recoil separators & approaches for low energy nuclear astro measurements

recoil separators

low-energy radioactive beam measurements
recoil separator measurements

approach

- directly measure capture reactions with low-energy beams of radioactive nuclei incident on a H or He gas target

advantages

- directly obtain resonance strengths
- experiments are conceptually simple – just count the recoils
- high efficiencies possible with devices of modest acceptance
- detectors inexpensive compared to gamma arrays
- coincidence measurements possible for cleaner results

proof of concept with $^{12}\text{C}(p,\gamma)^{13}\text{N}$
Smith, Rolfs, Barnes NIMA306 (1991) 233
challenge of recoil separator measurements

Particle Identification in \( ^{17}\text{F(}p, \gamma )^{18}\text{Ne} \) at DRS Focal Plane

Challenges - backgrounds

- only 1 in \( \sim 10^{12} \) beam particles fuse with protons
- all fusion reaction products and unreacted beam particles enter separator located along beam axis
- many unreacted beam particles will reach the focal plane detector after multiple scatters – signal/noise \( \sim 10^{-3} \)
- need beam rejection \( 10^{-10} – 10^{-12} \) (or more) of separator & good focal plane detector
challenge of recoil separator measurements

“plunger” system measuring decays of implanted $^{17}$F in $^{17}$F(p,$\gamma$)$^{18}$Ne experiment

other challenges

- beam current & target thickness normalization
- tracking the composition in time of an impure beam
- beam intensities that are too low for capture [do (p,p) instead]
- beam intensities too low for particle – gamma coincidences
### Beam Rejection in Recoil Separators

<table>
<thead>
<tr>
<th>Particle Property</th>
<th>Separating Device</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v$  velocity</td>
<td>$\propto v$ velocity filter</td>
</tr>
<tr>
<td>$B_\rho$  Magnetic Rigidity</td>
<td>$\propto v(M/Q)$ magnetic dipole</td>
</tr>
<tr>
<td>$E_\rho$  Electric Rigidity</td>
<td>$\propto v^2(M/Q)$ electric dipole</td>
</tr>
</tbody>
</table>

- Properties are proportional to $v$ and $(M/Q)$

- Design principle: select $M/Q$ by **combining devices** bending on $v$ and $v(M/Q)$ or $v$ and $v^2(M/Q)$
  - velocity filter & magnetic dipole or electric dipole & magnetic dipole

- Putting a number of these **filters (device pairs)** in series will increase your rejection of scattered beam
Daresbury Recoil Separator (DRS)

Angular acceptance: ±45 mrad horizontal and vertical
Mass/charge acceptance: ± 1.2%
Mass/charge resolution: 1/300
Mass/charge dispersion: 0.1% per mm
Energy acceptance: ± 5%
Velocity acceptance: ± 2.5%
Velocity filter length: two at 1.2 m each
Vel. filter plate separation: 100 mm
Vel. filter plate voltage: ± 150 kV typical (± 300 kV max)
Vel. filter B-field gap: 350 mm
Vel. filter B-field strength: 0.5 Tesla max
Sector magnet bending angle: 50 degrees
Overall length: 13 m
Weight: 90 tons

beam rejection: $10^{-8} – 10^{-12}$
recoil separators for astrophysics measurements

DRAGON at TRIUMF ISAC
Used to measure $^{21}$Na($p,\gamma$)$^{22}$Mg

ARES at Louvain-la-Neuve
Used to measure $^{19}$Ne($p,\gamma$)$^{20}$Na

also …
• ERNA (Bochum)
• CRIB [CNS RIKEN]

DRS at ORNL HRIBF
Used to measure $^{17}$F($p,\gamma$)$^{18}$Ne

FMA at ANL ATLAS
Used to measure $^{18}$F($p,\gamma$)$^{19}$Ne
recoil separators – desired properties

from the ARIA [Astrophysics at RIA] working group

• factor of $10^{10} - 10^{13}$ rejection of unreacted beam particles desired
  with separator alone -- additional rejection from focal plane detectors

