Future Studies of the Symmetry Energy with the R³B Experiment at FAIR

Marielle Chartier
The Future International Facility FAIR
Beams of Ions and Antiprotons
The Future International Facility at GSI: FAIR

Beams of Ions and Antiprotons

UNILAC
SIS 18
FRS
ESR
SIS 100/300
NESR
CR

Primary Beams

- $10^{12}$/s $^{238}\text{U}^{28+}$ @ 1.5-2 AGeV; factor 100-1000 over present intensity
- $2\times10^{13}$/s 30 GeV protons
- $10^{10}$/s $^{238}\text{U}^{73+}$ up to 25 (-35) AGeV

Secondary Beams

- Broad range of radioactive beams up to 1.5 - 2 AGeV; up to factor 10 000 in intensity over present
High-Energy Radioactive Beams

Highest energy RIBs in the world
=> unique opportunities for new experiments

NuSTAR high-energy cave
=> R³B experiment
The $R^3B$ Experiment at FAIR

Universal setup for kinematically complete measurements of reactions with high-energy RIBs

Experiments
- elastic scattering
- knockout and quasi-free scattering
- electromagnetic excitation
- charge-exchange reactions
- fission
- spallation
- fragmentation

Physics goals
- radii, matter distribution
- single-particle occupancies, spectral functions, correlations, clusters, resonances beyond the drip lines
- single-particle occupancies, astrophysical reactions (S factor), soft coherent modes, giant resonance strength, $B(E2)$
- Gamov-Teller strength, spin-dipole resonance, neutron skins
- shell structure, dynamical properties
- reaction mechanism, applications (waste transmutation, ...)
- $\gamma$-ray spectroscopy, isospin-dependence in multifragmentation, EOS
The \( R^3B \) Experiment at FAIR

Universal setup for kinematically complete measurements of reactions with high-energy RIBs

- Identification and beam "cooling" (tracking and momentum measurement, \( \Delta p/p \sim 10^{-4} \))
- Exclusive measurement of the final state:
  - Identification and momentum analysis of fragments
    (large acceptance mode: \( \Delta p/p \sim 10^{-3} \), high-resolution mode: \( \Delta p/p \sim 10^{-4} \))
  - Coincident measurement of neutrons, protons, gamma-rays, light recoil particles
- Applicable to a wide class of reactions
The ALADIN/LAND Set-up at GSI

Excitation energy $E^*$ from kinematically complete measurement of all outgoing particles:

$$E^* = \left( \sqrt{\sum_i m_i^2} + \sum_{i \neq j} m_i m_j \gamma_i \gamma_j (1 - \beta_i \beta_j \cos \theta_{ij}) - m_{proj} \right) c^2 + E_\gamma$$
R³B – The Startup Version

Transition from ALADIN/LAND to R³B – improvement in sensitivity needed –

• increase precision → granularity x10-100
• adapt to higher rates → 20 kHz dead-time free incoming ID
• adapt to higher energies → strong dipole magnet → x-ray suppression
The CALIFA Calorimeter

**CALIFA**
Calorimeter (and spectrometer) for γ-rays and protons
- sum energy as well as individual particles or γ-rays
- large dynamic range: 50 keV to 300 MeV

Technical implementation based on scintillation detectors

Coordinator: D. Cortina Gil,
Univ. Santiago de Compostela (Spain)

Large Doppler effects
... tiling with small slabs

Barrel

Forward Endcap
## CALIFA Barrel

### CsI(Tl) crystals

<table>
<thead>
<tr>
<th>Crystals</th>
<th>2560</th>
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<tbody>
<tr>
<td>Crystals by Ring</td>
<td>64</td>
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<tr>
<td>Crystals by polar direction</td>
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</tr>
<tr>
<td>Crystals by alveolus</td>
<td>4</td>
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<tr>
<td>Alveoli</td>
<td>640</td>
</tr>
<tr>
<td>Alveoli by Ring</td>
<td>32</td>
</tr>
<tr>
<td>Alveoli by polar direction</td>
<td>20</td>
</tr>
</tbody>
</table>

### Alveolus

- 300 μm wrapping
- 300 μm carbon fibre
Large Doppler effect
- Higher $\gamma$-ray energies
- Lorentz boost

- CsI or LaBr$_3$/LaCl$_3$?
- Phoswich solutions?
- No PMT because of GLAD \rightarrow APD readout!

