Energy acceptance of the St. George recoil separator

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Abstract

Radiative alpha-capture, (α, γ) , reactions play a critical role in nucleosynthesis and nuclear energy generation in a variety of astrophysical environments. The St. George recoil separator at the University of Notre Dame's Nuclear Science Laboratory was developed to measure (α, γ) reactions in inverse kinematics via recoil detection in order to obtain nuclear reaction cross sections at the low energies of astrophysical interest, while avoiding the γ -background that plagues traditional measurement techniques. Due to the γ ray produced by the nuclear reaction at the target location, recoil nuclei are produced with a variety of energies and angles, all of which must be accepted by St. George in order to accurately determine the reaction cross section. We demonstrate the energy acceptance of the St. George recoil separator using primary beams of helium, hydrogen, neon, and oxygen, spanning the magnetic and electric rigidity phase space populated by recoils of anticipated (α, γ) reaction measurements. We find the performance of St. George meets the design specifications, demonstrating its suitability for (α, γ) reaction measurements of astrophysical interest.

Keywords:

Recoil mass separator; Radiative alpha-capture;

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1. Introduction

Precise (α, γ) reaction cross sections are crucial to accurately model a variety of astrophysical phenomena [1], such as the production of the s -process neutron-source nucleus ^{22}Ne [2], the carbon-to-oxygen abundance ratio of stellar cores [3], nucleosynthesis in massive stars [4], the abundance of ^{44}Ti produced in core-collapse supernovae [5], and the nuclear reaction sequence occurring in type-I x-ray bursts [6]. Owing to the relatively low kinetic energies of nuclei in the relevant astrophysical conditions, traditional nuclear reaction measurements in which the outgoing γ ray is measured often suffer from prohibitively high γ -backgrounds and, for high Q -value reactions, complicated γ -ray cascades [7]. One approach which has been adopted to overcome this difficulty employs inverse kinematics and a recoil separator, in which the nuclear recoil produced in the (α, γ) reaction is electromagnetically separated from unreacted beam nuclei on the basis of their mass differences and identified with various combinations of time-of-flight and energy-loss measurements [8]. Recoil- γ coincidences substantially improve the signal-to-noise

compared to traditional techniques and provide significantly reduced cross section uncertainties [9].

In order to undertake (α, γ) reaction cross section studies at astrophysically relevant energies for nuclei with nuclear mass $A \leq 40$, the St. George recoil separator at the University of Notre Dame's Nuclear Science Laboratory (NSL) has been developed [10]. The recoil separator technique generally relies on using inverse kinematics, where a heavy ion beam is impinged on a lighter nuclear target; for (α, γ) reactions with St. George, the HIPPO helium gas-jet produces the desired target [11, 12]. Unreacted incident beam particles and nuclear reaction recoils both exit the gas-jet with similar momenta. For a typical cross section of $1 \mu\text{b}$ and a gas-jet density of 10^{17} atoms/cm², the ratio for recoils to unreacted beam nuclei is 1 part in 10^{13} . In order to be effective, a recoil separator must accept all (or most [13]) of the nuclear reaction recoils and have a mass separation sufficient to produce a recoil/beam ratio allowing for practicable particle identification.

Due to the prompt γ -ray emission, nuclear reaction recoils leave the target with a range of energies and angles, according to the reaction Q -value, γ -ray cascade, and γ emission angles [8]. For St. George, the 'acceptance' is the angle-energy phase space of nuclear reaction recoils that the separator transmits to the recoil detection-plane with 100% efficiency. Accurate cross section measurements with the recoil separator technique rely on a thorough charac-

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49 terization of the recoil separator acceptance. 99
50 In a crucial first step of the St. George recoil separa-100
51 tor commissioning process, we have determined the energy101
52 acceptance of St. George for a range of beam species, span-102
53 ning the magnetic and electric rigidity phase space antic-103
54 ipated for recoils of future (α, γ) cross section measure-104
55 ments. We discuss the experimental set-up in Section 2,105
56 our energy acceptance measurement method in Section 3,106
57 and the measurement results and discussion thereof in Sec-107
58 tion 4, prior to summarizing our work in Section 5. 108