• near 100 % transport efficiency of chosen recoil charge state

• mass resolution $m/\delta m \sim 200$ or larger

• very large acceptance [large bore] of components $\sim 30 - 50$ mrad

• tuning with different ion-optical modes possible for different experiments

• devices to ensure careful preparation of beam (high purity, low emittance,
  negligible halo) UPSTREAM of target

• very flexible target and focal plane areas enabling rapid change of equipment
eDRS – modified design (1999)

- combination of two independent M/Q spectrometers
- each with velocity filter VF & mag dipole
- arrange as **mirror images** with intermediate focus for high scattered beam rejection
- mirror image arrangement can **cancel some aberrations** like $d\theta/dv$
- dipoles match dispersion of VF

- 2 VFs, 2 dipoles, 16 quads, 2 sextupoles
- Sextupoles correct 2$^{\text{nd}}$ order aberrations
- floor space $\sim$ 25 m x 20 m

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ornl
- operate as two independent M/Q spectrometers, can **fine tune** for each experiment

- slit between the two spectrometers will give high scattered beam rejection

- sextupoles correct the sizeable 2\(^{nd}\) order aberrations
eDRS – modified design (1999) **not built**

- slit between the two spectrometers will give high scattered beam rejection
eDRS – modified design (1999) not built

vertical

MAX = +/- 0.100 TLU

Z-MAX = 27.026
eDRS – modified design (1999)

SIZE OF WINDOW
X = +/− 1.080E−02 TLU
Y = +/− 1.080E−02 TLU

DEFINITION OF THE INITIAL PHASE SPACE
X = +/− 1.080E−03 LLU
A = +/− 3.000E−02 RAD
DM = 5.000E−03 ±100%
DK = 3.000E−02 ±100%
Y = +/− 1.080E−03 TLU
B = +/− 3.000E−02 RAD

Statistical Informations
Number of Started Particles: 1000
Number of Arrived Particles: 1000 (100.0 %)
Number of Counted Particles: 1000 (100.0 %)
eDRS – modified design (1999)

**SIZE OF WINDOW**

- \( X = \pm 2.0 \times 10^{-2} \) TLU
- \( d = \pm 4.0 \times 10^{-2} \) TLU

**Mass Resolution**

- \( \sim 1/100 \)

**Mass Dispersion**

- \( \sim 0.07\% / \text{mm} \)

**Energy Acceptance**

- \( \sim \pm 3\% \)

**Definition of the Initial Phase Space**

- \( X = \pm 1.0 \times 10^{-3} \) LLU
- \( A = \pm 3.0 \times 10^{-2} \) RAD
- \( D_M = 5.0 \times 10^{-3} \) \( \pm 100\% \)
- \( D_K = 3.0 \times 10^{-2} \) \( \pm 100\% \)
- \( Y = \pm 1.0 \times 10^{-3} \) TLU
- \( B = \pm 3.0 \times 10^{-2} \) RAD

**Statistical Information**

- Number of started particles: 1000
- Number of arrived particles: 956 (95.6\%)
- Number of counted particles: 956 (95.6\%)

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eDRS – modified design (1999)

not built

Energy Distribution at Focal Plane

Size of Window

X = \pm 2.000E-02 TLU
Y = \pm 1.000E-03 LLU
D = \pm 4.000E-02 TLU
A = \pm 3.000E-02 RAD

Mass Resolution
\sim 1 / 100

Mass Dispersion
\sim 0.07 \% / mm

Energy Acceptance
\sim \pm 3 \%
recoil separator – SECAR

• Separator for Capture Reactions (SECAR) preliminary design

• 9 Dipoles, 2 velocity filters

• designed to fit in a relatively compact space – 16m x 18m

• are there alternative designs using the same components? not restricted by size?
recoil separator – modified design

- Separator for Nuclear Astrophysics at low Kinetic Energies - SNAKE
recoil separator – modified design

• **Separator for Nuclear Astrophysics at low Kinetic Energies - SNAKE**

• use same design principles as eDRS but with St. George components

• 10 dipoles, 2 velocity filters – just **one more dipole** than preliminary design

• not compact in design … long and lean

• may be worthwhile to compare ion optical properties of this modified design with first design

• main point: a design optimized to physics – not room size – is important
recoil separators – optics & design issues

- what reactions? \((p,\gamma)\) alone? \((p,\gamma)\) & \((\alpha,\gamma)\)?

