Thermalization and Extraction of Projectile Fragments

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Outline

- Introduction to beam thermalization at NSCL
- Experimental results
- Challenges and improvements

Future: Advanced Cryogenics Gas Stopper (ACGS)

Future: Cyclotron Stopper
Why Thermalized beams

Projectile Fragmentation provides wide range of very exotic nuclei at high energies without decay losses and without chemical separation.

- Study properties of exotic nuclei far from stability
- Search for driplines

Some experiments are only possible with low energy beams (0 – 100 keV).

- High precision mass measurements
- Laser spectroscopy (Charge radii, nuclear moments)
- Nuclear astrophysics experiments (Safe coulomb excitation, transfer reactions)
Scheme for Thermalization of Projectile Fragmentation

- Production of fragments from high energy beam
  - Large momentum spread due to reaction mechanism and production target.

- Bρ and ΔE separation
  - A1900 spectrometer (High acceptance: 5% Δp/p), achromatic wedge

- Momentum compression and thermalization
  - Narrow momentum spread beams lead to high stopping efficiency (L. Weissman et al., NIM A 522 (2004) 212)

- Gaseous ions collection

- Low energy transport

Method for producing an ideal incident beam:
- Thermalize beam at the object point
History of Beam Thermalization at NSCL

NSCL has pioneered the beam thermalization in gas since 2002.

- Operated 25 L volume gas catcher, 1 bar, 298 K
- Delivered thermalized beams to LEBIT for Penning trap mass measurements
- First high precision mass measurement: $^{38}\text{Ca}^{2+}$

NSCL expand it’s capabilities to provide thermalized beams to low energy experimental areas (since 2012).
Low Energy Beam Area at NSCL

Beam thermalization facility (N4 vault)

LEBIT (Mass measurements)
User Demand:
(LEBIT)
Very low rates with high purity

Low energy beam area
User Demand:
(ReA3 & BECOLA)
High rates and high purity

A1900 fragment separator

LEBIT & Reaccelerator

BECOLA (Laser Spectroscopy)
Beam Thermalization Facility

Future: Advanced Cryogenics Gas Stopper (ACGS)

- ANL gas catcher
- RFQ ion guide
- North HV
- South HV
- Dispersive focal plane
- Object point
- Degraders PIN detector
- D0952
- D1000
- D1030
- Beta detector MCP Faraday cup
- Beta detector MCP
- Mass Analyzer

Large gas catcher constructed by Argonne National Lab

Beam from A1900

A182

Degraders PIN detector

Future: Advanced Cryogenics Gas Stopper (ACGS)
ANL Gas Catcher

- Large linear gas catcher constructed by Argonne National Lab
- 120 cm long gas catcher operate at pressure of 70 Torr and temperature of -10 °C
- Operate with Radio-frequency (RF) + DC voltage gradient
- Current measurements capabilities:
  - Window current (± ions)
  - RFQ ion guide electrode current
  - D0952 Faraday Cup Current

Nozzle
1.3 mm diameter

RF electrodes in Gas Catcher

Differential Pumping Station

Al thin Window

Ion Extraction System

D0952
RFQ Ion Guide

- Beam cooling with He
- Transverse confinement with RF quadrupole electric field
- Axial drag field with DC voltage gradient

RFQ operates at:
- RF frequency range of 3 - 4.5 MHz
- Peak-to-peak amplitude ~ < 500 V
Beam Thermalization: $^{40}$S fragment

$^{40}$S Fragment
Production @ A1900

$^{48}$Ca 140 MeV/u primary beam

Production Rate ~ 5.9E5 pps
Incoming beam energy ~ 75 MeV/u
Purity = 92%
d$p/p = 2$

$B_{\rho_{3,4}} = 3.1824$ Tm

$B_{\rho_{1,2}} = 3.5163$ Tm

$D/E$ TOF (ns)

PID @ A1900 focal plane

40S
41Cl
42Ar
Beam Thermalization: $^{40}$S fragment

$^{40}$S Fragment thermalized with adjustable degrader and fixed angle wedge at the dispersive focal plane

Incoming rate ~ 5.9 E5 pps
Ions: $^{40}$S, $^{41}$Cl & $^{42}$Ar

PID @ AC233

Object point

Dispersive focal plane

Degrader Thickness (um)

Positive Current
Scaled

Negative Current

Current (A)

Degrader THickness (microns)

