NOVEL FOCAL PLANE DETECTOR CONCEPTS FOR THE NSCL/FRIB S800 SPECTROMETER

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Outline:
1) Introduction (nuclear physicist experiment with RIBs)
2) S800 Spectrometer and Focal-Plane detector system upgrade
3) A new MPGD-based readout for the tracking system
4) A new concept for ΔE/E measurement based on ELOSS detector
Fantastic Nuclei and where to find them

Nuclear Science Challenges addressed by Rare Isotope Beam Physics

Properties of atomic nuclei
- Study of predictive model of nuclei & their interactions, Many-body problem & physics of complex system

Astrophysics: Nuclear Processes in the Cosmos
- Origin of the elements, energy generation in stars, stellar evolution & the resulting compact objects

Use atomic nuclei to tests of laws of nature
- Effects of symmetry violations are amplified in certain nuclei

Societal applications and benefits
- Medicine, energy, material sciences, national security, etc. etc.

Example: $^{86}\text{Kr} \rightarrow 78\text{Ni}$

Rare Isotope Beam Physics -> Projectile Fragmentation
Pre-FRIB Science Opportunities at NSCL with Fast, Stopped, Reaccelerated Beams
Major US Project: Facility for Rare Isotope Beams (FRIB)

- Funded with financial assistance from DOE Office of Science (DOE-SC) with cost share and contributions from Michigan State University (MSU) & State of Michigan.

- Key features is 200 MeV/u 400 kW beam power ($5 \times 10^{13} \text{ }^{238}\text{U}/\text{s}$)
- Tremendous discovery potential: 80% coverage $Z < 82$

- Separation of isotopes in-flight

- Science program requires range of energies: Fast, Stopped, & reaccelerated beams

- Upgradable to 400 MeV/u & multi-user
Fast-beam experiment with the S800

Identification and beam transport
80-100 MeV/nucleon
100-10^6 pps

Reaction target
100-400 mg/cm^2

A1900 fragment separator

Production target
Beam energy from cyclotrons 100-150 MeV/nucleon

Focal Plane detector system for heavy-ion PID
Current Design of the S800 FP Detectors System

Ionization Chamber (IC):
- Z number identification
- 16 stacked-parallel plate ion chambers (each 1" long), filled with P10 (300-600 Torr)
- Slow detector → low rate (<5KHz)
- Low SNR
- Good resolution only up to Z=50

Cathode Readout Drift Chamber (CRDC):
- Position and angles
- Two CRDCs, 1 m apart, with 30x60 cm² effective area filled with CF4/(20%)C4H10
- Slow detector → low rate (<5KHz)
- Position resolution → <1 mm FWHM
- Aging problems

Same basic design planned for the HRS

Reaction target 100-400mg/cm²

Hodoscope
TKE, isomer tagging

Ionization Chamber
\( \Delta E \)

Plastic Scintillator
TOF

CRDC
Tracking

Beam
Goal 1 ➔ Upgrade of the DC gas avalanche readout

Wire-Based Detector:
“Mechanics”, Economic but Secondary effects ➔ Gain limits Space charge ➔ Counting-rate limits Aging ➔ Damage after long-term operation

Goal ➔ development of a new readout based on a hybrid MPGD structure, for the upgrade of the Cathode-Readout Drift-Chamber (CRDC) based tracking system
Position-sensitive Micromegas readout

Giomataris et al. NIM A 376 (1996) 29

Micromesh Gaseous Chamber:
-) a thin mesh supported by 50-100 μm insulating pillars, mounted above readout structure
-) E field similar to parallel plate detector.
-) $E_{\text{ampl}}/E_{\text{drift}} > 100 \Rightarrow$ high e⁻ transparency & ion back-flow suppression
Multi-layer THGEM (M-THGEM)
Manufactured by multi-layer PCB technique out of FR4/G-10/ceramic substrate

2-Layer M-THGEM
- Low pressure applications
- AT-TPC & pure gases

3-Layer M-THGEM
- Robust avalanche confinement ➞ lower secondary effects
- Long avalanche region ➞ high gain @ low pressure
- Field geometry stabilized by inner electrodes ➞ reduced charging-up

Design of the new MPGD-DC

Drift chamber based on hybrid MPGD readout

\[
\text{CF}_4/20\%\text{iC}_4\text{H}_{10} \text{ (40 Torr)}
\]

