Recoil Separators for Nuclear Astrophysics studies

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Outline

• Nuclear astrophysics
• Radiative capture kinematics
• Past, present and future of recoil separator dedicated to radiative capture
• Conclusions
Radiative Capture Reactions are Present in Most Stellar Reaction Networks

- From pp-chain to r- and s-process
- Those involving charged particles \((p,\gamma)\) and \((\alpha,\gamma)\) plays crucial role in
  - Stellar burning e.g. \(^{12}\text{C}(\alpha,\gamma)^{16}\text{O}\), and reaction sequence leading to (and competing with) \(^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}\)
  - Explosions in cataclysmic binaries e.g. \(^{30}\text{P}(p,\gamma)^{31}\text{S}\)
  - X-ray burts e.g. \(^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}\) (and a lot more in the rp-process)
  - In Supernova, production of \(^{26}\text{Al}\) and \(^{44}\text{Ti}\) are influenced by \((p,\gamma)\) rates
<table>
<thead>
<tr>
<th>Ref.</th>
<th>Reaction(s)</th>
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<tbody>
<tr>
<td>Schardt et al. [16] (1952)</td>
<td>$(p, \alpha_0)$</td>
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<td>Hagedorn [17] (1957)</td>
<td>$(p, p)$</td>
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<td>Hagedorn and Marion [18] (1957)</td>
<td>$(p, \alpha_0)$</td>
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<td>Bashkin et al. [19] (1959)</td>
<td>$(p, p), (p, \alpha_0), (p, \alpha_1)$</td>
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<td>Hebbard [6] (1960)</td>
<td>$(p, \gamma_0)$</td>
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<tr>
<td>Larson and Spear [20] (1964)</td>
<td>$(\alpha, \gamma_0)$</td>
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<tr>
<td>Mitchell and Ophel [21] (1965)</td>
<td>$(\alpha, \alpha_1), (\alpha, p)$</td>
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<tr>
<td>Morris et al. [22] (1968)</td>
<td>$(\alpha, \alpha_0)$</td>
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<tr>
<td>Kernel et al. [23] (1971)</td>
<td>$(\alpha, \gamma_0)$</td>
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<tr>
<td>Brochard et al. [24] (1973)</td>
<td>$(\alpha, \gamma_0), (p, \alpha_0), (p, \gamma_0)$</td>
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<td>Rolfs and Rodney [7] (1974)</td>
<td>$(p, \gamma_0)$</td>
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<tr>
<td>D’Agostino Bruno et al. [25] (1975)</td>
<td>$(\alpha, \alpha_0)$</td>
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<tr>
<td>Ophel et al. [26] (1976)</td>
<td>$(\alpha, \gamma_0)$</td>
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<tr>
<td>Bray et al. [27] (1977)</td>
<td>$(p, \alpha_0)$</td>
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<tr>
<td>Zyskind and Parker [28] (1979)</td>
<td>$(p, \alpha_0)$</td>
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<tr>
<td>Redder et al. [29] (1982)</td>
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<tr>
<td>Sawicki et al. [30] (1986)</td>
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<tr>
<td>Feng et al. [31] (1994)</td>
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<tr>
<td>Schürmann et al. [14] (2005)</td>
<td>$(\alpha, \gamma)$</td>
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<tr>
<td>La Cognata et al. [32] (2007)</td>
<td>$(p, \alpha_0)$</td>
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<td>Tischhauser et al. [15] (2009)</td>
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<td>Bemmerer et al. [33] (2009)</td>
<td>$(p, \gamma)$</td>
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<tr>
<td>LeBlanc et al. [9] (2010)</td>
<td>$(p, \gamma)$</td>
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<tr>
<td>Caciolli et al. [34] (2011)</td>
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<tr>
<td>Schürmann et al. [35] (2011)</td>
<td>$(\alpha, \gamma), (\alpha, \gamma(6.05)), (\alpha, \gamma(6.13)), (\alpha, \gamma(6.92)), (\alpha, \gamma(7.12))$</td>
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<td>deBoer et al. [36] (2012)</td>
<td>$(p, p), (p, \alpha_0)$</td>
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<tr>
<td>deBoer et al. [37] (2012)</td>
<td>$(\alpha, \alpha_0), (\alpha, \alpha_1), (\alpha, p)$</td>
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<tr>
<td>Imbriani et al. [38] (2012)</td>
<td>$(p, \alpha_1 \gamma), (p, \gamma(6.05)), (p, \gamma(6.13)), (p, \gamma(7.12))$</td>
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1) Consistent data.