$E_\gamma = 662$ keV

... by pulse shape analysis!

O. Tengblad et al., IEM/CSIC Madrid (Spain)
The Silicon Recoil Tracker

- Multiple layers of Si microstrip detectors to track outgoing protons from LH$_2$ target in QFS reactions e.g. (p,2p), (p,pn)
- Aims for separation-energy resolution of ~1 MeV and angular resolution ~1 mrad
- Sits inside the CALIFA calorimeter
- New ASIC designed by RAL (UK)

Design constraints studied with Monte Carlo simulations (R3BRoot) – geometry, strip pitch, Si thickness... => Impact on energy resolution, efficiency, mechanics, FEE...

- Must detect protons at most forward angles
- Inner layer as thin as possible (~100um)
- At least 3 layers – strip redundancy
- Inner layer as close to target as possible – accurate determination of reaction vertex
- No shielding between detector and target

Coordinator: R. Lemmon, STFC Daresbury Lab (UK)
The Silicon Recoil Tracker

Two design options studied:
- Barrel+endcap
- Trapezoidal shape (lampshade)

Resolution almost the same for both but advantages for lampshade design:
- sensors easier to make with high yield (no double metallisation required)
- less noisy on both sides
- no endcap required
- all FEE (incl. cooling) and mechanical support at one end (backward angles)

Number of channels ~100k
50um strip pitch
Stereo angle (diamond pixel)

Design by Daresbury/Liverpool, UK
NeuLAND – New Large Area Neutron Detector

- >90% efficiency for 200-1000 MeV neutrons
- Time resolution $\sigma < 100$ ps
- Acceptance 80 mrad @ 12 m distance: active area 200 cm x 200 cm
- Multi-hit capability for up to 5 neutrons

Example invariant-mass resolution: NeuLAND-target distance 30 m $\Delta E \approx 20$ keV above the neutron threshold

Coordinator: K. Boretzky, GSI (Germany)
NeuLAND Detector Design: 2 Alternatives

**NeuLAND based on MRPC’s:**
- Alternating layers of passive converter material and Resistive Plate Chambers (RPC) for the detection of secondary particles
- **Detector size** $2\times2\times\sim1\ m^3$
- $\sim7.000$-$8.000$ channels

**NeuLAND based on organic scintillator:**
- Full active detector
- Bar structure read out from two sides by PMs/APDs
- **Detector size** $2\times2\times\sim2$-$3\ m^3$
- $\sim3.200$-$5.000$ channels

HZDR design

GSI Design
Symmetry Energy and $R^3B$

Possible future measurements with $R^3B$

1) Nuclear structure measurements

- Neutron skins: Giant resonances Matter distributions
- Correlations in nuclei: Hadronic quasifree scattering

Heavy-ion induced electromagnetic excitation

p-induced QFS e.g. (p,2p) and (p,pn)

Nucleus of interest | Excited Fragment | n,d,t,...
--- | --- | ---
A | A-x | Photon(s)

Nucleon/Cluster | Recoil q | x
--- | --- | ---
Proton | | 0

Separation Energy

$$E_S = T_1 + T_x + T_A - T_0$$

Internal Momentum

$$q = -p_{A-x} = p_1 + p_x - p_0$$

p elastic scattering with an active target (low-momentum transfer)
Heavy-Ion Induced Electromagnetic Excitation

See D. Rossi’s presentation at NuSYM10

RQRPA calculations performed by N. Paar

Analysis of $^{130,132}$Sn provide mean EOS parameters:
$\Rightarrow \langle a_4 \rangle = 32.0(1.8)$ MeV
$\Rightarrow \langle p_0 \rangle = 2.3(0.8)$ MeV/fm$^3$

Values of the neutron skin thickness also obtained:
$\Rightarrow ^{130}$Sn: 0.23(4) fm
$\Rightarrow ^{132}$Sn: 0.24(4) fm