Intermediate Zap board
(include protection circuitries for the GET electronics and 16X2 channels reserved for the Ionization chamber signals)

Front end AsAd board
- 4 AGET per board, 64 channel each \(\rightarrow\) 512 channels
- 480 channels for the MM-readout
- 16 channels for the ionization chamber
- 16 spare channels

GET electronics fully integrated into the NSCLDAQ

Non-dispersive coordinate

Dispersive coordinate
Beam Test @ the S800 focal plane

Settings:
- MPGD-DC detector replaced the CRDC\textsubscript{2}
- Performance test (~7 hours) with \(^{78}\text{Kr}^{36+}\) (150 MeV/u) & fragmentation beam cocktail (Z \sim 4 to 36) from \(^{86}\text{Kr} + \text{Be}\) (2.7 mm)

Waveform traces recorded for each “fired” pad

- Number of samples (up to 512 time “buckets”)
- Clock “sampling” frequency (time/sample)
- Peaking time; gain
- ...

\[\text{Pulse Height} \rightarrow \text{Peak location (time)}\]

\[\text{X} \rightarrow \text{charge distribution (center of the gravity)}\]

\[\text{Y} \rightarrow \text{Arrival time (external trigger)}\]
Localization Capability: preliminary results

- **Pad number**
- **Pulse height (a.u.)**
- **Pad number**
- **Drift time (a.u.)**

**x-coordinate**

**y-coordinate**

- **σ = 0.25 mm**
Summary expected MPGD-DC properties

- Simple (construction) and robust
  - expected lower aging problems compared to the CRDC

- Better ions-backflow suppression
  - a few % compared to 60-70% of wire-based detector

- High detector gain @ low pressure (MM+THGEM)
  - large dynamic range

- High counting rate
  - faster gas + faster electronics + Multi-hit capability
  - expected up to 3 time lower dead time (@ 5kHz beam rate)

- High granularity (all pad are readout individually)
  - better position resolution along the dispersive coordinate
    (0.25 mm compared to 0.5 mm of the CRDC)
ΔE/E limit of the current S800 PID

- ToF typically of 100-150 ns (15 m reaction target - focal plane)
- Time resolution (plastic scintillator) ≈ 400 ps (FWHM)
- Energy resolution IC ΔE/E ≈ 1.2%
- Good PID resolution up to A < 100


Improve ΔE/E to explore new regions of the nuclear chart for nuclear structure and nuclear astrophysical studies ⇒ heavier beams expected from FRIB!

Lise++ Simulations

Present Ion Chamber

Proposed ELOSS (0.4%)
Goal 2 \(\rightarrow\) \(\Delta E/E\) measurement using Ionization chamber with optical readout

**Energy Loss Optical Ionization System (ELOSS)**

**OIC operational principle:**
- Gas excitation created along the particle track \(\rightarrow\) optionally electroluminescence mode of operation
- De-excitation with emission of prompt (fast decay time), scintillation photons (178 nm wavelength)
- The light is reflected by Al-foils \(\rightarrow\) large photon collection efficiency
- Light readout with array of PMTs
- Processed information \(\rightarrow\) \(\Delta E/E\), Timing, Position capability
Choice of the scintillating medium

### Noble gas & Mixtures

<table>
<thead>
<tr>
<th>Element</th>
<th>Z (A)</th>
<th>Ionization [e-/keV]</th>
<th>Scintillation [photon/keV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>2 (4)</td>
<td>39</td>
<td>15</td>
</tr>
<tr>
<td>Ne</td>
<td>10 (20)</td>
<td>46</td>
<td>7</td>
</tr>
<tr>
<td>Ar</td>
<td>18 (40)</td>
<td>42</td>
<td>40</td>
</tr>
<tr>
<td>Kr</td>
<td>36 (84)</td>
<td>49</td>
<td>25</td>
</tr>
<tr>
<td>Xe</td>
<td>54 (131)</td>
<td>64</td>
<td>46</td>
</tr>
</tbody>
</table>

Alternative solutions → wavelength shifter
- Halo-14 mixed with a noble gas (i.e. Ar)
- Ar/Xe mixture

Developed for LXe-TPC Dark Matter Search
ELOSS prototype: design and work plan

12 PMTs for an effective area of 84x84 mm²

Work plan:
- Operation mode (Efficiency and resolution)
  - Primary scintillation vs stimulated electroluminescence
  - Scintillating gases (Xe, Xe/CF₄, Ar/Xe, ...)
- Electroluminescence yield vs voltage (ionization chamber mode)
- Electroluminescence yield vs gas pressure
- Time resolution under different operational conditions

