Analogue signal processing

I

+ HV

100 kΩ

100 kΩ

V_{in}(t)

V_{max} = \frac{n_{eg}}{C}

RC = \ldots

RC >> t^*

I' << RC << t^*

(electron sensitive)
Analogue signal processing

Voltage sensitive preamplifier

\[ V_0 = \frac{Q}{C_{tot}} \]

Gain dependent on the detector capacitance (can vary)

Charge sensitive preamplifier

\[ V_0 = -\frac{Q}{C_f} \]

Output is proportional to charge integrated on \( C_f \), if signal is fast compared to \( R_fC_f \)

Noise is proportional to \( C_d \)
Analogue signal processing

**Charge sensitive preamplifier**

- Fast rise-time – pulse height proportional to input signal
- Slow rise-time – rise and decay convolved (non-linear signals, worse resolution) – *ballistic deficit*

*Position dependent RC*
Digital signal processing

- Process (and sometimes store) a digital approximation of the trace from a detector/preamp
- All information encoded in the preamp trace can be processed (software)
- Single data stream can be multiplied and each stream processed independently

Analogue signal processing

- Hardware filter detector signals for particular qualities (energy resolution, timing, etc)
- Excellent resolution, but some information is discarded
- Separate optimized processing required for different parameters (energy, time, etc)
Leading-edge discriminators

Voltage

threshold
Leading-edge discriminators
Leading-edge discriminators

Voltage

jitter

threshold
Leading-edge discriminators

- **jitter**: Good for trigger decisions, bad for timing.
- **amplitude walk**: Good for trigger decisions, bad for timing.
Constant-fraction discriminators

A = raw
B = attenuated
C = delayed & inverted
B+C

Better for timing
Signal processing

- Det
- Preamp
- Shaping Amp
- Disc
- Timing
- Logic
- Digitizers

Det 1 → start
Det 2 → stop

TDC
Analogue signal processing

High pass filter

\[ \tau = RC \]

Low pass filter

\[ \tau = RC \]

risetime < RC < decay time

signal length < RC
Shaping amplifiers

Shape pulses to:

• Improve signal to noise
• Reduce pileup effects

CR-RC shaping

Undershoot leading to degraded energy resolution

Pole zero variable resistor used to tune undershoot
Shaping amplifiers

Shape pulses to:

- Improve signal to noise
- Reduce pileup effects
- Keep signal height information
- Lose information (e.g., trace shape)

![Graph showing Preamp and Shaped signals over time and voltage axes.](image)
Shaping amplifiers – ballistic deficit

A = Shaping time too short
B = Shaping time better matched
signal processing

0.5μs

1.0μs

1.5μs
signal processing

![Graph showing signal processing data]

- **Preamp Output (mV)**
- **Time (μs)**

- **1000μm - Far signal**
- **1000μm - Near signal**
- **140μm - Near signal**
- **140μm - Far signal**
Shaping amplifiers

Shape pulses to:
• *Improve signal to noise*
• *Reduce pileup effects*

![Graph: Comparison between Preamp and Shaped signals]

Keep signal height information

Lose shape information

Genuine second pulses missed

→ *Digital!*
Digital signal processing
• Process (and sometimes store) a digital approximation of the trace from a detector/preamp
• All information encoded in the preamp trace can be processed (software)

Analogue signal processing
• Hardware filter detector signals for particular qualities (energy resolution, timing, etc)
• Excellent resolution, but some information is discarded
• Separate optimized processing required for different parameters (energy, time, etc)
Digital Signal Processing

• Digital information can be stored, retrieved and duplicated without losses
• Duplicated data streams processed independently (eg one optimized for energy, another for time)
• Correlations between separate data streams can be made on arbitrary time scale (time-stamping)
• Full traces can be recorded, and processed offline
• Information on signal shape (eg rise-time) and closely-timed events (eg implantation-decay) is maintained
• Data sampling rate MHz – GHz (depending on signal properties)

Thanks to Robert Grzywacz, University of Tennessee
Induced current

Integrated current (idealised)

Large volume detector (e.g., Ge, gas detectors) has a pulse shape dependence on interaction position.