$E(\rho,0) = E(\rho,0) + S_2(\rho)\alpha^2 + O(\alpha^4)\,,$ $\alpha = \frac{N-Z}{A}$

$S_2(\rho) = \frac{1}{2} \frac{\partial^2 E(\rho,\alpha)}{\partial \alpha^2} |_{\alpha = 0} = a_4 + \frac{p_0^2}{\rho_0^2} (\rho - \rho_0) + \frac{\Delta K}{18 \rho_0^2} (\rho - \rho_0)^2 + ...$

$a_4$: symmetry energy per nucleon in pure neutron matter
$p_0$: symmetry energy pressure

- RQRPA calculations performed by N. Paar
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Elastic Proton Scattering from Halo Nuclei

Investigation of nuclear matter density distributions of halo nuclei by elastic proton scattering at low momentum transfer with the active target IKAR and ALADIN magnet setup at GSI

- Extended neutron distribution in $^8$He and $^{11}$Li obtained
- Size of core, halo and total matter distributions determined with high accuracy
- *with charge radius from laser spectroscopy (R. Sanchez et al.) neutron radius and neutron skin (halo) determined


<table>
<thead>
<tr>
<th>nucleus</th>
<th>$R_{\text{matter}}$, fm</th>
<th>$R_{\text{core}}$, fm</th>
<th>$R_{\text{halo}}$, fm</th>
<th>$R_n^*$, fm</th>
<th>$R_n-R_p^*$, fm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^4$He</td>
<td>1.49 (3)</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$^8$He</td>
<td>2.45 (7)</td>
<td>1.55 (15)</td>
<td>3.08 (10)</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>$^9$Li</td>
<td>2.43 (7)</td>
<td>--</td>
<td>--</td>
<td>2.59 (9)</td>
<td>0.48 (9)</td>
</tr>
<tr>
<td>$^{11}$Li</td>
<td>3.62 (19)</td>
<td>2.55 (12)</td>
<td>6.54 (38)</td>
<td>4.06 (23)</td>
<td>1.73 (23)</td>
</tr>
</tbody>
</table>
Elastic Proton Scattering with IKAR

Active Target IKAR and Aladin Magnet

**Active Target is foreseen as alternative recoil detector for R³B**

⇒ advantage:
- low threshold
- high detection efficiency (rel. thick target)

⇒ well suited as alternative technique to EXL for:
- short lifetimes ($T \leq 1$ sec)
- low RIB intensities ($\leq 10^4$ sec$^{-1}$)
Beyond the Nuclear Mean-Field

**Nucleon-Nucleon correlations:**
- Short-range (SRC)
- Tensor
- Long-range (LRC)

Modification of NN correlations as a function of density, temperature, isospin asymmetry determine the nature of many-body systems:
- Finite nuclei, nuclear structure
- Extended nuclear matter, EOS
- Compact astrophysical object e.g. neutron stars

Very challenging theoretically to incorporate correlations in the nuclear many-body system starting from bare NN interactions
- Experimental studies crucially needed
Hadronic Quasifree Scattering

- Proton and electron induced quasifree scattering (QFS) e.g. (e,e’p), (p,2p), (p,pn)...

Most direct experimental probes to investigate single-particle properties of nuclei and the role of nucleon-nucleon correlations

- Construct spectral functions for bound nucleons (probability that a nucleon as a certain energy and momentum within the nucleus)

Integrated strength ⇒ spectroscopic factors, occupation probabilities

To probe SRC (short distance scales) ⇒ high energy and momentum ⇒ Need high energy beams

Both valence and deeply-bound nucleons can be removed ⇒ different densities probed ⇒ disentangle LRC and SRC

High-energy, high-intensity radioactive ion beams at GSI (and in future at FAIR) opportunity to perform such studies with isospin asymmetric nuclei

T. Aumann, M. Chartier, R. Lemmon et al.
Decays from bound states: γ-rays detected in the Crystal Ball

2- and 3-body $^{12}\text{C}(p,2p)X$ channels included in the reconstruction of the s-state:

$^{12}\text{C}(p,2p)^{10}\text{B}+n$  
$^{12}\text{C}(p,2p)^{9}\text{Be}+d$  
$^{12}\text{C}(p,2p)^{6}\text{Li}+\alpha+n$  

$^{12}\text{C}(p,2p)^{10}\text{Be}+p$  
$^{12}\text{C}(p,2p)^{7}\text{Li}+\alpha$  
$^{12}\text{C}(p,2p)\alpha+\alpha+t$

Excitation energy spectrum for $^{11}\text{B}$ reconstructed by invariant mass method

$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j (1 - \beta_i \beta_j \cos \theta_{ij}) + E_\gamma - m_{proj}}$$

Counts

**gs**  
**p-shell knockout**  
$1/2^-$  
$3/2^-$  
**s-shell knockout**

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PhD Thesis J. Taylor, Univ. Liverpool (UK) and V. Panin, TU Darmstadt (Germany)
$^{12}\text{C}(p,2p)^{11}\text{B}$ in Inverse Kinematics

Excitation energy spectrum for $^{11}\text{B}$ reconstructed by invariant mass method

\[ E^* = \sqrt{\sum_i m_i^2 + \sum_{i\neq j} \gamma_{ij}m_im_j(1 - \beta_{ij}\cos\theta_{ij})} + E_\gamma - m_{proj} \]

Counts

Excitation energy of $^{11}\text{B}$
- gamma from $^{11}\text{B}$
- n + 10B
- p + 10Be
- 7Li + 4He
- Be9 + 2H
- Li6+He4+n
- He4+He4+H3
- Be7+H3+n
- total

Normal Kinematics


RCNP, Osaka
$E_p = 392$ MeV
Two spectrometer measurement
Energy resolution (FWHM) \( \approx 450 \) keV

PhD Thesis J. Taylor, Univ. Liverpool (UK) and V. Panin, TU Darmstadt (Germany)
Symmetry Energy and $R^3B$

Possible future measurements with $R^3B$

2) Heavy-ion collision measurements:

- Collective flows, particle ratios and yields, particle production ($\pi^+/\pi^-$, $K^+/K^0$, $\Sigma^-/\Sigma^+$)...

High densities, maximise isospin asymmetry in reaction, reduce Coulomb effects through double ratios and differences e.g. $^{106}_{\text{Sn}}+^{112}_{\text{Sn}}$ and $^{132}_{\text{Sn}}+^{124}_{\text{Sn}}$

See talks by R. Lemmon and P. Russotto et al. (ASYEOS)

FAIR will provide the highest energy RIBs in the world

$=>$ Unique opportunity to probe higher densities!

Short meeting tonight?
If interested to discuss, see myself or R. Lemmon

- New detectors needed, opportunities for new projects e.g.
  GLAD TPC or other
  TPC at target position + TOF wall (FOPI-like)
  Active target/TPC working group recently formed

- Collaboration open to new collaborators and new ideas!

- Synergies with other projects around the world
The GLAD TPC

- A prototype is being constructed at Saclay
- Collaborators welcome

For details during this symposium, see R. Lemmon (R³B Technical Coordinator)

CEA Saclay (France)
plegou@cea.fr
The $R^3B$ experiment is being designed to exploit the future RIBs from the Super-FRS at FAIR

⇒ A universal set-up for kinematically complete measurements of reactions with high-energy RIBs

Applicable to a wide class of reactions

Possible future measurements relating to the Symmetry Energy with $R^3B$:

Nuclear structure measurements
Heavy-ion collision measurements

FAIR will provide the highest energy RIBs in the world

⇒ New experiments to perform hadronic QFS and study correlations
⇒ Unique opportunity to probe higher densities in HIC with large isospin asymmetries
⇒ Optimum for proton elastic scattering or giant resonances for skin measurements
⇒ ...

New detectors needed (e.g. active target/TPC or other)

New ideas and new collaborators welcome!
A next generation experimental setup for studies of Reactions with Relativistic Radioactive Beams

Spokesperson: Tom Aumann

>50 institutes
20 countries
>220 participants
embedded in NUSTAR

http://www.gsi.de/forschung/kp/kr/R3B_e.html

Thank you for your attention!