59 2. Experimental set-up 109

60 Stable ion beams are delivered to St. George by the112
61 recently installed 5 MV single-ended Pelletron accelerator113
62 St. Ana, from National Electrostatics Corporation², at the114
63 NSL. Ion beams produced by a Nanogan ECR ion source,115
64 from Pantechnik³, are accelerated with St. Ana, energy-116
65 selected by a 90° analyzing magnet, and transported down117
66 a ≈ 22 m beam-line, which contains several quadrupole and118
67 steerer magnets, to St. George with beam intensities up-119
68 wards of 100 μA . The configuration of the transport line120
69 at the time of this experiment, shown in Figure 1, con-121
70 sisted of the horizontal X and vertical Y steerer magnet122
71 pair XY₁ and XY₂ following the accelerator momentum-123
72 analyzing magnet and preceding the quadrupole doublet124
73 QD₁, followed by said quadrupole doublet, steerer pair125
74 XY₃ and XY₄, the second quadrupole doublet QD₂, the126
75 single steerer XY₅, a dipole ‘switching’ magnet, and (not127
76 shown) an XY steerer and a quadrupole triplet. Beam po-128
77 sition monitors, Faraday cups, and fluorescing quartz win-
78 dows are employed at various locations along the transport,129
79 line to provide diagnostic information during beam tuning.

80 St. George consists of eighteen ion optical elements: six130
81 dipole magnets, eleven quadrupole magnets (four doublets131
82 and one triplet), and a Wien filter, as shown in Figure 2.132
83 The last quadrupole, Q11, is followed by an ion detection133
84 chamber in which ions can be identified via total energy134
85 loss and time-of-flight. Several ports are available along135
86 the St. George beam line and on the magnets for diag-136
87 nostic equipment to assess the properties of transmitted137
88 ions. For future (α, γ) reaction measurements, St. George138
89 will be preceded by the HIPPO gas-jet [11], which will139
90 serve as a relatively uniform high-density reaction tar-140
91 get [12]. For the acceptance measurements presented here,141
92 the primary beam from St. Ana was transmitted directly142
93 into St. George, where two 2 mm diameter collimators143
94 20 cm apart were employed just prior to the entrance of144
95 St. George to ensure the beam entered St. George on-axis.145
96 The collimators had the added benefit of limiting beam146
97 currents to a few μA in order to protect diagnostic equip-147
98 ment. 148

Diagnostic equipment along St. George includes Fara-
day cups, fluorescing quartz windows, and electrically in-
sulated slits. Faraday cups, used to monitor beam trans-
mission, are located following the first, second, and fifth
dipole magnets, the Wien filter, and the eleventh quadrupole
magnet. Each Faraday cup is equipped with a -300 V sec-
ondary electron suppression electrode to ensure reliable
current readings. Electrically insulated slits with current
readouts, used for the energy acceptance measurements to
monitor the beam width and centering, are located before
and after each dipole magnet, as well as 1.59 m down-
stream of the Wien filter exit. These slits will be used
in future (α, γ) reaction measurements to improve beam-
rejection properties of St. George. In particular, the slits
following the Wien filter, referred to as the ‘mass slits’,
are located at the position optimized for beam-rejection,
which provides a horizontal achromatic focus for recoil nu-
clei. The slits and Faraday cups each have a lower-limit
for their current sensitivity of ≈ 1 pA. The 0° exit port of
the first, third, and fifth dipole magnets, as well as the exit
port of the recoil detection chamber, are equipped with flu-
orescing quartz windows from McMaster–Carr⁴, outside of
which (at atmosphere) is a camera. The quartz windows
are used to assess the beam shape at their respective lo-
cations and, more importantly, are used to determine if
the beam is being transported along the ion-optical cen-
ter of the quadrupole magnets preceding that quartz. The
quartz viewers also serve as a crude way to determine beam
transmission, as their fluorescence is visible at relatively
low beam currents.

3. Energy acceptance measurement method

In inverse kinematics, the products of an (α, γ) reaction
are emitted from the target position with the same aver-
age momentum as the unreacted beam in a narrow cone,
where the opening angle is primarily determined by the re-
action Q -value and center-of-mass energy (See Equation 13
of Reference [8]). St. George is designed to accept and
transmit all recoil nuclei of a single charge-state emitted
from the target with a maximum angle of ± 40 mrad and
energy spread from the central recoil energy of $\pm 8\%$ [10].
The maximum recoil energy deviations occur when γ rays
are emitted at 0° or 180° in the center of mass.

