Decay Studies at Fragmentation Facilities

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Bulk Activity Measurements

Implant activity into a stopper material for time $t_{\text{implant}}$. Cease implantation and observe decay for time $t_{\text{decay}}$. If necessary, introduce a “clean” stopper material and repeat.

For deposit of a single isotope:

$$A = A_0 e^{-\lambda t}$$

$$\lambda = \frac{\ln 2}{t_{1/2}}$$

For example shown:

$$t_{\text{implant}} = t_{\text{decay}} = 4 \times t_{1/2}$$
Addressing the Challenges of Bulk Activity Experiments

Challenges of bulk activity measurements

• Beam purity
• Beam duty cycle
• Determining sample size and absolute branches

The fast beams from projectile fragmentation offer a means of overcoming some of these challenges

• Reduced background from in-flight tracking and identification of individual isotopes in the beam on a particle-by-particle basis
• Low beam losses due to the fast (sub-microsecond) and chemistry independent separation and transport to experiment
• Primary beam of intermediate-energy heavy ions (E > 20 MeV/A)
• “Thick” target (typically Be)
• Projectile is abraded, resulting projectile-like fragment travels with a velocity similar to initial projectile

• Produce many isotopes below the initial projectile A and Z, both stable and radioactive
• Separation does not depend on the chemical properties of the isotopes
Fragmentation Transport Losses

Since the surviving projectile is traveling with a velocity similar to the incident beam velocity, there is no need to re-accelerate.

Also, no need to extract radioisotopes from an ion source, so all elements can be extracted with similar efficiencies.

A fragment separator and the differential energy loss method, can be used to select a subset of the nuclei produced by the fragmentation reaction.

Each fragment can be uniquely identified using time-of-flight, energy-loss, and magnetic rigidity.

\[ ^{78}\text{Kr} \text{ Fragmentation} \]
\[ 70\text{MeV/nucleon} \]
$^{58}\text{Ni} (75 \text{ MeV/A}) + ^{\text{nat}}\text{Ni}$

**Decay energy spectrum**

- $T < 15$ ms
- $T > 15$ ms

**Decay time spectrum**

- $T_{1/2} = 5.7^{+2.7}_{-1.4}$ ms
- $T_{1/2} = 4.7^{+3.4}_{-1.4}$ ms

Production rate: $1 \ ^{45}\text{Fe}/2$ h

$^{101}\text{Sn}$ beta decay @ GSI

FRS@GSI
$^{112}\text{Sn}$ (1 GeV/u) + Be (4 g/cm$^2$)

4 DSSD, 0.5 mm pitch
$4\pi$ segmented Beta Calorimeter

$E_p = 2.93$ MeV
$E_\beta = 1.28$ MeV

Stolz, private communication (2003).
NSCL Beta Counting System and Calorimeter

Permits the correlation of fragment implants and subsequent beta decays on an event-by-event basis

Implant detector: 1 each MSL type BB1-1000
4 cm x 4 cm active area
1 mm thick
40 1-mm strips in x and y

Calorimeter: 6 each MSL type W
5 cm active area
1 mm thick
16 strips in one dimension

Prisciandaro et al., NIMA 505, 140 (2003)
Response to low-energy events

Challenge:
\[ \beta \Delta E \sim 100\text{'s of keV} \]
\[ \text{beam } E \sim 1\text{'s of GeV} \]

CPA16 dual gain preamp from MultiChannel Systems

16 channels, \( 50\Omega \) input impedance,
2V output, \(~350\text{ ns rise time} \)

Low gain:
\[ 0.03 \text{ V/pC} \]
output directly to ADCs

High gain:
\[ 2.0 \text{ V/pC} \]
output to Pico Systems
16 channel shaper/discriminator
Detector Array for $\beta$-Delayed Neutron Decay

Specifications:
- 60 counters total (16 $^3$He, 44 BF$_3$)
- 60 cm x 60 cm x 80 cm polyethylene block
- Extensive exterior shielding
- 45% total neutron efficiency

Efficiency vs. Energy (MeV)

- Inner
- Middle
- Outer
- Total

MSU (Schatz), Mainz, PNL collaboration
MSU Segmented Germanium Array (SeGA)

Nominal 75% Ge crystal with etching of outer area of the crystal in each detector into 8 segments along the crystal axis and 4 segments perpendicular to it, for a total of 32 segments and one central contact.