- what beam rejection is needed?

- transfer reactions [for use at another facility with higher beam energies]?

- compatibility with a solenoid? [for use at another facility with higher beam energies]?

- should DRAGON be taken as a reference design, or a modified DRAGON?
  - note: DRAGON is tested, and shortcomings are well known

- should St. George be taken as a reference design? what modifications will be considered (minor? major?)

- what mass resolution is needed? 200 ? 300 ?

- Velocity Filters or separated Electric / Magnetic dipoles?
  - dipoles cheaper but no straight through tune, give a longer optical axis
  - VF hard to match fields, multiple orbits possible, residual fields are a challenge

- can you demonstrate (to a reviewer) that performance will be better than a much cheaper FMA or RMS type E – D – E separator?
• do you want to really move this separator? Fold this into the DESIGN & COST?

• will gas target system be developed? Will this be moveable?

• will gamma-recoil coincidences be relied upon for clean measurements?

• for what reactions do you really anticipate having enough intensity for $(p,\gamma)$?

• how will you organize the design effort, the commissioning effort? What do you realistically see as the role of collaborators?
recoil separators – associated equipment

- windowless, high-density, differentially-pumped, H / Helium gas / jet target

- focal plane detection systems for measurement of recoil arrival time, position, Z, energy

- charged particle detectors at target to monitor beam current & target thickness

- paddle system, harp, or other clever trick to monitor current of impure beams

- high count rate trigger detection system upstream of target

- recoil time of flight system for particle identification

- multiple position determination at focal plane to reconstruct [with ray tracing kinematics] recoil emission angle at target

- flexible system at target and focal plane to accommodate rapid changes between variety of systems
low energy measurements – general comments

- reactions of interest will often have the **lowest beam intensities**
  - plan experiments at intensities **well below** "projected" intensities
  - better yet, start planning experiments from **zero intensity** and up ...
  - background rejection & other low-intensity approaches crucial
  - utilize beam diagnostics to identify each beam particle
    - enables measurements with impure beams

- utilize beams with **precisely defined energies** (if possible) or determine energy of each particle interacting with target
  - energy dependence of cross sections critical when converting to reaction rates
  - rates also depend strongly on resonance energies
  - use time of flight techniques to **tag beam particle energy**
low energy measurements – reaction choice

- combining direct & indirect measurements can provide valuable, complementary information on the reactions and nuclei of interest
  - especially important as indirect approaches usually require lower intensities…

- advantageous to
  - measure kinematically complete reactions
    - especially necessary with impure beams for precision work
  - measure multiple reaction channels
    - resolve ambiguities
    - reduce uncertainties
    - better determine reactions / structure information of interest
    - requires creativity – avoid “one beam, one experiment” attitude
low energy measurements – example of combined approaches

- indirect studies with low-intensity \([10^3 - 10^5 \text{ ions / s }]\) beams
  - scattering reactions to locate resonances

- indirect studies with higher intensity \([10^4 - 10^6 \text{ ions / s }]\), higher energy beams
  - transfer reactions to determine \(J^\pi\) and spectroscopic factors
  - identifies “important” resonances

- direct study with higher intensity \([>10^6 \text{ ions / s}]\), low-energy beam
  - capture reaction to measure strength \(\omega_\gamma\) of important resonances

Bardayan et al, PRC 2000
\[ ^1H(18_F,p)18_F \]

\[ \text{19}^F \text{ Excitation Energy via } ^{18}F(d,p) \]
Kozub et al, 2003

\[ E_{cm} (\text{keV}) \]
\[ \text{counts / (20 keV)} \]
\[ E (\text{MeV}) \]

\[ 6.5 \text{ MeV} \]
\[ 6.2 \]
\[ 4.4 \]

\[ 7.3 \]
\[ 8.1 \]

\[ \sigma (\mu b) \]
\[ E_{cm} (\text{MeV}) \]
low energy measurements – example of kinematic completeness

\[ p(^{18}\text{F}, ^{15}\text{O})\alpha \]

\[ p(^{18}\text{F}, ^{18}\text{F})p \]

\[ ^{18}\text{F} \text{ radioactive beam} \]

\[ \text{thin foil } (\text{CH}_2)_n \text{ target} \]

