A Large Acceptance Spectrometer
for Deep-Inelastic Scattering with Reaccelerated Radioactive Beams

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Research objectives:
- **structure studies** of neutron-rich nuclei (at high spin states) around the projectile
- **reaction dynamics** (e.g. peripheral collisions, N/Z equilibration, symmetry energy, EOS)

Present work:
- Preliminary design of a large acceptance spectrometer for above-barrier energies: E/A=6-15MeV/u

Requirements:
- design specific for binary reactions
- large angular acceptance (ΔΩ>20msr) and high momentum resolving power (>1000) via trajectory reconstruction [“Raytracing spectrometer”]
- Z, A identification of projectile residues up to Z~60, A~150
- flexibility in target and focal plane detector setups:
  - target location: accommodate a 4π Gamma Array (and charged particle array)
  - focal plane: accommodate a decay setup
- spectrograph and associated detectors must be rotatable (θ= -20-120degrees)

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Large Acceptance Spectrometers in Europe:

**VAMOS:** RNBs from SPIRAL, combined with EXOGAM and TIARA

**PRISMA** (combined with CLARA)  **MAGNEX** (RNBs from EXCYT or FRIBs)
Example of nuclide production in DIC with RIBs:

Calculated nuclide cross sections:

Very important:

Neutron-pickup channels !!! along with proton stripping

Rate estimate: $^{94}\text{Kr}$ from “FRIB” at $\sim10^8$ pps, $^{64}\text{Ni}$ (20 mg/cm$^2$): 1 mb => 200 pps

References:


Large Acceptance Spectrograph: preliminary layout

Target

Segmented IC and/or Si “Wall” => \( \Delta E, E \)

Acceptances:
\( \Delta \theta = 100 \text{mr} \) (5.7\(^{\circ}\))
\( \Delta \varphi = 400 \text{mr} \) (22.9\(^{\circ}\))
\( \Delta p/p = 10 \% \)

Focal plane size: 60cmX20cm

\( B_{\rho_{\text{max}}} = 2.5 \text{ Tm} \)

Focal plane size: 60cmX20cm
Large Bore Quadrupoles (30-40cm diameter). Large Gap Dipole magnet (20-25cm)
Room temperature vs superconducting magnets (either option possible)

Target - Q1 distance: 30-120cm. “Nominal”: 50cm

Quadrupole Q1: aperture: 30cm, length 60cm, $B_{\text{max,tip}} = 1.5\text{T}$ (Y focusing)
Quadrupole Q2: aperture: 40cm, length 80cm, $B_{\text{max,tip}} = 0.5\text{T}$ (X focusing).
  Collins type (elliptical aperture) can also be used (e.g. VAMOS)
  Superposition of higher multipoles is also considered

Dipole: bending radius: 150cm, bending angle: $70^\circ$, gap: 25cm, $B_{\text{max}} = 1.7\text{T}$
  Entrance and exit pole face rotation: $+20^\circ$ (Y-focusing)
  Entrance and exit pole face curvatures ($1/R_1=0.2$, $1/R_2=0.0$) to be optimized
  (along with inclusion of possible higher-order profiling etc.)

Dipole - MWPC1: 2.0m, MWPC 1- MWPC2: 1.0m (this version, can be shorter also)

Length of central trajectory: 7.6 m
Appropriate for mass A determination via TOF: 130ns at 15MeV/u,
  160ns at 10MeV/u, 210ns at 6 MeV/u

Rays through LAS: $^{94}\text{Kr}^{34+}(15\text{ MeV/u})$ $B_\rho=1.54$ Tm

Ion Optics calculations with COSY-Infinity
**Large Acceptance Spectrograph: optics summary:**

**First-order optics** (point-to-point focusing in x,y at MWPC2):
Dispersions: \( \frac{x}{\delta} = 4.6 \text{ cm/}\% \), \( \frac{\theta}{\delta} = 12 \text{ mr/}\% \)
Magnifications: \( M_x = \frac{x}{x} = -0.80 \), \( M_y = \frac{y}{y} = -7.0 \)
\( M_\theta = \frac{\theta}{\theta} = 1.24 \), \( M_\phi = \frac{\phi}{\phi} = -0.14 \)
Path length dependences: \( \frac{l}{\delta} = 3.5 \text{ cm/}\%, \quad \frac{l}{\theta} = -0.3 \text{ cm/mr} \)

The most important **higher-order aberrations in x,y (cm)**
at full acceptable phase space: \( \Delta \theta = \pm 50 \text{ mr} \), \( \Delta \phi = \pm 200 \text{ mr} \), \( \Delta p/p = \pm 5 \% \)