Movement of the charge inside the detector induces image charges.
Integrated current (preamplifier)

\[ I = \frac{dq}{dt} \]

Integrated current (digitized)

\[ I = \frac{\Delta q}{\Delta t} \]
Digital Signal Processing

Gamma ray tracking

“cylindrical field”
Digital Signal Processing

Trapezoidal Filter

A digital equivalent to shaping

Sensitive to fast changes in signal

\[ V = V_{L2}^{av} - V_{L1}^{av} \]

Detector pulse

Match G to rise-time of the signal

L performs some shaping (low-pass)

Can run signal through multiple filters, optimized for different things

Transformed pulse
Digital Signal Processing –– double events

- Detect very short lived proton emitting nuclei at the final focus of the recoil separator
- Very rare event (mHz) in the presence of large implantation (kHz)

Expected decays

\[0.5 \, \mu s - 32 \, \mu s\]

\[E_{\text{implant}} \sim 20-30 \, \text{MeV}\]
\[E_{\text{decay}} \sim 1-2 \, \text{MeV}\]

50 \, \mu s long signal traces
Digital Signal Processing

- $E_D = 1.73$ MeV
- $T_D - T_R = 0.55 \mu s$

Diagram showing the amplitude of the pre-amp signal over time, with markers for $T_R$, $T_D$, and $E_R$. The diagram includes two traces: a front trace and a back trace.
Experiments
Direct measurement for nuclear astrophysics - $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ (K.A. Chipps, et al.)

- Counting

Requirements:
- Selectivity
- Efficiency
- Resolution

$^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ comparable to beta decay rate in novae

The $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ rate is important for
- Energy generation
- $^{17}\text{O}$ production
- $^{18}\text{F}$ production and gamma rays
- $^{17}\text{F}(p,\gamma)^{18}\text{Ne}(e^+\nu_e)^{18}\text{F}$
Binary systems

Mira system

420 light years away

6.5 billion miles apart (twice the distance between the sun and Pluto)

UV image of 13 LY-long tail of Mira [GALEX]

HST UV image
Only two significant contributions to the rate:
- $3^+$ resonance
- Direct capture

The important $3^+$ resonance location was unknown

Various predictions for its location had significant impact on its contribution to reaction rate in novae

The $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction rate – resonance location

The $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction rate – resonance location

- Only two significant contributions to the rate:
  - $3^+$ resonance
  - Direct capture

- The important $3^+$ resonance is too high in energy to have a dominant contribution at nova temperatures
- The $3^+$ resonance will dominate the reaction rate at higher temperatures, e.g. in X-ray bursts
- Resonance strength unknown
The $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction rate – resonance strength

5x10^6 pps $^{17}\text{F}$ (50% purity)

The $^{17}$F($p,\gamma$)$^{18}$Ne reaction rate – resonance strength

5x$10^6$ pps $^{17}$F (50% purity)

The $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction rate – resonance strength

- $\omega_\gamma = 33 \pm 14 \text{ (stat)} \pm 17 \text{ (sys)} \text{ meV}$
- Constrained resonant cross section to within factor of 2

- The direct capture cross section dominates the $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ reaction rate in novae
- Direct measurement of $^{17}\text{F}(p,\gamma)^{18}\text{Ne}$ at nova temperatures requires $\sim 10^{10}$ pps of $^{17}\text{F}$/s, or $\sim 40$ years at current beam rates!
- Indirect method required…
Direct capture occurs via an electromagnetic transition at large radii.

The cross section can be accurately calculated from the Asymptotic Normalization Coefficients (ANC’s) with little model dependence.

The ANC’s can be determined by measuring the cross section for peripheral proton transfer reactions.