2) Global fit achieved.
Radiative capture reaction studies

• Center of mass energies
  • $(\alpha,\gamma)$: ~0.01 MeV to ~15 MeV
    – (experimentally ~0.3 MeV to ...)
  • $(p,\gamma)$: ~0.01 MeV to ~4 MeV
    – (experimentally ~0.2 MeV to ...)

• Direct kinematics
  • With stable ions ($^1$H and $^4$He beams)
    – Detection of the gamma’s
    – Sometime measurement of the activity of the produced elements

LUNA underground laboratory is able to reach lower
Radiative capture reaction studies

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- **Direct kinematics**
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- **Inverse kinematics**
  - Radioactive beams
  - Stable (to improve efficiency and signal to background ratio)
  - Recoil detection:
    - Coincidence between gamma’s and recoil

LUNA underground laboratory is able to reach lower
Radiative capture kinematics

In the center of mass frame

Radiative capture of a by A forming B

Energy and momentum conservation

$E_{R} = E_{c.m.}$

$A + a$

$B^*$

$E_x$

$Q$

$B$

Russbach 2015
Radiative capture kinematics

Velocity in the lab

Russbach 2015
Radiative capture kinematics

Velocity in the lab

Angular and energy limits

Russbach 2015
Example

• DISCLAIMER:
  – OLD EXAMPLE USING EXPERIMENT PARAMETERS OF AN EXPERIMENT THAT RAN AT NOTRE DAME
  – WHILE THE NUMBERS ARE CORRECT THEY ARE NO QUESTIONS REGARDING THE ABILITY TO STUDY THIS SPECIFIC REACTION IN DIRECT KINEMATIC (LENA AND LUNA DID IT!)
\[^{14}\text{N}(p,\gamma)^{15}\text{O}\]

- Proton beam energy: 0.27 to 3.6 MeV
- \(E_{cm}\): 0.252 to 3.358 MeV
- \(Q\approx7.3\text{MeV}\)
- For \(E_{cm}=1.65\text{MeV}\)
  - \(\sum E_{\gamma}\approx7.3+1.65=8.95\)
  - \(E_{^{15}\text{O}}\in[0.08,0.15]\) MeV

Indirect studies are critical and provide invaluable data.

Detection of \(\gamma\) OK 😊

Since early time of nuclear physics radiative capture are successfully studied with \(\gamma\) detection. However, at lower energies or for certain specific reaction measurement are limited or impossible. Reaction involving radioactive elements are a clear example.
$^{14}\text{N}(p,\gamma)^{15}\text{O}$

- $E_{\text{cm}}$: 0.252 to 3.358 MeV
- $^{14}\text{N}$ beam energy: 3.78 to 54 MeV
- For $E_{\text{CM}}=1.65\text{MeV}$ $E_{\text{beam}} \approx 24.75\text{MeV}$
  - $\sum E_{\gamma} \approx 7.3+1.65=8.95$
  - $E_{^{15}\text{O}} \in [23.59,22.56] \text{ MeV}$
Inverse kinematics

Maximum angular aperture

\[ \theta_{\text{max}} = \arctan \left( \frac{E_\gamma / c}{\sqrt{2m_b E_b}} \right) \]

Momentum spread

\[ p_r = p^* \pm p_\gamma = \sqrt{2m_b E_b} \left( 1 \pm \frac{E_\gamma / c}{\sqrt{2m_b E_b}} \right) \]
**Principles**

High efficiency
Reduced background for γ spectroscopy

\[ \theta_{\text{max}} = \arctan \left( \frac{E_{\gamma} / c}{\sqrt{2m_b E_b}} \right) \]

\[ P_{\text{recoil}} = P_{\text{beam}} \pm P_{\gamma} \]

\( \gamma \) detector

target

projectiles

projectiles + recoils

separation

recoils

Detecton Identification

Velocity/energy selection

Ionization chamber
Position sensitive detector
Time of flight

Drawings from D. Schürmann

Russbach 2015
Recoil separator: Basis principle

Magnetic dipole

\[ \frac{p}{q} = B \rho \]

