Verification of Recoil Separator Properties Through Reaction Measurements

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Introduction

Capture Reactions

Stellar energy production depends on the interior conditions of the star, such as the isotopic enrichment and temperature/pressure

Hydrogen burning: (p, γ) reactions

- low mass energy production through *pp*-chains
- massive stars core and shell burning through CNO, NeNa, and MgAl cycles

Helium burning: (α, γ) reactions

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

Commonly studied by detecting the emitted γ

Detection is difficult due to:

- large background count rates (target impurities, background radiation)
- limited by HPGe detector efficiency
- potentially low count rates

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

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
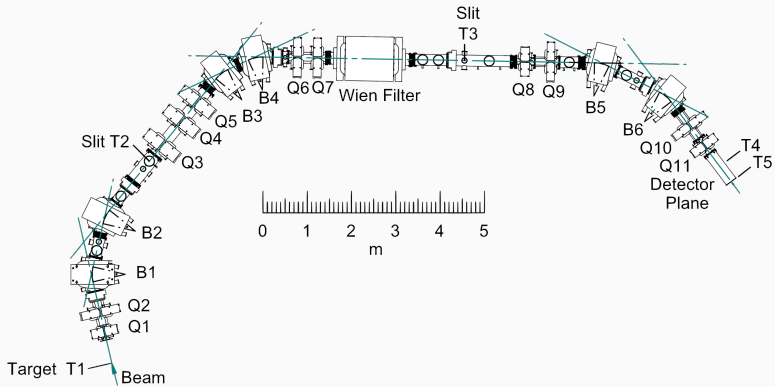
Couder et al., 2008

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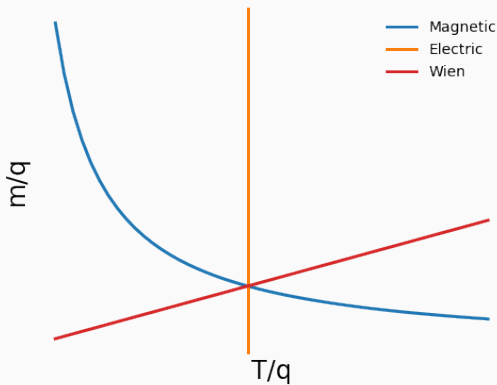selects a single momentum: $p = q \cdot B\rho$

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

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

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

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

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

Can divide commissioning between three possible cases:

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Joint
adjust both at the same time

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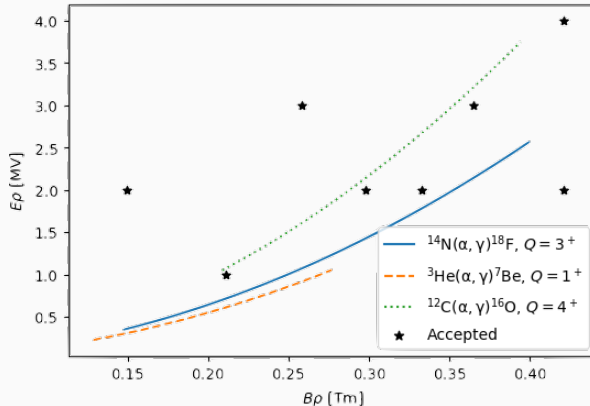
All experiments will have an angular and energy spread, so must confirm that the acceptances can be achieved at the same time

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

Joint acceptance measurements are costly to cover all of the possibilities
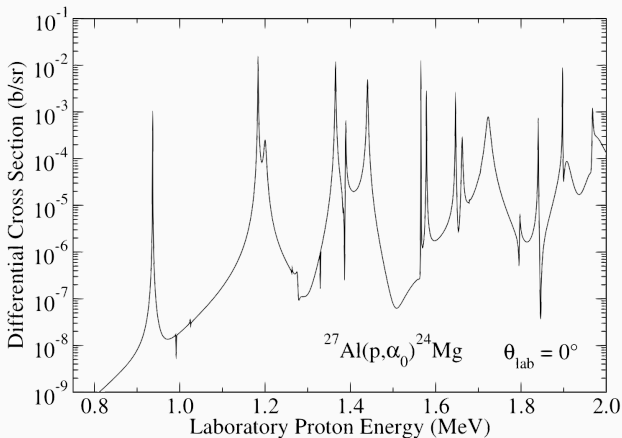
Reactions can be used to "bootstrap" the process