In this study, we mimicked the recoil energy spread by
employing a beam in the absence of a target in order to
verify that, at 0° (i.e. for no angular deflection), 100%
of ions within $\pm 8\%$ of the energy for which the separator
was tuned were transmitted to the end of St. George. A
similar technique was employed to determine the energy
acceptance of the ERNA recoil separator [14, 15]. Trans-
mission through the recoil separator was determined by
comparing beam current measurements provided by the

²<http://www.pelletron.com>

³<http://www.pantechnik.com>

⁴<http://www.mcmaster.com>

Figure 1: Schematic of the St. Ana accelerator and transport beam line to St. George (The vertical accelerator beam line is folded here for convenience.). “QD” correspond to quadrupole magnet doublets, which are used to focus the beam, while “XY” correspond to steerer magnets, which are used to ensure the beam is transported down the ion optical centers of the quadrupoles via small corrections.

Faraday cups at the target location and in the recoil de-
detection plane, where equal currents correspond to 100%
transmission. Various charge states and beam energies
were employed for ions of helium, hydrogen, neon, and oxy-
gen in order to determine the energy acceptance for nuclei
within the designed electric and magnetic rigidity⁵ limits
of St. George, $E\rho \leq 5.7$ MV and $0.1 \text{ Tm} \leq B\rho \leq 0.45 \text{ Tm}$,
respectively [10].

The energy acceptance measurements for each species,
defined by a given $B\rho$ – $E\rho$, consisted of two main proce-
dures, which each consisted of several steps. Summarized
briefly, the first procedure consisted of adjusting the mag-
netic elements prior to and within St. George to ensure
that the ion beam was traveling down the ion optical cen-
ter of the separator when at the tune-energy. The second
procedure consisted of adjusting the focusing elements
within St. George to maximize the energy range about the
tune-energy within which all ions would be transmitted
through the separator. The second procedure was neces-
sary to find the optimal tune about the nominal ion optical
settings [10] provided by calculations performed with the
software COSY Infinity⁶ [16].

The first procedure, centering the ion beam within
St. George so that quadrupole magnets only provided fo-
cusing and not beam steering, was accomplished by per-
forming the following steps:

- 1.1. The accelerator magnetic and electrostatic elements
and St. Ana transport beam-line magnetic elements

⁵For an ion of kinetic energy T in MeV, mass A in MeV, and
charge q in units of the electron charge, $B\rho = \frac{\sqrt{T^2 + 2TA}}{300q} \text{ Tm}$ and
 $E\rho = \frac{2T}{q} \text{ MV}$.

⁶http://www.bt.pa.msu.edu/index_cosy.htm

(See Figure 1.) were adjusted to deliver an ion beam
of the chosen species and energy with a current of
several hundred nA to the St. George target loca-
tion. The accelerator and transport line elements
were adjusted to send beam through the two colli-
mators at the target location.

- 1.2. With no field in the B1 dipole magnet⁷, the beam
was impinging on the B1 0° quartz viewer. The Q1
and Q2 quadrupole magnets of St. George separately
had their field strengths adjusted from the minimum
to $> 50\%$ of the maximum field strength. The image
of the beam-spot on the B1 0° exit-port fluorescing-
quartz was monitored for shifts in the spot centroid.
Any deviation from a ‘non-steering’ beam, shown in
Figure 3, was corrected by adjusting the last few
steering magnets of the St. Ana transport line.
- 1.3. The B1 and B2 dipole magnets were adjusted to
their nominal fields for the species of interest at the
tune-energy, sending the beam to the B3 0° exit-port
quartz-viewer, with no field on the B3 dipole. The
correction process of the previous step was repeated.
Though this step is seemingly redundant, the longer
distance of travel of the beam from Q1 and Q2 to
this quartz provided a higher sensitivity to the pres-
ence of steering in the ion optics. This step could
not be repeated for the 0° exit port of the B5 dipole
magnet since the ion beam was too defocused at that
location without using quadrupole magnets Q3–Q9,
a necessary condition to test for beam steering.

⁷We note that residual magnetic fields on the dipoles do not im-
pact our methods, as the effect would only be a horizontal translation
of the beam spot on a quartz viewer.