96 Si Strip Detectors

Gas Ionization Counter

\[ \alpha \]

Tandem - excellent beam energy resolution & easily variable energy

Silicon Detector Array (SIDAR) size and resolution

particle identification

\[ ^{18}\text{F}(p,p) \]

\[ ^{18}\text{O}(p,p) \]

\[ \Delta E \]

\[ E \]
low energy measurements – example of kinematic completeness

- Measure low cross section reactions with low RIB intensities in fine energy steps
- Use of impure beams possible
- Nearly background-free yields
- Measure low cross section reactions with low RIB intensities in **fine energy steps**
summary

• low energy measurements are challenging but can provide excellent information on the nuclei and reactions of astrophysical importance

• lots of issues to discuss regarding the design of a **recoil separator** for low energy measurements with radioactive beams

• one option to consider may be the rearrangement of SECAR elements into the SNAKE - two mirror image filter pairs to
  • cancel some aberrations
  • give very good scattered beam rejection
  • enable fine tuning of each stage depending on reaction

• important to **plan** measurements with **very LOW beam intensities**, well below the projected intensities

• combining direct & indirect measurements can provide valuable, complementary information on the reactions and nuclei of interest

• advantageous to measure kinematically complete reactions, measure multiple reaction channels, and identify all beam particles
supplemental – silicon strip detectors from the ARIA [Astrophysics at RIA] working group

- large solid angle (75 % of reaction products)
- easy to configure detectors both upstream & downstream of target
- high segmentation enabling count rates > 10 kHz
- energy resolution of ~ 30 keV for particles with energy ~ MeV
- computer adjustable gains & trigger thresholds
- telescope arrangements dE - E for particle ID
- flexible geometry to accommodate extra detectors [e.g., Z-tagging with downstream gas ionization counter, gamma detectors]
- high-density modular electronics [ASICS]
- preamps closely coupled to Si detectors to reduce noise
- examples: SIDAR & ORRUBA [ORNL]; LEDA [Louvain]; TUDA [ISAC]; YLSA [Yale]; cost ~M$
silicon detector arrays for astrophysics measurements

LEDA at Louvain-la-Neuve
Used to measure $^{18}\text{F}(p,p)$, $^{18}\text{F}(p,\alpha)$ …

TUDA at TRIUMF ISAC
Used to measure $^{21}\text{Na}(p,p)$

SIDAR at ORNL HRIBF
Used to measure $^{17,18}\text{F}(p,p),(p,\alpha)$

YLSA at Yale
Used to measure $^{24}\text{Mg}(^{3}\text{He},tp)$

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supplemental – gamma detectors

from the ARIA [Astrophysics at RIA] working group

• excellent efficiency for gamma rays with energy ~ few MeV
• excellent performance for low multiplicity events
• geometry flexible to accommodate gas target assembly
• ability to reject high intensity (~MHz) background of 511 keV gammas from scattered beam particles
• large solid angle (~2π) with gas target assembly
• energy resolution equivalent to NaI or better
• fast timing (~ns) for recoil-gamma coincidences
• available for extended experiments (~month)
• examples: BGO array [ISAC]; BAF2 array [ORNL/MSU/TAMU]; GRETINA [portions…]
gamma detector arrays for astrophysics measurements

BGO Array at TRIUMF
Used to measure $^{21}\text{Na}(p,\gamma)^{22}\text{Mg}$

BaF2 at ORNL-MSU-TAMU

Nal Annulus / HPGe at LENA
Used to measure $^{14}\text{N}(p,\gamma)^{15}\text{O}$

GRETA
supplemental - other facility requirements

from the ARIA [Astrophysics at RIA] working group

• Robust, safe mechanism for flammable gas (H) handling

• Access to overhead crane > 10 ton capacity

• Electronics hut for sufficient air cooling of electronics modules, centralized grounding, and RF shielding

• Robust scheme for electrical grounding

• Magnet Power Supplies on scaffolding above floor

• DAQ rates up to 10 kHz in event mode

• Beam line height sufficient to clear gas target pumps & large detector systems

• Experiment duration from days [(p,p)] to ≤ month [(p,γ)]