<table>
<thead>
<tr>
<th>Horizontal (X)</th>
<th>Vertical (Y)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>2nd order:</strong></td>
<td></td>
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<tr>
<td>( \frac{x}{\theta \delta} ) =&gt; 4.5 cm</td>
<td>( \frac{y}{\theta \phi} ) =&gt; -2.2 cm</td>
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<tr>
<td>( \frac{x}{\delta^2} ) =&gt; -2.1 cm</td>
<td>( \frac{y}{\phi \delta} ) =&gt; 6.8 cm</td>
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<tr>
<td><strong>3rd order:</strong></td>
<td></td>
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<tr>
<td>( \frac{x}{\theta^3} ) =&gt; 1.5 cm</td>
<td>( \frac{y}{\phi^3} ) =&gt; -4.0 cm</td>
</tr>
<tr>
<td>( \frac{x}{\theta \delta^2} ) =&gt; -0.8 cm</td>
<td>( \frac{y}{\theta^2 \phi} ) =&gt; 0.6 cm</td>
</tr>
<tr>
<td></td>
<td>( \frac{y}{\theta \phi \delta} ) =&gt; -0.5 cm</td>
</tr>
</tbody>
</table>
Large Acceptance Spectrograph: 5th order optics

\[ \theta_0 = 50 \text{ mr} \]
\[ \varphi_0 = 200 \text{ mr} \]

Target
MCP t,X,Y
RIB

\[ \rho = 1.54 \text{ Tm} \]
\[ \Delta p/p = +5.0\% \]
\[ \Delta p/p = 0.0\% \]
\[ \Delta p/p = -5.0\% \]

\( ^{94}\text{Kr}^{34+}(15 \text{ MeV/u}) \)

MWPC1 | MWPC2

Rays through LAS: \( ^{94}\text{Kr}^{34+}(15 \text{ MeV/u}) \) Bρ=1.54 Tm

Ion Optics calculations with COSY-Infinity
LAS: 5th order optics, multipoles (H, O, D, DD) included

θ₀ = 50 mr
φ₀ = 200 mr

Rays through LAS: \(^{94}\text{Kr}^{34+}(15 \text{ MeV/u})\) \(B_ρ=1.54 \text{ Tm}\)

Multipoles (O, D, DD) superimposed on Q2,
Entrance pole face of dipole curved with \(R=+5\text{m}\) (convex)
Δθ₀ = 100 mr (5.7°)
Δφ₀ = 400 mr (22.9°)

Δp/p range: -5.0% -2.5% 0.0% +2.5% +5.0%

Effective Focal Plane and Detector size:
60 cm x 25 cm

5th order ion optics calculations with COSY-I
Details of Experimental Procedures:

**Momentum (=>Bρ) reconstruction:**

Measured quantities: after target:  (MCP): \( \theta_0, \phi_0 \)
At the focal plane detectors: (MWPC1,2): \( x_f, y_f, \theta_f, \phi_f \)

Assuming 1.5mm beam spot on target, x,y position resolutions of 1mm, and final angle resolution of 2mrad: momentum can be reconstructed with **resolution 1/2000** using calculated inverse **transfer maps** (determined to 5th order or higher with COSY) and accurate description of the fields of the magnets.

**Summary of measured and extracted quantities:**

Velocity (from TOF), Energy loss (from IC), Total Energy (IC+Si wall)
Mass-to-charge ratio: \( A/Q \) \[ B \rho \sim A/Q \times \nu \]
Atomic Number \( Z \) \[ Z \sim \nu \Delta E^{1/2} \]
Ionic charge \( Q \) \[ Q \sim f(E, \nu, B \rho) \]
Mass number \( A \) \[ A = Q_{int} \times A/Q \]

Complete Identification of heavy residues in \( Z, Q, A, \nu, \theta_r \)

Residue yield distributions in \( Z, A, \nu \) and \( \theta_r \) can be obtained
Layout of “LAS” + Gamma and Charged Particle Arrays:

Gamma Array:
- Gammasphere
- Gretina
- GRETA

Charged particle array:
- MCP
- \( t, X_0, Y_0, \theta_0, \phi_0 \)

Acceptances:
- \( \Delta \theta = 100 \text{mr} \) \((5.7^\circ)\)
- \( \Delta \phi = 250 \text{mr} \) \((14.3)\)
- \( \Delta \rho/\rho = 10\% \)

Focal plane size: 60cmX20cm
- \( B_{\rho_{\text{max}}} = 2.5 \text{Tm} \)

Segmented IC and/or Si “Wall” \( \Rightarrow \Delta E, E \)
LAS : preliminary layout of experimental room:

The room dimensions are: ~10m x 15 m, arc is ~7m radius; angular range -20 to 120 degrees
Overview of “LAS” tasks (partial list):

- Detailed definition of the spectrograph specifications
- Detailed design of the spectrograph according to these specifications
- Magnets (superconducting ?)
- Detectors: need state of the art detector systems:
  - tracking-MCP, MWPC/drift chambers
  - segmented IC
  - large area (+high uniformity) Si detectors for $E$ (“Si walls”)
- Target chamber(s)
- Electronics, data acquisition
Representative results from recent cross section measurements of neutron-rich products at 15MeV/nucleon with $^{40}$Ar and $^{86}$Kr beams at Texas A&M with the MARS recoil separator:
K500 SUPERCONDUCTING CYCLOTRON FACILITY
TEXAS A&M UNIVERSITY - CYCLOTRON INSTITUTE

MARS RECOIL SPECTROMETER
1982

RADIATION EFFECTS FACILITY
1994, 2000, 2005

BIG SOL SOLENOID
2003

NIMROD
1999

MDM SPECTROMETER
1993, 2000

TAPE TRANSPORT & PRECISION DECAY FACILITY
1999

ECR ION SOURCE

BEAM ANALYSIS SYSTEM 1994

CB-ECR SOURCE

LIGHT ION GUIDE

HEAVY ION GUIDE

K500 CYCLOTRON

ION INTERACTIONS LINE

K150 (88°) CYCLOTRON

35 FEET
MARS Recoil Separator and Setup for Heavy Rare Isotope Studies

Separation Stage I

D1
Production Target

Q1
Q2
Q3
Q4
Q5
K500 Beam

PPAC1
Start T, X, Y

Dispersive Image

PPAC2
Stop T, X, Y

Bρ = mv/Q

MARS Acceptances:
Angular: 9 msr
Momentum: 4%

Separation Stage II

Si Telescope

E_r
ΔE

D2
Wien Filter

Final Achromatic Image

D3
Q4
Q5

Rotatable Arm
Reaction Angle: 0-12° (selectable)

Rare Isotope Production at 15MeV/nucleon:

$^{86}\text{Kr} \ (15 \text{ MeV/nucleon}) + ^{64}\text{Ni}$

**Neutron-Rich Rare Isotopes** near and above the Fe-Ni region

*G. A. Souliotis et al., in preparation*
BigSol Setup for RIB production

Target
Axial beam blocker ($3^\circ$-$7^\circ$)

BIRSOL

Beam from K500 Cyclotron

PPAC1 ("start", X,Y)

Flight path: 5.5 m (PPAC1-PPAC2)

RIB diagnostics:
- P/Q aperture (1", ½", ¼" holes)
- PPAC2("stop", X,Y)
- DE,E Si telescope (5cmx5cm)

Optics: object/image $\sim$ 3 / 1
Results of BigSol test run: Charge State Distributions

Charge state distribution at PPAC2 of $^{40}$Ar (15MeV/u) thru PPAC1 (acting as a stripper).
Angular acceptance: 3.0-4.0 deg. (set by the blocker system)

$B \rho = 1.244 \text{ Tm}, \quad I_{\text{BigSol}} = 81.6 \text{ A}$

$B \rho = 1.320 \text{ Tm}, \quad I_{\text{BigSol}} = 86.6 \text{ A}$
Example of neutron-rich fragment production:

\[ ^{40}\text{Ar}(15\text{MeV/u}) + ^{64}\text{Ni} \]

\[ B \rho = 1.282 \text{Tm}, \]

\[ I_{\text{BigSol}} = 84.1 \text{ A} \]

Angular acceptance: 3.0-4.0 deg.
Example of Z-A distribution of fragments from $^{64}\text{Ni}(25\text{MeV/u}) + ^{64}\text{Ni}$

$B \rho = 1.473, \quad I_{\text{BigSol}} = 79.3$ A

Angular acceptance: 1.5-3.0 deg.

Neutron-Rich fragments from $^{64}\text{Ni} (25\text{MeV/u}) + ^{64}\text{Ni} (4.0\text{mg/cm}^2)$

$B \rho = 1.900 \text{Tm, } I_{\text{BigSol}} = 102.5$ A

$i_{\text{beam}} = 1 \text{ pnA}, 4 \text{ hour run}

Angular acceptance: 1.5-3.0 deg.
Example of Z-E/A distribution of fragments from $^{136}$Xe (20 MeV/u) data:

- $^{136}$Xe $+$ $^{124}$Sn
- $^{136}$Xe $+$ $^{232}$Th

$^{136}$Xe “elastic”

Angular acceptance: 1.5-3.0 deg.

$B \rho = 1.325 \, \text{Tm}$
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