12 SeGA detectors around the beta counting system. Efficiency ~5% at 1 MeV

Mueller et al., NIMA 466, 492 (2001)
Expt. 01016: Low energy structure of neutron-rich Ti isotopes

- **86Kr^{14+}** (12.2 MeV/A)
- **86Kr^{34+}** (140 MeV/A, \( I_{ave} \sim 3 \text{ pnA} \))

** setup details:**
- 330 mg/cm² Al degrader
- 1% momentum slit
- 376 mg/cm² Be
- \( B_{\rho_1} = 4.0417 \text{ Tm} \)
- \( B_{\rho_2} = 3.7554 \text{ Tm} \)

**Isotopes:**
- 53Sc
- 54Sc
- 55Ti
- 56V
- 57V
- 58Cr
$^{54}$Sc Delayed $\gamma$ Rays

Production rate: 0.5 $^{54}$Sc/s

$^{54}$Sc $\beta$-delayed $\gamma$ rays

$^{54}$Sc $\rightarrow$ $^{54}$Ti

$T_{1/2}$ = 360$\pm$60 ms

$Q_{\beta}$ = 11.3$\pm$0.6 MeV

$I$ (%) | log ft
---|---
15$\pm$10 | 5.45$\pm$0.72 (2+)
55$\pm$20 | 4.89$\pm$0.47 (4+)

1001 keV | 5.74$^{+0.05}_{-0.02}$ (2+)
1021 keV | 6.12$^{+0.30}_{-0.01}$ (4+)
1495 keV | 1494.8

Janssens, Broda, Mantica et al., PLB546, 55 (2002)
Deep Inelastic Collisions

$^{48}\text{Ca} + ^{208}\text{Pb} @ 305 \text{ MeV}$

GAMMASPHERE – 101 Compton suppressed high-resolution Ge detectors

$\text{Counts}$

Angular Momentum

Energy (arb. units)

yrast line

$\text{Energy (keV)}$

[Graph showing energy and angular momentum distribution]
Monopole Shift $\pi f_{7/2}^+ - \nu f_{5/2}^-$

GXPF1 interaction: N=34 magic structure expected

Lowering of $5/2^-$ due to strong $\pi f_{7/2}^+ - \nu f_{5/2}^-$ monopole interaction

Honma et al., PRC 65, 061301 (2002)

Prisciandaro et al., PLB 510, 17 (2001)
Signals from the DSSD supply the master gate trigger for both implants and decays. Upon a fragment implant, coincidence gamma rays are recorded for the duration of the Ge ADC gate (typically ~20 µs).

Problem: Difficult to distinguish a beta decaying isomer with a half-life similar to the ground state decay (would require detailed spectroscopy).

Grzywacz et al., PRL 81, 766 (1998)
Microsecond Isomers

$^{124}$Xe (140 MeV/A) + $^9$Be

Production rate: $10^{98}$Cd/h

$^{49}$In

$^{48}$Cd

$^{47}$Ag

$^{46}$Pd
Charge State Ambiguities

$^{136}\text{Xe (120MeV/A)} + ^9\text{Be}$

Problem: For this process, the presence of H-like and He-like fragments increased the level of difficulty with particle identification. The PID spectrum looks well resolved, however, each “blob” contained several charges states.

Need to measure the total kinetic energies of implants
Total Kinetic Energy Measurements

123Cd^{47+}

Energy (keV)

Counts

126Cd^{48+}

Energy (keV)

Counts

"126Cd"

Total Kinetic Energy (arb. units)
Problem: The high-energy fragments incident on the DSSD produce a flash of prompt, low energy radiations.

The use of digital electronics as a method to reject prompt radiation produced within the first few $\mu$s of a high-energy implant has been employed at GSI.
Over time, the build-up of activity in the implantation detector will produce a saturated source with a decay rate proportional to the implantation rate and the number of fast beta decays along the decay chain.

\[
\text{background } T_{1/2} \sim N_{\text{branch}} \times \text{implants/s \cdot pixel}
\]

The average time between implants in any one pixel must be significantly larger than the half-life to maintain a reasonable sensitivity to the decay under study.
Summary

Fast fragmentation beams can be effectively used for stopped beam experiments
• fast beam separation
• chemical independent separation
• particle-by-particle identification

Entire range of decay spectroscopy experiments have been performed
• charged particle decays
• beta-delayed charged particle decay
• beta-delayed neutron decay
• beta-delayed gamma decay
• isomeric gamma decay

Problems needing attention: Implant rate (background), isomers, charge-state ambiguities, radiation flash