- Mukhamedzhanov et al., PRC56 (1997) 1302.
- Gagliardi et al., PRC59 (1999) 1149.
Transfer experiments in inverse kinematics

- Energies
- Angles
- Counting

Requirements:
- Resolution
- Efficiency
- Selectivity

Traditionally performed in normal kinematics (light ion beam, heavy target nucleus) with magnetic spectrograph (excellent resolution)

- Short-lived exotic nuclei must be the beam
- Inverse kinematics on CD$_2$ targets
- Si array, or solenoid (HELIOS) device
- [Augmented with gammas]
(d,p) reactions

CoM Frame

CoM to Lab transformation
CoM velocity
Lab velocity

Normal Kinematics
(d,p) reactions

Inverse Kinematics

CoM to Lab transformation
CoM velocity
Lab velocity

θ_{lab}
(d,p) reactions

CoM to Lab transformation
CoM velocity
Lab velocity

Inverse Kinematics

$\theta_{\text{lab}}$
(d,p) reactions

Inverse Kinematics

CoM to Lab transformation
CoM velocity
Lab velocity

\(\theta_{\text{lab}}\)
(d,p) reactions

CoM to Lab transformation

CoM velocity

Lab velocity

Inverse Kinematics
(d,p) reactions

Inverse Kinematics
(d,p) reactions

\[ \theta_{\text{lab}} \]

Inverse Kinematics
Inverse Kinematics

(d,p) reactions

CoM to Lab transformation
CoM velocity
Lab velocity

\( \theta_{\text{lab}} \)
(d,p) reactions

Inverse Kinematics

CoM to Lab transformation

CoM velocity

Lab velocity

$\theta_{\text{lab}}$

$\text{p}$
(d,p) reactions

Inverse Kinematics
Inverse Kinematics

\[ \theta_{\text{lab}} \]

\( \text{CoM to Lab transformation} \)

\( \text{CoM velocity} \)

\( \text{Lab velocity} \)

\((d,p)\) reactions
(d,p) reactions

CoM to Lab transformation

CoM velocity

Lab velocity

Inverse Kinematics
(d,p) reactions

CoM to Lab transformation

CoM velocity

Lab velocity

θ_{lab}

Inverse Kinematics
(d,p) reactions

Inverse Kinematics

CoM to Lab transformation

CoM velocity

Lab velocity

θ_{lab}
(d,p) reactions

CoM to Lab transformation
CoM velocity
Lab velocity

Inverse Kinematics
Proton Energy-Angle Systematics

$^{132}\text{Sn}(d,p)$ @ 4.5 MeV/A

- High Solid Angular Coverage
- Good energy and angular resolution
- Large dynamic range
(d,p) reactions

Elastically scattered carbon
Elastically scattered deuterons
Protons from (d,p)
Elastically scattered protons
(d,p) reactions

- ORRUBA gives ~80% $\phi$ coverage over the range $47^\circ \rightarrow 132^\circ$
- 2 rings – $\theta < 90^\circ$: 12 telescopes (1000$\mu$m R + 65$\mu$m NR)
  - $\theta > 90^\circ$: 12 detectors (500$\mu$m R)
- 324 channels total (288 front side, 36 back side)
- HI beam
- Deuterated plastic targets
$^{132}\text{Sn}(d,p)^{133}\text{Sn}$

- Measure single-particle levels above $N=82$
- 50k pps $^{132}\text{Sn}$ average, at 630 MeV
- $\sim175$ $\mu$g/cm$^2$ CD$_2$ target
- First transfer measurement on $^{132}\text{Sn}$

K.L. Jones, University of Tennessee

Fast IC

\begin{align*}
1g_{7/2} & \quad 2d_{5/2} \\
2f_{7/2} & \quad 2d_{3/2} \\
3s_{1/2} & \quad 3p_{1/2} \\
3p_{3/2} & \quad 2f_{5/2} \\
1h_{11/2} & \quad 82
\end{align*}
Table 1 | Properties of the four single-particle states populated by the $^{132}\text{Sn}(d,p)^{133}\text{Sn}$ reaction

