E\rho$ test particles (100 % transmission found through current measurements)



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

- 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

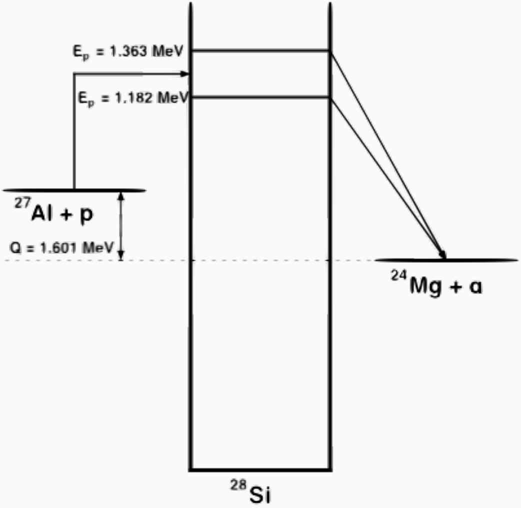
Justification for Reaction Measurements

Joint acceptance measurements are costly to cover all of the possibilities

Reactions can be used to “bootstrap” the process

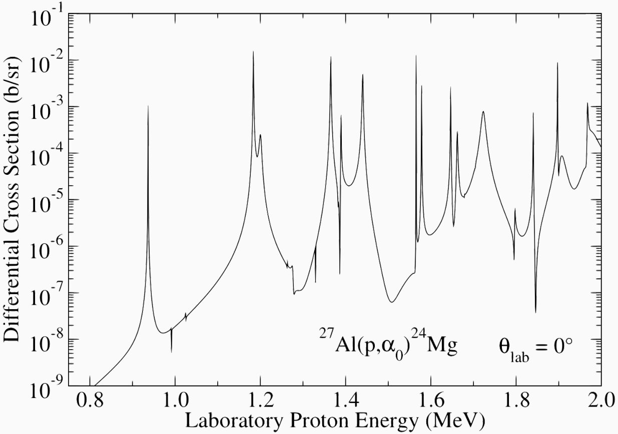
- Reactions have a known cross section, angular and energy spread, etc.
- If all of the expected produced recoils reach the detector, the separator is performing optimally

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



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

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



Courtesy of R. J. deBoer, 2017

Alternate Tune

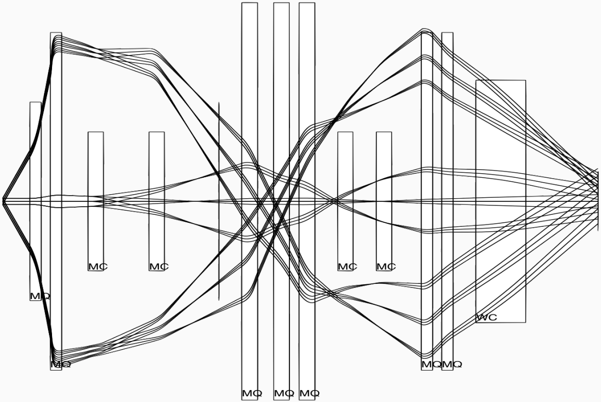
Since the last segment of St. George has not been fully commissioned (full angular acceptance not yet verified), we can use the focal plane after the Wien filter to perform cross section measurements

For (p, α) reactions, the expected 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

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



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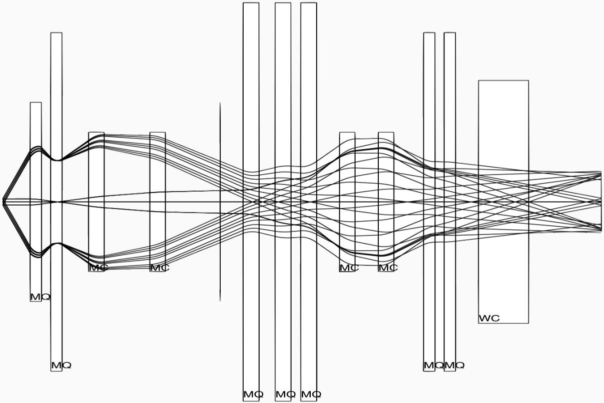


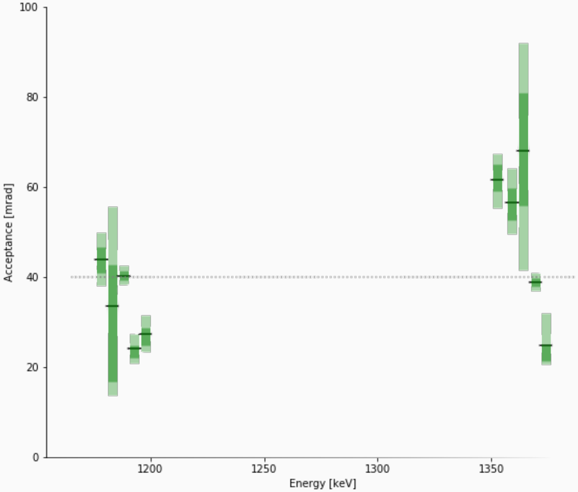
Angular Acceptance Measurement

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

- target cup restricts us to ≈ 40 mrad acceptance
- we will attempt to transport all α particles to the detector

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


100
80
60
40
20
0
Acceptance [mrad]
1200
1250
1300
1350
Energy [keV]

Acceptance Uncertainty

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

- On-resonance: dominated by current uncertainty
- Below resonance: dominated by energy uncertainty
- Attribution through a hybrid Monte Carlo/Bayesian approach

Final irreducible uncertainty cannot be avoided, but controllable uncertainty can be minimized

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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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

$\dagger$: 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