Figure 2: Schematic of the St. George recoil separator, where the labels correspond to “B” for dipole magnets, “Q” for quadrupole magnets, “WF” for the Wien filter, and “MS” for the mass slits. The target position is located upstream of Q1 and the recoil detection system (not shown) is downstream of Q11.

- 1.4. With fields on Q1 and Q2 set to provide a narrow waist at the B3 0° exit-port quartz-viewer, the B1 and B2 fields were adjusted to minimize steering in the quadrupole magnets Q3–Q5. These adjustments were generally within $\lesssim 0.3\%$ of the calculated optimal field setting. A tune with simultaneously non-steering Q1–Q2 and Q3–Q5 was not achievable, likely due to a minor misalignment of the quadrupole magnets. However, the shift of the beam spot position from steering was minimized to a vertical deflection of $\lesssim 2.5$ mm on the quartz viewer, which corresponds to a maximum deflection of $\lesssim 2$ mrad by the Q5 quadrupole magnet at maximum field strength. Given the Q5 field gradient, the observed deflection indicates the vertical misalignment of the Q3–Q5 quadrupoles is $\lesssim 1$ mm with respect to the Q1–Q2.
- 1.5. Quadrupole magnets Q1–Q5 and dipole magnets B3–B4 were adjusted to their nominal fields for the species of interest at the tune-energy, sending the beam to the B5 0° exit-port quartz-viewer, with no field on the B5 dipole. A small electric field was applied to the Wien filter to offset the residual magnetic field. The B3 and B4 fields were adjusted to achieve the non-steering condition on the B5 0° exit-port quartz-viewer for the Q6–Q7 quadrupole magnets.
- 1.6. The Wien filter magnetic and electric fields, as well as the magnetic field clamps, were set to their nominal values for the species of interest at the tune-energy. The Wien filter magnetic field was then adjusted to achieve the non-steering condition for the Q8–Q9 quadrupole magnets on the B5 0° exit-port quartz-viewer.
- 1.7. The electrically insulated slits with charge readouts located 1.59 m downstream of the Wien filter, the so-called ‘mass slits’, were then closed to the point of reading $\lesssim 1$ pA on the left and right mass slits. This provides a measurement of the beam width, which we

can use to estimate the anticipated beam-rejection of the separator.

- 1.8. The B5 and B6 dipole magnets were then set to and adjusted about their nominal field settings for the species of interest at the tune-energy until the non-steering condition was achieved for the quadrupole magnets Q10–Q11 on the quartz-viewer located on the 0° exit port of the recoil detection chamber.

The second procedure, maximizing the energy acceptance of St. George, was accomplished by performing the following steps:

- 2.1. Transmission was checked by monitoring the beam current on a collimator upstream of the target location and monitoring the beam current on Faraday cups at the target and recoil detection locations, while extending and retracting the target location Faraday cup (See Figure 4.). For the calculated ion optical tune for the species of interest, we did not find 100% beam transmission from the target location to the recoil detector plane. Therefore, the quadrupole magnets Q1–Q11 required adjustment to achieve 100% transmission. With all other quadrupole magnets set to their nominal field setting, each quadrupole was individually adjusted in order to maximize the beam transmission to the recoil detector plane. Then, for each of the N quadrupole magnets which improved beam transmission upon adjustment, the field was adjusted from the nominally calculated value by $1/N$ times the individual adjustment required for that quadrupole magnet to improve beam transmission. This naïve scaling procedure resulted in 100% beam transmission (See Figure 4a.).
- 2.2. Having achieved 100% beam transmission for the tune-energy, the St. Ana terminal voltage was adjusted so that the beam would have an energy -8%

Figure 3: Demonstration of a non-steering ion optical tune. (a)–(d) show images of the B3 dipole magnet 0° quartz viewer for a 1 MeV H^+ beam, where the Q2 quadrupole magnet is scaled from its minimum field strength (a) up to ≈ 0.13 T, which is $\sim 50\%$ of its maximum value (d), where (b) and (c) are at arbitrary intermediate field strengths. The red oval and black crosses provide a reference for the size and center of the beam. The height and width of the red oval correspond to ≈ 3 mm and ≈ 1.5 mm, respectively, on the quartz viewer.

below the tune-energy, e.g. to 1.84 MeV from a tune-energy of 2 MeV. In general, 100% transmission was not achieved. If beam current was lost on the mass slits, quadrupole magnets Q1–Q6 were adjusted as described in the previous step to optimize beam transmission. Once beam current was removed from the mass slits, quadrupole magnets Q8–Q11 were adjusted as described in the previous step to optimize beam transmission.