<table>
<thead>
<tr>
<th>$E_r$ (keV)</th>
<th>$J^\pi$</th>
<th>Configuration</th>
<th>$S$</th>
<th>$C^2$ (fm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7/2$^-$</td>
<td>$^{132}\text{Sn}<em>{gs} \otimes \gamma</em>{7/2}$</td>
<td>0.86 ± 0.16</td>
<td>0.64 ± 0.10</td>
</tr>
<tr>
<td>854</td>
<td>3/2$^-$</td>
<td>$^{132}\text{Sn}<em>{gs} \otimes \gamma</em>{3/2}$</td>
<td>0.92 ± 0.18</td>
<td>5.61 ± 0.86</td>
</tr>
<tr>
<td>1,363 ± 31</td>
<td>(1/2$^-$)</td>
<td>$^{132}\text{Sn}<em>{gs} \otimes \gamma</em>{1/2}$</td>
<td>1.1 ± 0.3</td>
<td>2.63 ± 0.43</td>
</tr>
<tr>
<td>2,005</td>
<td>(5/2$^-$)</td>
<td>$^{132}\text{Sn}<em>{gs} \otimes \gamma</em>{5/2}$</td>
<td>1.1 ± 0.2</td>
<td>$(9 \pm 2) \times 10^{-4}$</td>
</tr>
</tbody>
</table>

The spectroscopic factors ($S$) were extracted from the data by using the Strömlin optical potentials, a radius parameter $r = 1.25$ and diffuseness $a = 0.65$. The asymptotic normalization coefficient (ANC) is quoted as $C^2$. All errors are expressed as standard deviations. Excitation energies were taken from the ENDF/B-VII.1 database (http://www.nndc.bnl.gov/ensdf/) and the present work.
• Last experiment to run at the HRIBF!
• 12k pps $^{132}$Sn average, at 560 MeV
• ~150 $\mu$g/cm$^2$ CD$_2$ target
• First (d,t) measurement on a heavy fission fragment in inverse kinematics

$^{132}$Sn(d,t)$^{131}$Sn

Riccardo Orlandi, CSIC Madrid

Fast IC

$^{132}$Sn(d,t)$^{131}$Sn

$^{132}$Sn(d,p)$^{133}$Sn

$^{132}$Sn(d,t)$^{131}$Sn

$^{132}$Sn(d,p)

Photon Energy (MeV)

Laboratory Angle (deg)
$^{132}\text{Sn}(d,t)^{131}\text{Sn}$

$^{131}\text{Sn}$ E$_x$

- $1h_{11/2}$
- $3s_{1/2}$
- $2d_{3/2}$
- $2d_{5/2}$
- $1g_{7/2}$

$^{132}\text{Sn}(d,t)^{131}\text{Sn}$

- $(7/2^+)$ 2.434 MeV
- $(5/2^+)$ 1.654 MeV
- $(1/2^+)$ 0.331 MeV
- $(11/2^-)$ 0.065 MeV
- $(3/2^+)$ 0.000 MeV

Graphs showing calculated differential cross-sections in both the centre-of-mass (CoM) frame and the laboratory frame using inverse kinematics.
$^{132}\text{Sn}(d,t)^{131}\text{Sn}$
$^{132}\text{Sn}(d,t)^{131}\text{Sn}$
26Al nucleus was the first radioisotope detected in the interstellar medium

- Half life of $7.2 \times 10^5$ years
- Observation of $\gamma$ rays associated with its decay provides evidence of nucleosynthesis
- Temperatures $\geq 0.03$ GK, the $^{26}\text{Al}(p, \gamma)^{27}\text{Si}$ reaction is expected to govern the destruction of $^{26}\text{Al}$
- Essential to reduce the uncertainty in order to determine the contribution of heavy stars to the overall Galactic abundance of $^{26}\text{Al}$

