A Large Acceptance Spectrometer for Deep-Inelastic Scattering with re-accelerated 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)
● additional research topics of interest to the community...

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 ($\Delta\Omega>20\text{msr}$) 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 $4\pi$ Gamma Array (and charged particle array)
    ● focal plane: accommodate a decay setup
● spectrograph and associated detectors must be rotatable ($\theta= -20\text{-}120\text{degrees}$)

● further suggestions...
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 estimates: $^{94}$Kr from “RIA” at $\sim 10^8$ pps, $^{64}$Ni (20 mg/cm$^2$) : 1 mb $\Rightarrow$ 200 pps

**GEMINI:** R. Charity et al., Nucl. Phys. A483 391 (1988)
Large Acceptance Spectrograph: preliminary layout

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

Focal plane size: 60cmX20cm

\[ B \rho_{\text{max}} = 2.5 \text{ Tm} \]
LAS prelim. specifications: QOD type, $B_{\text{max}} = 2.5 \text{Tm}$

Large Bore Quadrupoles (30-40cm diameter). Large Gap Dipole magnet (20-25cm)
Room temperature vs superconducting magnets (to be decided)

**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
RIA Large Acceptance Spectrograph: 1st order optics

Target

MCP t,X,Y

RIB

$\theta_0 = 50 \text{ mr}$

$\varphi_0 = 200 \text{ mr}$

$\rho = 1.54 \text{ Tm}$

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

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

**First-order optics** (point-to-point focusing in x,y at MWPC2):

Dispersion: \((x/\delta) = 4.6\text{cm/\%}, \ (\theta/\delta) = 12 \text{mr/\%}\)

Magnifications: \(M_x = (x/x) = -0.80, \ M_y = (y/y) = -7.0\)

\(M_\theta = (\theta/\theta) = 1.24, \ M_\phi = (\phi/\phi) = -0.14\)

Path length dependences: \((l/\delta) = 3.5\text{cm/\%}, \ (l/\theta) = -0.3\text{cm/mr}\)

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

θ₀ = 50 mr
φ₀ = 200 mr

Target
MCP t,X,Y

RIB

θ₀ = 50 mr
φ₀ = 200 mr

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

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

θ₀ = 50 mr
φ₀ = 200 mr

Target
RIB from RIA

MCP t,X,Y

x-z plane

Q2
Dipole

y-z plane

Rays through LAS: \(^{94}\text{Kr}^{34+}(15 \text{ MeV/u})\)  Bρ=1.54 Tm
Multipoles (O,D,DD) superimposed on Q2,
Entrance pole face of dipole curved with R=+5m (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:
60cm x 25cm

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

Momentum (=>B\rho) 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: \( A/Q \)
- Atomic Number \( Z \)
- Ionic charge \( Q \)
- Mass number \( A \)

\[ B\rho \sim A/Q \times \nu \]
\[ Z \sim \nu \Delta E^{1/2} \]
\[ Q \sim f(E, \nu, B\rho) \]
\[ A = Q_{int} \times A/Q \]

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, and eventually: GRETA

MCP
$t, X_0, Y_0, \theta_0, \phi_0$

Charged particle array

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

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 $\Delta E$, E (“Si walls”)
- Target chamber (s)
- Electronics, data acquisition
- Many more things to be added in the list and to be discussed ...
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:

G.A. Souliotis et al, in preparation
Nuclide cross sections from: $^{40}\text{Ar} (15\text{MeV/nucleon}) + ^{64}\text{Ni}, ^{58}\text{Ni}, ^{27}\text{Al}$

- $^{40}\text{Ar} + ^{64}\text{Ni}$
- $^{40}\text{Ar} + ^{58}\text{Ni}$
- $^{40}\text{Ar} + ^{27}\text{Al}$

$^{38}\text{S} \quad \sigma = 20 \text{ mb}$

largest cross sections with the n-rich $^{64}\text{Ni}$ target

G. A. Souliotis et al., TAMU Cyclotron Institute Annual Report 2009
Comparison: Data, Calculations: $^{40}\text{Ar}$ (15MeV/nucleon) + $^{64}\text{Ni}$

- MARS data
  
  - DIT/GEMINI
  
  - CoMD/GEMINI
  
  - EPAX

Data show enhanced cross sections of n-rich nuclides close to the projectile

Model Calculations underestimate the cross sections on the neutron-rich side

DIT: Deep Inelastic Transfer:

CoMD: Constraint Molecular Dynamics:

GEMINI: Binary decay code:

EPAX: Cross Section parametrization (high-energy)

G. A. Souliotis et al., TAMU Cyclotron Institute Annual Report 2009
Cross section measurements: $^{86}\text{Kr} (15 \text{ MeV/u}) + ^{64}\text{Ni}$

Large cross sections of neutron-pickup products near the projectile

**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**

*$\text{G. A. Souliotis et al., in preparation}$
Special thanks to:
Robert Janssens, Jerry Nolen, Ernst Rehm and Alan Wuosmaa
for discussions and support of this effort

Work on DIC at TAMU:
M. Veselsky, S. Galanopoulos, M. Jandel,
A. Keksis, D.V. Shetty, B. Stein, S.J. Yennello

This work was supported in part by:
The Department of Energy: Grant Number DE-FG03-93ER40773,
The Robert A. Welch Foundation: Grant Number A-1266