2.3. Beam transmission was checked again with the accelerator adjusted back to the tune-energy. If 100% beam transmission was not achieved, the procedure from the previous step was repeated. This and the previous step were performed iteratively until 100% beam transmission was obtained for both the tune-energy and the $-8\% \frac{\Delta E}{E}$ energy.

2.4. Having achieved 100% transmission for the tune-energy and -8% below the tune-energy, the St. Ana terminal voltage was adjusted so that the beam would have an energy $+8\%$ above the tune-energy, e.g. to 2.16 MeV from a tune-energy of 2 MeV. If 100%

transmission was not achieved, adjustments needed to be made to Q1–Q11. These adjustments, along with a re-verification of transmission at the tune-energy and -8% below the tune-energy, were performed in an iterative fashion, as described in the previous step. In general, we found the ion optical tune needed little to no adjustment to achieve 100% transmission at $+8\%$ above the tune-energy once 100% transmission was achieved for the tune-energy and -8% below the tune-energy.

We note that the second of the two aforementioned procedures was greatly expedited for ensuing energy acceptance measurements, as the suspected optimum values for the nominal tune were improved with time. For instance, for the third successful energy acceptance measurement only a single adjustment of quadrupole magnets Q10–Q11 was required in order to achieve $\pm 8\%$ energy acceptance.

Figure 4 demonstrates $\pm 8\%$ energy-acceptance for a 2 MeV $^{16}O^{2+}$ beam. The fluctuations observed in beam intensity are thought to be mainly due to instabilities in the St. Ana ECR ion source. The spikes in current for the Faraday cup at the target location following its insertion and retraction are thought to be due to current induced by the motion of the cup apparatus.

As seen in Figure 5, we observe full transmission to a precision of ~ 1 nA for a beam intensity of ~ 100 nA, i.e. $> 99\%$.

4. Results and Discussion

Energy acceptance measurements were performed as described in the previous section for 8 ion beams, which were chosen to span the phase space of $E\rho$ and $B\rho$ where recoil nuclei from (α, γ) reactions of astrophysical interest are anticipated. Table 1 lists the ion beams for which an energy acceptance measurement was performed.

Table 1: Ion beams for which $\pm 8\%$ energy acceptance was verified for the St. George recoil separator. Uncertainties for kinetic energy T , magnetic rigidity $B\rho$, and electric rigidity $E\rho$ are $\approx 1\%$, which is dominated by the present uncertainty of the analyzing magnet energy calibration.

Species	Mass [u]	Charge [e]	T [MeV]	$B\rho$ [Tm]	$E\rho$ [MV]
$^{16}O^{4+}$	16	4	2.0	0.211	1.0
$^1H^{1+}$	1	1	1.0	0.149	2.0
$^4He^{1+}$	4	1	1.0	0.298	2.0
$^{20}Ne^{4+}$	20	4	4.0	0.333	2.0
$^{16}O^{2+}$	16	2	2.0	0.421	2.0
$^4He^{2+}$	4	2	3.0	0.258	3.0
$^{16}O^{4+}$	16	4	6.0	0.365	3.0
$^{16}O^{4+}$	16	4	8.0	0.421	4.0

Figure 4: (color online.) Demonstration of 100% beam transmission through St. George for $^{16}\text{O}^{2+}$ ions with the recoil separator tuned for $B\rho = 0.421$ Tm, $E\rho = 2.0$ MV (2 MeV ions, in this case.). Figures (a), (b), and (c) show the beam current read at the target location (thick red lines), detector plane (thick blue-dashed lines), and collimator upstream of St. George used to monitor the incoming beam-current stability (thin black lines), for 2 MeV (a), 2.16 MeV (b), and 1.84 MeV (c) ions.