Focus on $^{26}\text{Al}^g$ reactions

$5^+ \text{gs, } 0^+ \text{ isomeric state at 228 keV}$
• Core-collapse supernovae
  massive star collapses
  $T_c \sim 3 \text{ GK}$
  long favored source

• Novae
  accretion onto a white dwarf
  estimated < 0.4 $M_\odot$ $^{26}\text{Al}$
  ejected – depends on uncertain reactions
  $T < 0.4 \text{ GK}$

• Wolf-Rayet stars
  >30 $M_\odot$ stars – develop strong stellar winds blowing material into space
  $T < 0.05 \text{ GK}$

need to know $^{26}\text{Al}+p$ rates over large temperature range

Excess of $^{26}\text{Mg}$ found in calcium and aluminium inclusions of the Allende meteorite

*If* decay occurred in situ, then $5 \times 10^{-5}$ $^{26}/^{27}$ at time of solar system formation

February 8, 1969

Several tons of material deposited

Material dated to predate formation of the Earth
Largest germanium spectrometer placed in orbit at that time

HEAO (High Energy Astronomy Observatory)

First astronomical observation of $^{26}$Al

High Resolution Gamma Ray Spectrometer (HRGRS):
- 50 keV - 10 MeV
- 3 keV resolution
- FOV 30°

Four p-type Ge detectors
CsI anti-coincidence

1979-1981
26$^{\text{Al}}$ – galactic mapping

Compton Gamma Ray Observatory - COMPTEL

Energy resolution
5 - 8% (FWHM)

Angular resolution
1.7 - 4.4 degrees (FWHM)

Launched 1991

Weight: 1460 kg
Dimensions: 2.61 m x 1.76 m diameter
Power: 206 W

young giant stars

Weight: 1460 kg
Dimensions: 2.61 m x 1.76 m diameter
Power: 206 W
Launched October 2002

**Field of View**
- fully coded: 14° flat to flat,
- 16° corner to corner

**Energy resolution (FWHM):**
- 2.2 keV at 1.33 MeV for each detector
- (3 keV for the entire spectrometer)

**Angular resolution**
- 2.5° for point sources

**Field of View**
- fully coded: 14° flat to flat,
- 16° corner to corner

Launched October 2002
Radioactive $^{26}\text{Al}$ from massive stars in the Galaxy

Doppler shifts suggest $^{26}\text{Al}$ is co-rotating with the Galaxy

Line width dominated by instrumental resolution

$^{26}\text{Al}$ is a pan-galactic source

SPI (INTEGRAL)
${}^{26}\text{Al}$ – astrophysically important states

26 Al + p
Q = 7463

Lotay et al., PRL 102, 162502 (2009)

Al Al – astrophysically important states
\(^{26}\text{Al} – \text{identification of mirror states}\)

G. Lotay et al., *PRL* 102, 162502 (2009)

- Fusion-evaporation reaction to populate states and study \(\gamma\) decays with Gammasphere
- 6 pnA, 26 MeV beam of \(^{16}\text{O}\) ions on \(\sim 150 \mu\text{g/cm}^2\) thick \(^{12}\text{C}\) target
- Location of low-lying resonances constrained stellar rate
- SF for these states necessary for further constraint

\[
\begin{array}{|c|c|c|}
\hline
\text{E}_{\text{res}} (\text{keV}) & \text{E}_{\text{ex}} & \text{J}^\pi \\
\hline
6 & 7468 & 5/2^+ \\
68 & 7532 & 5/2^+ \\
94 & 7557 & \\
127 & 7592 & 9/2^+ \\
189 & 7652 & 11/2^+ \\
231 & 7690 & 5/2^+ \\
241 & 7702 & 7/2^+ \\
276 & 7740 & 9/2^+ \\
332 & 7792 & 7/2^+ \\
368 & 7831 & 9/2^- \\
\hline
\end{array}
\]

lowest direct \((p,\gamma)\) measurement

C. Ruiz et al., *PRL* 96, 252501 (2006)
What about proton transfer?

• (d,n) is tricky because of neutron detection

• Can measure (d,n) by measuring only the recoil, and coincident gamma rays, but no angular distributions, feeding issues, etc