Charge selection

Momentum filter

Electric dipole

\[ \frac{2E}{q} = U \rho \]

Mass selection

Energy filter

Wien filter

\[ v_0 = \frac{U}{B} \]

Velocity filter

Drawings from D. Schürmann

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Recoil separator: Design parameters

• Ratio: $\Delta M/M$ to reject
  • e.g. $^{14}\text{N}(p,g)^{15}\text{O}$  $\Delta M/M=1/15$

• Angular acceptance
  • Target effects to be included

\[
\theta_{\text{max}} = \arctan\left(\frac{E_\gamma/c}{\sqrt{2m_bE_b}}\right)
\]

• Momentum or energy acceptance

\[
p_r = p^* \pm p_\gamma = \sqrt{2m_bE_b} \left(1 \pm \frac{E_\gamma/c}{\sqrt{2m_bE_b}}\right)
\]

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Some interesting reactions

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

- Holly grail of Nuclear Astrophysics, determine the ratio of $^{12}\text{C}/^{16}\text{O}$ after Helium burning as well as abundance of elements after subsequent evolution
  $\Delta\theta=\pm31\text{mrad} \quad \Delta E=6.5\% \ (\sim 100\mu\text{A})$

$^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$

- Triggers X-ray burst (escape from $\beta$ limited hot-CNO) and contribute to determine their light curve
  $\Delta\theta=\pm17\text{ mrad} \quad \Delta E=3\% \ (\sim 10^{11} \text{ part/s})$

$^{13}\text{N}(p,\gamma)^{14}\text{O}$

- First reaction involving radioactive beam, triggered the development of recoil separators to study radiative capture

$^{18}\text{O}(\alpha,\gamma)^{22}\text{Ne}$

- Populate one of the two main ingredient for production of neutron in the s-process
  $\Delta\theta=\pm40\text{ mrad} \quad \Delta E=7.4\%$

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He

Charge selection

Mass selection

4He

Det.
Mass separation

First order spot size

width of the recoil spot at the mass selection slits

Magnification

=0 we want a focus

=0 we want an achromatic focus

Spot size is due to magnification

\[ x_1 = x_0(x | x) + a_0(x | a) + \frac{\delta E}{E} (x | \delta E) + \frac{\delta m}{m} (x | \delta m) \]

\[ ^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne} @ 2. \text{MeV} \]
For absolute cross section, full transmission of the selected charge state is needed.

Attempt at FMA to study $^{13}\text{C}(p,\gamma)^{14}\text{N}$ and $^{18}\text{O}(p,\gamma)^{19}\text{F}$ and $^{18}\text{F}(p,\gamma)^{19}\text{Ne}$ but limited in transmission.

From: PoS(ENAS 6)058
DEDICATED DEVICES
The availability of post accelerated radioactive beams opened the door to direct cross section measurements.

For example, the $^{13}$N beam of Louvain-la-Neuve allowed the study of $^{13}$N(p,γ) in inverse kinematics.

At Caltech, a recoil separator was constructed out of existing elements of the accelerator lab to demonstrate the feasibility of a recoil separator.

- $^{13}$C(p,γ)$^{14}$N
- $^{16}$O(α,γ)$^{20}$Ne
- $^{12}$C(α,γ)$^{16}$O
European Recoil separator for Nuclear Astrophysics

NABONA in Naples study $^7\text{Be}(p,\gamma)^8\text{B}$

Parts moved to Bochum (Germany)

Addition of Caltech Wien filter -> ERNA

Dedicated to the study of $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

- Angular acceptance $\pm 32$ mrad
- Energy acceptance $\pm 10\%$

For $^{16}\text{O}$ at $E_{\text{lab}}=3.0 - 15.0$ MeV

Adapted from a slide of L. Gialanella

ERNA at the DTL, Bochum,
ERNA at CIRCE, Caserta

3MV Pelletron
High intensity stable and radioactive ($^7,^{10}$Be) ion beams (possible $^{26}$Al)

Plans:
- $^7$Be($p,\gamma$)$^8$B
- $^{12}$C($\alpha,\gamma$)$^{16}$O
- $^{16}$O($\alpha,\gamma$)$^{20}$Ne
- $^{33}$S($p,\gamma$)$^{34}$Cl
- $^{14,15}$N($\alpha,\gamma$)$^{18,19}$F

SHE in nature

Slide of L. Gialanella
Angular Acceptance: 6.5 msr (+/- 45 mrad horizontal and vertical)
A/Q Acceptance: +/- 1.2 %
Velocity Acceptance: +/- 2.5 %
Energy Acceptance: +/- 5 %
A/Q resolution: 1/300
A/Q dispersion: 0.1 %/mm
Overall Length: 13 m

Radioactive beam!