Figure 5: (color online.) Demonstration of $>99\%$ beam transmission through St. George for 2.16 MeV $^{16}\text{O}^{2+}$ ions with the recoil separator tuned for $B\rho = 0.421$ Tm, $E\rho = 2.0$ MV (2 MeV ions, in this case.). The ratio (left axis) of the current on the target-cup (red line) and detector cup (blue-dashed line) to the upstream collimator current (gray-dotted line, right axis) are shown for a time of near-constant upstream collimator current in order to avoid unwanted current induced by the motion of the target cup and (2) vertically: the average current ratio (black line) and standard deviation of the current ratio (gray band). The mean current ratios differ by less than 1%, indicating better than 99% beam transmission.

The field strengths for the ion-optical elements of St. George which were used for the energy acceptance measurements generally agreed with the values provided by the calculations featured in Reference [10]. However, the absence of an angular opening of the beam for the energy acceptance measurements performed here allowed for considerable flexibility in the ion optical tune of St. George. We expect the full angular and energy acceptance measurements performed in the future to provide much tighter constraints on the settings of the ion-optical elements.

We compare the magnetic rigidity of measured ions to recoils of astrophysical interest in Figure 6. Our measurements verify the required energy acceptance for the major-

ity of the range of astrophysical interest, where example cases considered for the design of St. George (See Table 1 of Reference [10].) are chosen for comparison. We show only the low $E\rho$ cases highlighted in Reference [10], since the high $E\rho$ cases are in general less astrophysically interesting due to the corresponding high kinetic energies that are absent in all but the highest temperature environments. Our acceptance measurements also demonstrate the capability to, for instance, repeat the $^3\text{He}(\alpha, \gamma)^7\text{Be}$ measurement performed with the recoil separator ERNA [18]. Such a measurement may help to improve constraints on Big Bang nucleosynthesis [6] and resolve discrepancies in solar fusion calculations [20], particularly if performed in conjunction with angle-resolved γ -detection at the target location. Furthermore, a direct measurement of $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ in the energy range previously studied in regular kinematics [19] is well within reach, which would help constrain the role of the $^{22}\text{Ne}(\alpha, n)$ s -process neutron source. Finally, we demonstrate our ability to accept ^{16}O recoils from $^{12}\text{C}(\alpha, \gamma)$, noting that the large angular acceptance anticipated for St. George will allow the lowest-energy direct measurement of this reaction to date.

We used the measured width of the beam at the mass slits, as determined in Step 1.7, to provide a first-order estimate of the anticipated beam rejection capabilities of St. George. The smallest anticipated spatial separation between beam and recoil nuclei provided by the Wien filter is ≈ 5 cm, which is for the case of an (α, γ) reaction on an $A = 40$ nucleus. In order to achieve the desired mass rejection of 1 part in 10^{15} , the magnitudes of the beam and recoil nuclei distributions must be similar at the location of the mass slits when the amplitude of the beam distribution is 10^{15} times larger than the amplitude of the recoil distribution. If we assume beam and recoil nuclei both have Gaussian horizontal distributions with the same width, but the beam distribution is 10^{15} larger in amplitude and has a centroid 5 cm horizontally displaced

Figure 6: (color online.) Rigidity phase space designed to be ac-421
cepted by the St. George recoil separator, where the $B\rho$ - $E\rho$ of ions
with a measured energy acceptance are indicated with black stars.422
Examples of recoils of astrophysical interest, low recoil-energy cases423
from Table 1 of Reference [10], assuming the most populous equilib-424
rium charge-state from the dilute gas model of Reference [17] that is425
within the $B\rho$ - $E\rho$ limits of St. George, are indicated by the red-filled426
circles. The solid blue line indicates the $B\rho$ - $E\rho$ space for $q = 2^+$ re-427
coils from the $^3\text{He}(\alpha, \gamma)^7\text{Be}$ reaction at the energies measured in the428
past with the recoil separator ERNA [18]. The long-dashed mauve429
line corresponds to $^{26}\text{Mg}^{6+}$ recoils from the $^{22}\text{Ne}(\alpha, \gamma)$ reaction for430
energies covered by a previous measurement in forward kinemat-431
ics [19]. The short-dashed green line corresponds to $^{16}\text{O}^{4+}$ recoils432
from $^{12}\text{C}(\alpha, \gamma)$ for center of mass energies from 700–3000 keV.433