• \(^3\text{He},d\) can be performed with detectors just like for (d,p), but how do you make a localized target?
  • Cell – backgrounds and straggling from windows, bulky (shadowing)
  • Implantation (difficult to make uniform, backgrounds from foils, thickness of foils)
  • *Can measure (d,p) and use mirror symmetry*
$^{26}$Al(d,p)$^{27}$Al data – Setup

- 117 MeV $^{26}$Al
- 5x$10^6$ pps
- 150 $\mu$g/cm$^2$ CD$_2$
$^{26}$Al(d,p)$^{27}$Al – Excitation Energy

PRELIMINARY

$E_x$ (MeV)

165 deg  83 keV (CoM)
138 deg  180 keV (CoM)
\( ^{26}\text{Al}(d,p)^{27}\text{Al} \) data – Excitation energy

- **SIDAR**
  - 83 keV (CoM)

- **ORRUBA**
  - 150 keV (CoM)

- \( \sim 130^\circ \)
- \( \sim 110^\circ \)
- \( \sim 165^\circ \)
$^{26}\text{Al}(d,p)^{27}\text{Al}$ data – Excitation energy

$^{26}\text{Al}$ beam + $\text{CD}_2$

$^{26}\text{Al}$ beam + $\text{C}$

$^{26}\text{Mg} + \text{CD}_2$

Lotay et al., PRL 102, 162502 (2009)
TIARA at GANIL

2x10^5 pps ^24Ne

1 mg/cm^2 CD_2 target

2 mm beam spot

Measurement of (d,p\gamma) reactions in inverse kinematics
Measurement of \((d,p\gamma)\) reactions in inverse kinematics

Only core signals from EXOGAM clovers, limiting Doppler correction to 65 keV broadening

2x10^5 pps \(^{24}\text{Ne}\)
1 mg/cm\(^2\) CD\(_2\) target
2 mm beam spot
Measurement of \((d,p\gamma)\) reactions in inverse kinematics

Only core signals from EXOGAM clovers, limiting Doppler broadening.
What about proton transfer?

• (d,n) is tricky because of neutron detection

• Can measure (d,n) by measuring only the recoil, and coincident gamma rays, but no angular distributions, feeding issues, etc

• \(^{(3}\text{He},d)\) can be performed with detectors just like for (d,p), but how do you make a localized target?
  • Cell – backgrounds and straggling from windows, bulky (shadowing)
  • Implantation (backgrounds from foils, thickness of foils)
  • Gas jet target
JENSA gas jet target

HRIBF beam

turbo turbo turbo

gas receiver

roots

roots

turbo turbo turbo
drs

high pressure laval nozzle

large-area Si detector array

JENSA : Jet Experiments for Nuclear Structure and Astrophysics
(Colorado School of Mines, ORNL, LSU, and NSCL)
Operates in a choked-flow mode (constant entropy), in which flow is proportional to inlet pressure.
JENSA gas jet target

Diagram showing the setup of the JENSA gas jet target with various components labeled and connected by arrows indicating the flow of gas and pressure.

Key components:
- 361C
- V 550
- Shimadzu
- WSU2001
- WSU1001
- 2-3 dry pumps
- Gas cleaning/cooling
- Diaphragm compressor
- Beam
- Low pressure side
- High pressure side
- Jet/receiver
- Vacuum components
After construction of JENSA at ORNL, it will be moved to the new reaccelerated beam facility (ReA3) at Michigan State University.
Thank you