Beta-delayed neutron studies of the fission fragments

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Figure: T. Kawano
Heavy $\beta n$-emitters are poorly studied due to limited accessibility, difficulty in detection of neutrons and complexity of data interpretation. New facilities and new capabilities.

Most of the neutron rich isotopes and all r-process nuclei are $\beta n$-emitters.
Decay strength distribution, lifetimes and branching ratios

$$\frac{1}{T_{1/2}} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z,Q_\beta - E_i)$$

$$S_\beta(E_i) = \langle \psi_f | \hat{O}_\beta | \psi_{mother} \rangle$$
Decay strength distribution, lifetimes and branching ratios

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\]

Neutron spectroscopy
Total absorption spectroscopy
High Resolution spectroscopy
Lifetime and $\beta$-delayed neutron emission sensitivities for a (cold) $r$-process

cold $r$-process: equilibrium between $(n,\gamma)$ and $\beta$ decay

Lifetime sensitivity

$Z=31$

M. Madurga et al., PRL 109, 112501 (2012)

K. Miernik et al., PRL 111, 132502 (2013)

Neutron branching ratio sensitivity

with $\beta n$

without $\beta n$

Neutron branching ratios from global formulas
Kratz – Herrmann formula (“average nucleus”)

Möller, P.; Nix, J. R.; Kratz, K.-L.
Atomic Data and Nuclear Data Tables, Vol. 66, p. 131

Pn(NNDC)
Single particle model of decays near $^{78}$Ni

"FORBIDDEN" transitions
small $S_β$

"ALLOWED" GT
large $S_β$

$1s1/2$

$1d5/2$

$0g9/2$

$1p1/2$

$1p3/2$

$0f5/2$

$N=50$

$Z=28$

$1p1/2$

$0f7/2$

$1p3/2$

$Z=28$

$N=50$

$Z=28$

$N=50$
Single particle model of decays near $^{78}\text{Ni}$ for $N>50$

Single particle description:
- "Valence" nucleons cannot decay via allowed Gamow-Teller transitions between spin orbit partners.
- Particle-hole excitations lead to population of high energy states.
- Important role of forbidden transitions ($\Delta l>0$ and parity changing).

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\end{itemize}

N=50

3-4 MeV

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$$B_{GT} = |M_{GT}|^2 = N_v \cdot \left(1 - \frac{N_f}{2j_f + 1}\right) \cdot |M_{GT}^0|^2$$
Beta decay of neutron rich nuclei beyond $N=50$

Single particle description:
- “Valence” nucleons cannot decay via allowed Gamow-Teller transitions between spin orbit partners
- Particle-hole excitations lead to population of high energy states

Forbidden and allowed transitions separated in energy scales (and decay modes).
Forbidden decay of $^{84}$Ga

(K. Kolos et al. Phys. Rev. C)
VANDLE – neutron time of flight and γ-ray detector

The Versatile Array of Neutron Detectors at Low Energy

Funding: Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science – DOE NNSA

Design goal:
Maximize the detection efficiency in the broad energy range (100 keV – 6 MeV)
Measure neutrons and gammas.

First implementation at HRIBF experiment:
- 48 bars 3x3 x 60 cm³
- $\Omega = 10\%$ ($23\%$) of 4π
- 3% (6%) total efficiency @ 1MeV
- 50 cm TOF radius
- 40-60% efficiency beta “START” detector

Gamma rays:
- 2 clovers, 3% efficient @ 1MeV

Fully digital system (250 MSPS):

Sub-nanosecond timing with 4ns digitization period

Low neutron detection threshold

Portability and flexibility

S. Paulauskas et al. NIM A737,22 (2014)
GEANT 4 model of VANDLE

Intrinsic efficiency 60 cm bar @30 keVee threshold

Exp vs. Geant 4

VANDLE response to mono-energetic neutrons

$E_n = 0.3, 1.0, 5.0$ MeV

S. Ilyushkin
(Colorado School of Mines)
Intense beam (~10 μA) of (50 MeV) protons on UCx targets. Isobar separation essential for success of the experiments! IRIS-1/IRIS-2 platforms, negative and positive ions.
Beta-delayed neutron emitters near r-process path studied at HRIBF/LeRIBSS in February 2012

VANDLE commissioning experiment
Selection of isotopes with large $Q_{\beta - S_n}$ and $I_{\beta n}$
29 cases measured, focus on new data