from the recoil distribution centroid, a standard deviation434
of $\sigma \approx 4$ mm for both distributions is sufficient to achieve435
a 1:1 ratio of beam-to-recoil nuclei -3σ left of the beam-436
line center at the mass slits (3σ is chosen as the point437
for comparison since $\pm 3\sigma$ encompasses 99.8% of the recoil438
distribution.). In Step 1.7 we determined the width of the439
ion distribution at the mass slits is $w \leq 20$ mm, which cor-440
responds to intercepting $\lesssim 1$ pA out of the full ~ 100 nA441
ion intensity (i.e. $\sim 0.001\%$). For a Gaussian distribution,442
this implies a mass slit opening of $\pm 4.5\sigma$. Therefore, from443
our measurement of w , we deduce $\sigma \lesssim 2.2$ mm, which is444
far less than the 4 mm required for the desired mass re-445
jection. We note that our estimate is a best-case scenario446
since more pathological beam distributions are often ob-447
served⁸. Furthermore, this estimate neglects effects such448
as beam scattering within the separator which adversely449
impact the mass rejection.450

5. Conclusions

We present first results from commissioning of the St. George
recoil separator. By performing measurements of stable

⁸This has been observed by an in-beam fluorescing quartz viewer
located after the mass slits, which was added to the set-up following
the measurements described in this work.

ion beams of varied elements, charge-states, and energies,
we verify that St. George meets the design specifications of
providing an energy acceptance of $\pm 8\%$ within the separa-
tor's rigidity phase space. Our ultimately employed mag-
netic field strengths generally agree with predictions from
ion-optical calculations performed with COSY Infinity;
however, some deviations persist. We attribute present
disagreements to the absence of realistic field maps in the
calculations and an absence of an angular opening of the
beam at the target location, which will be more restric-
tive when determining the optimum ion-optical tune. Our
comparison to the properties of recoils from anticipated
future nuclear reaction measurements demonstrates that
St. George will be a vital tool used to obtain precise cross
sections for (α, γ) reactions of astrophysical interest.

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References

- [1] C. R. Brune, B. Davids, Ann. Rev. Nucl. Part. S. 65 (2015) 87.
- [2] F. Käppeler, et al., Astrophys. J. 437 (1994) 396.
- [3] M. Wiescher, F. Käppeler, K. Langanke, Annu. Rev. Astron. Astr. 50 (2012) 165.
- [4] C. Tur, A. Heger, S. Austin, Astrophys. J. 671 (2007) 821.
- [5] G. Magkotsios, F. X. Timmes, A. L. Hungerford, C. L. Fryer, P. A. Young, M. Wiescher, Astrophys. J. Suppl. S. 191 (2010) 66.
- [6] R. H. Cyburt, A. M. Amthor, A. Heger, E. Johnson, Z. Meisel, H. Schatz, K. Smith, Astrophys. J. 830 (2016) 55.
- [7] A. Cacioli, et al., Eur. Phys. J. A 39 (2009) 179.
- [8] C. Ruiz, U. Greife, U. Hager, Eur. Phys. J. A 50 (2014) 99.
- [9] C. Akers, et al., Phys. Rev. Lett. 110 (2013) 262502.
- [10] M. Couder, G. Berg, J. Görres, P. LeBlanc, L. Lamm, E. Stech, M. Wiescher, J. Hinnefeld, Nucl. Instrum. Meth. A 587 (2008) 35.
- [11] A. Kontos, et al., Nucl. Instrum. Meth. A 664 (2012) 272.
- [12] Z. Meisel, K. Shi, A. Jemcov, M. Couder, Nucl. Instrum. Meth. A 828 (2016) 8.
- [13] C. Matei, et al., Phys. Rev. Lett. 97 (2006) 242503.
- [14] D. Rogalla, et al., Nucl. Instrum. Meth. A 513 (2003) 573.
- [15] D. Rogalla, et al., Eur. Phys. J. A 6 (1999) 471.
- [16] K. Makino, M. Berz, Nucl. Instrum. Meth. A 427 (1999) 338.
- [17] R. O. Sayer, Rev. Phys. Appl. 12 (1977) 1543.
- [18] A. Di Leva, et al., Phys. Rev. Lett. 102 (2009) 232502.
- [19] K. Wolke, et al., Z. Phys. A 334 (1989) 491.
- [20] E. G. Adelberger, et al., Rev. Mod. Phys. 83 (2011) 195.