- 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

$E_p = 1.363$ MeV

$E_p = 1.182$ MeV

^{27}Al + p

Q = 1.601 MeV

^{24}Mg + α

^{28}Si
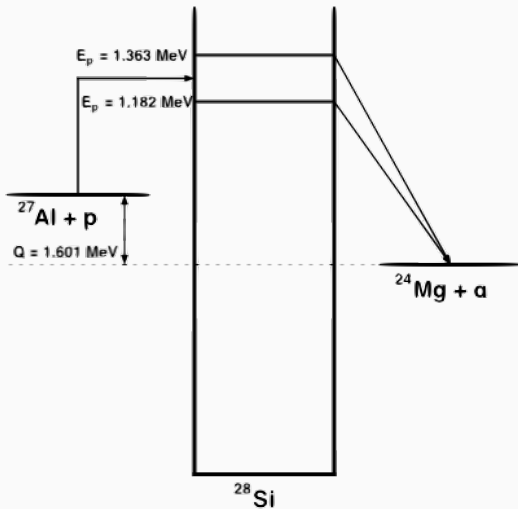
Cross section is well-known, reducing it as an uncertainty in the measurements

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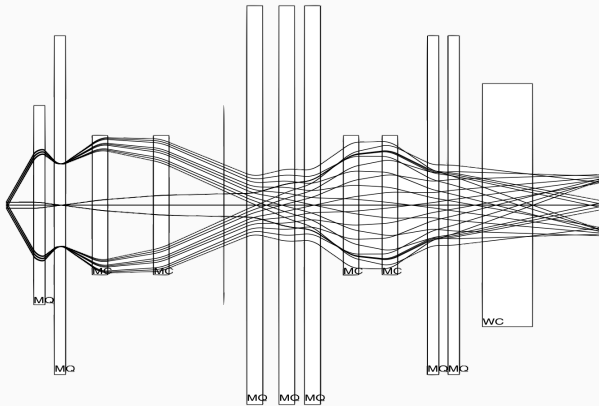
Determined expected field strengths using COSY and verified with
direct particle transport before the experiment
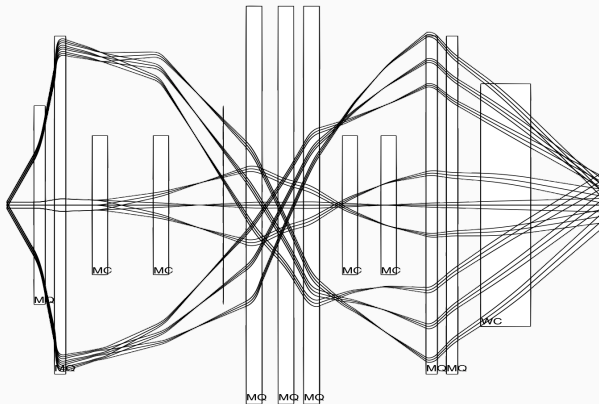
Determined expected field strengths using COSY and verified with direct particle transport before the experiment

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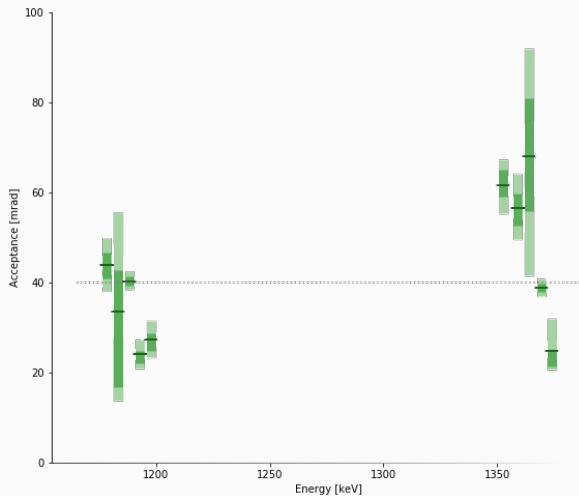
We can attribute the uncertainty at each measurement to the underlying variables within our control: energy, current, time, and target thickness

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

Final irreducible uncertainty comes from the underlying cross section, particle count rate, potential non-uniformity, etc.

Future Directions

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

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

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

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

- 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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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
$\delta E, \delta t$	47.4	7.2	96.7	73.4	93.4	63.8	39.6	13.2	101.4	50.2
$\delta E, \delta i$	12.0	1.7	23.0	18.1	55.5	20.1	12.5	3.0	24.0	42.7
$\delta E, \delta \Delta$	46.8	7.6	100.3	72.0	73.8	60.4	38.0	12.9	103.5	20.6
$\delta t, \delta i$	88.0	97.2	13.4	50.1	64.6	78.2	96.8	96.9	15.2	94.7
$\delta t, \delta \Delta$	98.5	98.3	98.2	86.7	83.5	99.4	102.0	98.8	99.8	75.9
$\delta i, \delta \Delta$	87.7	95.9	26.6	29.7	29.1	76.9	93.4	93.5	25.6	72.9
$\delta E, \delta t, \delta i$	11.1	1.0	8.1	18.6	54.0	17.8	11.5	1.5	8.3	43.5
$\delta E, \delta t, \delta \Delta$	47.4	7.2	96.8	70.1	76.0	59.9	39.0	12.9	99.4	20.4
$\delta E, \delta i, \delta \Delta$	7.9	1.6	21.4	8.4	5.0	8.4	7.4	2.7	22.4	4.6
$\delta t, \delta i, \delta \Delta$	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

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 ±%	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