Stimulated scintillation configuration
ELOSS Prototype: GEANT4 simulations results

1 atm Xe (2.5 cm absorption thickness)

Time resolution

σ = 26.5 ps

Absorbed Energy (KeV)

57.4 MeV

σ = 2.3%

Position X (cm)

σ = 4 mm

Counts

Position Resolution

Counts

Absorbed Energy (KeV)

Time (ns)
Summary expected ELOSS properties

Compared to conventional IC:
- A (“3 times”) better resolving power
- Sensitivity to high-Z particles (above Z = 50)
- Larger dynamic range (sensitive also to light particles)
  \[ \text{changing the pressure of the filling gas} \]
- Higher rate capability (up to a few hundred of KHz)
  \[ \text{i.e. Xe the light is emitted within a few hundred ns} \]
- Good time resolution (< 100 psec) – not possible with IC
- Localization capability (< 4 mm) – not possible with IC
Properties of Electroluminescence (no amplification):
- Good linearity (# of ph. vs $\Delta E/E$)
- Good intrinsic energy resolution (no amplification)
- Large dynamic range (large pressure range)
- Conversion region & (optical) readout capacitive decoupled
- Single photo-electron sensitivity $\Rightarrow$ High SNR
- Isotropic emission $\Rightarrow$ use reflectors for high ph. collection
- No aging problems
- Timing (a few tens of ps) and localization (a few mm) $\Rightarrow$ not possible with conventional IC
Preliminary results from other groups

Presented at the DREB2018 - 10th International Conference on Direct Reactions with Exotic Beams

Development of the gaseous Xe scintillation detector for the particle identification of high intensity and heavy RI beams

T. Harada³, J. Zenihiro⁴, S. Terashima⁵, C. Y. Matsuda⁶, D. H. Sakaguchi⁷, S. Ota⁸, M. Dozono⁹, K. Kawata⁴, K. Kasamatsu⁴, D. P. S. Ishida⁴, D. Toho Univ.⁴, RIKEN Nishina Center⁴, Belhang Univ.⁵, CYRIC, Tohoku Univ.⁶, RCNP, Osaka Univ.⁷, CNS, Univ. of Tokyo⁸,

Energy resolution
- the energy resolution 1.0% is achieved. (Xe 3 atm ~ 5 atm)
- Time resolution (F3 Pla TDC - Xe TDC)
- The time resolution 130 ps is achieved. (Xe 4 atm)
- Secondary beam (A/Q ~ 2.3 @ 300 MeV/v)
- Z and A/Q were deduced from TOF between F1 Pla and F3 Pla and energy loss information of Xe detector. The resolution of ΔZ = 0.2 (5σ separation) is achieved.
- The resolution of ΔZ = 0.27 (Z=54) in high rate beam (55 kppp) is achieved. (low rate: ΔZ = 0.19 at Z=54)

Xe scintillation detector

R0041-406 Hamamatsu
The PMT was developed for liquid Xe φ: 2 inch
window Material: Synthetic silica glass
Spectral Response Range: 160-650 nm
QE at 175nm: 30%
Detector efficiency vs Z-number

Low gain operation

High gain operation

Large dynamic range!
Full detection efficiency for light elements (Z<10) recovered @ high detector gain.
Localization of saturated traces based on fitting distribution tails.
GEANT4 parameters (Xe gas)

Primary scintillation yield $W_{SC} = 7$ ph/KeV

- Literature $\Rightarrow$ 13.8 ph/KeV soft X-rays – Arxiv:1009.2719
- 16.3 ph/KeV gamma – Arxiv:1409.2853

A lower $W_{SC}$ is used to take into account gas impurity quenching & other effects (filling factor =0.64)

Hamamatsu PMT QE $\Rightarrow$ 30%

Xe gas pressure $\Rightarrow$ 1 atm

IC length $\Rightarrow$ 25.7 cm

Foil reflectivity = 100% (Al foil) $\Rightarrow$ $\approx 90\%$

ELOSS Prototype: GEANT4 simulations

GEANT4 snapshot with a reduced $W_{SC}$

Beam $\Rightarrow$ $^{78}$Kr$^{36+}$ (140 MeV/u)