Rejection \(\sim 10^8\text{ to }10^{12}\)
Radioactive beam!

Two stages

Electrostatic dipoles
Rejection $\sim 10^{10}$-$10^{13}$

Last news:
- $^4\text{He}(^3\text{He},\gamma)^7\text{Be}$
  With rejection $>10^{14}$
- Conditioning ED up to +/-230kV

NIMB 266 (2008) 4171
Some specs (for a $^{15}$O(a,g)$^{19}$Ne tune):

Optical path length 20.4 m

**Acceptance**
- ang.: (+/-20 horiz. & +/- 25 vert.)
- velocity +/- 2 %

Resolving power:
200 at first stage
600 for second stage

Effective mass resolution:
~ 90 after 1st stage,
~ 200 after 2nd stage
Difficult reaction to study

**NABONA:**
- ~1995 $^7\text{Be}(p,\gamma)^8\text{B}$

**DRS:**
- ~2009 $^17\text{F}(p,\gamma)^{18}\text{Ne}$
- ~1995 $^7\text{Be}(p,\gamma)^8\text{B}$

**DRAGON:**
- ~2004 $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$
- ~2010 $^{23}\text{Mg}(p,\gamma)^{24}\text{Al}$
- ~2006 $^{26}\text{Al}(p,\gamma)^{27}\text{Si}$

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6 Radioactive beam induced radioactive capture studies in ~17 years !!!

Resonances only ... Resonances energies are critical parameters

A lot more induced by stable beams Possibility to study direct capture
SEparator for Capture Reaction

SECAR to be installed at ReA3

Radiative capture induced by radioactive beam

Based on design of St. George

JENSA Gas Jet target: up to $10^{19}$ at/cm$^2$

Features:
Two steps charge state selection
Attention to Wien filter design:
• E and B field homogeneity
• E/B ratio kept constant with magnetic field clamps and electrode design.
“Clean-up” section – additional momentum analysis

Acceptance:
$\theta = \pm 25$ mrad
$\Delta E = \pm 3.1\%$
$15 < A < 65$
$Bp \leq 0.8$ Tm

First stage:
Resolving power: 750
Mass resolution: **520**

Second stage:
Resolving power: 1330
Mass resolution: **775**

Design: G.P.A. Berg, M. Couder
SECAR
Upgrade path

Wien filter:
Match hardware design to COSY Expectation

Qualitative evaluation of background sources
Rare Isotopes Science Project
Korea

- Recoil separation with p-rich RI beams from ISOL system
  - radiative capture reactions: \((p,\gamma), (\alpha,\gamma)\) reactions
  - background reduction \(~10^{-15}\)
- gamma-array @ F0, recoil detection @ F6
Yuri Litvinov talk ...
Measurements with Stable Beams

\[ ^{12}\text{C}(\alpha,\gamma)^{16}\text{O} \]

Total cross section

From: PoS(ENAS 6)058

\[ S(E) \text{ [keV b]} \]

\[ E \text{ [MeV]} \]

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Measurements with Stable Beams


Summary

- Dedicated separator for radiative capture
  - A tool developed for radioactive beam used successfully for stable and unstable beam
  - Important tools for direct measurements of astrophysical interests
  - Rely on direct kinematic measurements, on indirect methods

- For RI beam experiments, need stable beams to commission and tune
  - Can be used during fast beam operation

- Did not mention target, detection system, diagnostics
  - They are critical

- ~30 years of separators dedicated for nuclear-astrophysics
  - Strong interaction between stable and RI Beam community

- New recoil separators are coming
Thanks!

- ERNA
  - Lucio Gialanella
  - Daniel Schürmann
- KUTL separator
  - Kenshi Sagara
- DRS
  - Daniel Bardayan
- DRAGON
  - Dave Hutcheon
- SECAR
  - Georg Berg