Beta decay measurement @ D0952

Range Measurement

Lost before gas catcher

Range (mm): window projection

$T_{1/2} = 8.8$ sec

$^{40}$S

$T_{1/2} = 95$ sec

$^{40}$Cl

$^{40}$Ar

Lost on the back wall

19% of total beam captured in gas catcher

LISE++ simulation

Ionization Curves

$^{40}$S

$^{41}$Cl

$^{42}$Ar

Decay rate (cps)

Yield

$^{1/2}_t = 8.8$ sec

$^{1/2}_t = 95$ sec

$^{40}$S

$^{41}$Cl

$^{42}$Ar

Range Measurement

Degrader Thickness (microns)
Beam Thermalization: $^{40}$S fragment

$^{40}$S Fragment thermalized with:
1) first degrader at the object point
2) second adjustable degrader and fixed angle wedge at the dispersive focal plane

- Incoming rate ~ 5.9 E5 pps
- Ions: $^{40}$S, $^{41}$Cl & $^{42}$Ar

$^{40}$S $T_{1/2} = 8.8$ sec
$^{40}$Cl $T_{1/2} = 95$ sec
$^{40}$Ar

Object point

Dispersive focal plane

Lost before gas catcher
32% of total beam captured in gas catcher

Lost on the back wall

Rate increased by 1.7 times
Dispersion match to wedge

Beta decay measurement @ D0952

LISE++ simulation

Yield vs. Degradar thickness (um)

Two degrader sets

Range (mm): window projection

Ions thermalized in 1200 mm long gas catcher

Low energy beam

High energy beam

Degrader 1426 μm

Wedge 1016 μm

Angle 4.9 mrad
Beam Thermalization: $^{40}$S fragment

Mass distribution of $^{40}$S Fragment after thermalization

Processes inside the gas catcher:

- Thermalization process produces ions and electron pairs. ($\text{He}_2^+$)
- Form stable molecular ions from impurity molecules in the gas.
- Transport of thermalized ions in the buffer gas is affected by the interactions with molecular ions in the gas. (Drift time ~ 70 ms, Depends on impurity concentration, fragment chemistry)

Transport through low energy beamline

[Diagram showing mass distribution and processes]

Activity mass distribution

Stable ion mass distribution
Measurements were made between AC233 and D0952 detectors. (corrected for beam currents and decay.)

- Total Efficiency includes stopping and extraction efficiencies of the gas catcher, and RFQ efficiency.
- RFQ extraction efficiency ~ 80 %
- Incoming particle rate to the gas catcher varies from $10^2$ to $10^8$ pps.

Q - Ionization rate density = \frac{\text{# of ion pairs} \times \text{Incoming beam rate}}{\text{Stopping volume}}
Challenges in Beam Thermalization Process

- Total efficiency of thermalization and extraction reduces with incoming beam rate and start saturation.
  - Space charge build up
    - Nozzle size (diameter ~1.3 mm)
    - Higher DC gradient
    - Fast extraction methods (Ion surfing on RF carpet – Future ACGS, Cyclotron Stopper)

- Chemical adducts formation with fragments

- Stable ion contaminants

- Decay product as contaminants

Total Efficiency Measurement

\[
Q = \text{Ionization rate density} = \frac{\# \text{ of ion pairs} \times \text{Incoming beam rate}}{\text{Stopping volume}}
\]
Chemical Adducts Formation

- Impurity molecules in buffer gas form molecular ions with fragments (Depends on impurity concentration & fragment chemistry).
- Reduce thermalized beam rate for low energy experiments.

Mass distribution of $^{37}$K (before clean up)

$^{37}$K Molecular Breaking

- Apply additional voltage at RFQ
- Install a pump directly attached to the gas catcher (Clean up purpose)

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Stable Ion Contaminants

- Stable ions are formed during thermalization process.
- Contribute to high beam current (~ 600-800 pA)
- Major issue for low rate experiments

37K experiment

Stable ions mass distribution (before clean up)

- Activity identify from beta detector and slits
- Mass analyzer resolution (R) \( \frac{m}{\Delta m} \approx 1500 \)
- Some cases, stable ions can be rejected with slits

Stable and radioactive masses at A=29 e.g. COH+

29P experiment: Mass measurements
MCP image @ D1030 (set for mass = 29)

- Activity on the left

This is all A=29

Stable ion mass distribution (after clean up)

- CO groups show: gas catcher become very clean

\[ \text{[COH]}^+ \]
\[ \text{[CO]}_2^+ \]
\[ \text{[Ar]}^+ \]
\[ \text{[CO]}_3^+ \]

Count rate (cps)
Mass/charge

34Ar experiment

20 25 30 35 40 45 50 55 60 65 70 75 80
1
10
100
1000
10000

\[ \text{[34Ar]}^+ \]
\[ \text{[34ArCO]}^+ \]
\[ \text{[34ArCO]}_2^+ \]
Decay Products as Contaminants

- Thermalized beams are some time contaminated with decay products.