M. Madurga, W. Peters
S. Paulauskas ...

and VANDLE

$T_{1/2} > 50$ms
rates > 10pps
$I_{\beta n} > 1$
$3\text{MeV} < Q_{\beta n} - S_n < 8\text{MeV}$
"Resonant" decay of $^{84}$Ga ($\sim$30 h measurement)

- $Q_\beta = 13.69$ T
- $T_{1/2} = 85(10)$ ms
- $Q_\beta - S_n = 8.5$ MeV, $P_n = 74(14)\%$
Spectrum deconvolution – from TOF to decay strength
Spectrum deconvolution – from TOF to decay strength

TOF

Decay strength $S_\beta$

Neutron energy

$B(GT)$ in MeV$^{-1}$
Neutron+gamma coincidences

Gate on 1348keV

Singles
Neutron+gamma coincidences

Neutron spectrum deconvolution
$^{84}\text{Ga}$ and $^{83}\text{Ga}$ decay strength from neutrons

- observed large beta strength at high excitations in the daughter
- structures in the neutron spectrum
Shell-model interpretation
sd-neutrons as spectators

Beta decay of $N<50$ nuclei (shell model)
(Nushell with $^{56}\text{Ni}$ core and jj44bpn interactions).

$\beta^-$ decay: $84\text{Ga}$ ($N=53, Z=31$)
may look like

$\beta^-$ decay: $78\text{Ga}$ ($N=47, Z=31$)
shifted by $\sim 3$ MeV
($N=50$ shell gap)
BGT for $^{83}$Ga and shell model

- observed large beta strength at high excitations compatible with GT-decay of $^{78}$Ni core states

- contribution of GT decays from states outside $^{78}$Ni core is factor x100 smaller (blue)
BGT for $^{83}$Ga and shell model

- observed large beta strength at high excitations compatible with GT-decay of $^{78}$Ni core states

- contribution of GT decays from states outside $^{78}$Ni core is factor $\times 100$ smaller
Shell-model $B(GT)$ in $^{78}$Ni region

Excitation energy [MeV]
Shell-model predictions of feedings in $^{78}\text{Ni}$ region
Neutron spectroscopy in very neutron rich heavy nuclei

\[ ^{84}\text{Ga} \]
\[ Q_\beta - S_n = 8.5 \text{ MeV}, \quad P_n = 74(14)\% \]

\[ ^{85}\text{As} \]
\[ Q_\beta - S_n = 4.9 \text{ MeV}, \quad P_n = 60\% \]

\[ ^{137}\text{I} \]
\[ Q_\beta - S_n = 2.0 \text{ MeV}, \quad P_n = 7\% \]
Beta-n channels in very n-rich nuclei

Möller, P.; Nix, J. R.; Kratz, K.-L.
Atomic Data and Nuclear Data Tables, Vol. 66,(1997) p.131
Hybrid-3He (HRIBF) combination of gamma and neutron detection:

$$^{3}\text{He} + n \rightarrow ^{3}\text{H} + ^{1}\text{H} + 765\text{keV}$$

48x $^{3}\text{He}$ tubes + 2 clover detectors


$^{85}\text{Ga}$

beta-neutron-gamma
beta-gamma
Beta-delayed 2n emission in $^{86}$Ga decay
$\beta_{1n} \sim 60\%$, $\beta_{2n} \sim 20\%$

Very powerful combination of RILIS + Isobar separator + 3 Hen!

Pure beam (Laser Ion Source)
Production rates comparable or better than at RIKEN
First confirmation of the predicted large $\beta_{2n}$ branching ratios
$\frac{I_{\beta_{1n}}}{I_{\beta_{2n}}}$ (FRDM-QRPA) 21% / 44%,
$\frac{I_{\beta_{1n}}}{I_{\beta_{2n}}}$ (DF3a+CQRPA) 28% / 22%

$^{86}$Ga: neutron $\beta$+n+g spectrum
VANDLE - a multipurpose neutron detector for decay and reaction studies

New trigger detectors
(fragmentation and ISOL experiments)
Survey of ~30 isotopes in a HRIBF campaign with VANDLE
Completed VANDLE data analysis for $^{83,84}$Ga.
Intense neutron peaks attributed to Gamow–Teller decays
Data consistent with simplified shell–model calculations
based on $^{78}$Ni core decay.
Ongoing work on more complete SM calculations.

VANDLE improved for future experiments
1m TOF configuration with larger bars
New TOF start detectors
Higher gamma detection efficiency
($\text{LaBr}_3$ array HAGRID).
Complementary Total Absorption Spectroscopy !