ReA3 Experiment: Measurement of the $^{75}\text{Ga}(a,n)$ and $(a,2n)$ cross sections important for neutrino driven wind nucleosynthesis – Z. Meisel

- $^{75}\text{Ga}$ beam was thermalized in ANL gas catcher and delivered to reaccelerator.
- Stable ion contaminants were expected from EBIT, BCB and gas catcher.
- Beam is 95% pure $^{75}\text{Ga}$ and found 1.1% of $^{75}\text{Ge}$ (daughter of $^{75}\text{Ga}$).
- Decay products come from gas catcher.

ReA3 Experiment: Measurement of the $^{34}\text{Ar}(a,p)$ $^{37}\text{K}$ reaction cross section – K. Chipps

- $^{34}\text{Ar}$ beam was delivered for reacceleration.
- Beam composition: $^{34}\text{Ar}$ (38%), $^{34}\text{Cl}$ (16%), $^{34}\text{S}$ (46%).
- Stable ion contaminants were expected from EBIT, BCB.
- Decay products come from gas catcher.
- Beam is 95% pure $^{75}\text{Ga}$ and found 1.1% of $^{75}\text{Ge}$ (daughter of $^{75}\text{Ga}$).
- Decay products come from gas catcher.
Wedge for High Intense Beam

- Homogeneous wedges can be manufactured with glass
- High intense beams can damage fused silica glass wedges

Damage glass wedge
Wedge for High Intense Beam

- In-house built Al wedge (size: 15 cm X 15 cm; angle = 5 mrad; middle thickness = 1.0 mm)

- Check the wedge for homogeneity with $^{82}$Se beam

![Beam position on the wedge diagram]

Thicker  Beam position on the wedge  Thinner
Wedge for High Intense Beam

![Graphs showing the relationship between thickness (um) and positive current (nA) for different strips (B, A, C) with indicated points for thicknesses of 1250, 1450, 1650, 1850, and 2050 um. The graph shows how the positive current changes with varying thicknesses for each strip.]

1  2  3  4  5  6  7  8

B-Strip
A-Strip
C-Strip

Thicker  Thinner
Improvement: Tunable Wedge System

- Stopping efficiency can be increased by having tunable wedge system.

Tunable wedge system installed recently.

- Two fused silica wedges rotate opposite direction to get the desired angle
- Angle per wedge = 2.5 mrad; middle thickness = 0.5 mm; Max wedge angle = 5 mrad
- Tested with $^{75}$Ga beam

{\textbf{Preliminary results}}

Stopping efficiency can be increased by having tunable wedge system.

- Two fused silica wedges rotate opposite direction to get the desired angle
- Angle per wedge = 2.5 mrad; middle thickness = 0.5 mm; Max wedge angle = 5 mrad
- Tested with $^{75}$Ga beam
Outlook

- Beam thermalization facility at NSCL provides beams successfully to low energy experimental programs

- Momentum compression improves beam thermalization efficiency

- Challengers for beam thermalization were identified and some of improvements were implemented

- New beam thermalization capabilities are on the way to reality soon (ACGS, Cyclotron Stopper)

ANL Gas Catcher Operation

- First Beam to ANL gas catcher: Aug 2012

<table>
<thead>
<tr>
<th>Beams for LEBIT</th>
<th>Beams for BECOLA</th>
<th>Beams for ReA3</th>
</tr>
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<tbody>
<tr>
<td>Fe-62,63,67</td>
<td>Fe-51,52,53</td>
<td>Ga-76</td>
</tr>
<tr>
<td>Co-63,64,65,68,69</td>
<td>K-35,36,37</td>
<td>K-37</td>
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<td>Br-72</td>
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<td>Ar-46</td>
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<td>Na-21</td>
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</tbody>
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- Gas Catcher experiments

  | Ga-76 | Mg-29 |
  | K-37,38,47 | O-14 |
  | P-29 | Si-26 |
  | Cl-33 | Br-72 |
  | S-40 | Kr-73 |
  |       | Ar-46 |
Thank you