Studies of astrophysically-relevant nuclei around $^{78}\text{Ni}$

Chiara Mazzocchi

Zakład Fizyki Jądrowej, IFD
Overview

✓ Physics context and motivations:
  - nuclear structure
  - nuclear astrophysics

✓ Experimental approaches:
  - production of exotic nuclei near $^{78}$Ni
  - detection methods

✓ Results & discussion:
  - b-decay gross properties measurements for the r-process
  - structure of nuclei north-east and south-west of $^{78}$Ni

✓ Summary
the neighbourhood of $^{78}$Ni

✓ Decay studies of very neutron-rich nuclei:
  - understanding the evolution of nuclear structure
    • excited levels $\rightarrow$ single-particle levels around shell gaps
    • $\beta$-strength function and its consequences
    • masses $\rightarrow$ Q-values/separation energies
    • ...

the neighbourhood of $^{78}\text{Ni}$

✓ Decay studies of very neutron-rich nuclei:
  
  - $\beta$-decay properties for the analysis of post r-process isotopic distributions
    
    • half-lives
    
    • properties of $\beta n$ emission
    
    • branching ratios ($\beta\gamma$, $\beta n$)
    
    • low-energy isomers
    
    • ...

β-decay properties for the analysis of post r-process isotopic distributions

- Decay studies of very neutron-rich nuclei:
  - gross properties (mass, $T_{1/2}$, $P_n$) are often the only observables available
    - mass, $T_{1/2}$, $P_n$ necessary input for this analysis
    - not possible to measure them in the lab for all the nuclei involved
      → reliable theoretical predictions needed
    - models need to be verified
      → eventual modifications and improvements
  - β half-life:
    first decay property of an exotic nucleus experimentally accessible (only few ions needed!)
    ⇒ measuring $T_{1/2}$ provides the first test of models predictions
β-decay properties for the analysis of post r-process isotopic distributions

✓ Local tests for models before extension to *terra incognita*:

- most widely-used theoretical predictions:

  *global models* —> calculate fundamental properties of all nuclei (out of necessity!)

- review of the predictive power of the global models:

  • large N/Z ratios originate effects not present closer to stability

  • N>50: models must include GT and $ff$ transitions
    (neutrons in $\otimes$ parity orbitals and protons in $\ominus$ parity orbitals)

  • ordering of proton and neutron shells very important:
    $ff$ transitions are a non-negligible portion of the β strength

- testing the validity of $T_{1/2}$ predictions is essential

  (they used in network calculations when no experimental information exists)
β-decay properties for the analysis of post r-process isotopic distributions

✓ Local tests for models before extension to *terra incognita*:

- most widely-used theoretical predictions:

  *global models* $\rightarrow$ calculate fundamental properties of all nuclei (*out of necessity!*)

  e.g.:

  - FRDM+QRPA [Moeller 2003]:
    - FRDM + QRPA for GT part (& empirical spreading for quasiparticle strength) & gross theory for *ff* transitions

  - CQRPA+DF3a [I. Borzov]:
    - g.s. properties given by the DF3a energy density functional (tailored for n-rich nuclei around N=50)
    - self-consistent calculation of beta-strength functions for GT and FF transitions
    - CQRPA approximation
    - new values of the masses in the region taken into account
    - g.s. configurations in odd-A Ga (till A=83) blocked as 1f$_{5/2}$ proton single-particle state
    - not really global (only spherical nuclei calculated, but reliable within its range of applicability)
the neighbourhood of $^{78}\text{Ni}$
Experimental approaches

✓ Production, separation & identification:

- $Z < 28 \rightarrow$ fragmentation
  
  - $^{86}\text{Kr}$ or $^{82}\text{Se}$ beam @ 140 A·MeV on Be target $\rightarrow$ study of $n$-rich Fe and Co isotopes
  
  - in-flight separation of the fragments $\rightarrow$ A1900 @ NSCL
  
  - identification event-by-event: $\Delta E$ vs ToF matrix
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<table>
<thead>
<tr>
<th>$\Delta E$ (arb. units)</th>
<th>Time-of-Flight (arb. units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7000</td>
<td>7000</td>
</tr>
<tr>
<td>7500</td>
<td>7500</td>
</tr>
<tr>
<td>8000</td>
<td>8000</td>
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<td>8500</td>
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<td>9000</td>
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<td>9500</td>
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</tbody>
</table>

$74\text{Co}$

$72\text{Co}$

S. Go (UT), 2014
Experimental approaches

✓ Production, separation & identification:

- A~80 $\rightarrow$ proton-induced fission
  
  - proton beam @ 54 MeV ($\sim$10μA) on $^{238}$UC$_x$ target $\rightarrow$ study of *n-rich As and Ge isotopes*
  
  - ion source chemistry + two-stage electromagnetic separation of the fragments

$\rightarrow$ HRIBF @ ORNL
Experimental approaches

HRIBF: proton-induced fission of $^{238}$U
- neutron-rich nuclei (Z=29-63)
- large production rates

LeRibbs measuring station
Experimental approaches

- **ORIC**: 54 MeV protons, \( \sim 10 \, \mu\text{A} \)
- **LeRIBSS experiment**
- **IRIS-2 ion source + H\(_2\)S \rightarrow ^A\text{GeS}^+ \) molecules
- **Fission fragments**
- **200 kV platform**
- **Positive ions**
- **beam kicker**
- **Isobar separator** \( M/\Delta M \sim 10000 \)
- **Mass separator** \( M/\Delta M \sim 1000 \)
- **charge-exchange cell**
- **almost pure \(^A\text{Ge}^+\) beam**
- **almost pure \(^A\text{Ge}^+\) beam**
- **A**
- **very intense \(^{A+32}\text{Ag}\) suppressed**
- **A+32**
Experimental approaches

✓ Detection set-up: $\beta$ and $\gamma$ spectroscopy
  
  - @NSCL: separated ions implanted into DSSD detector
    * ion and $\beta$ particle detection + correlation in software
    * $\beta\gamma$ coincidences detected through the SeGA array
Experimental approaches

✓ Detection set-up: $\beta$ and $\gamma$ spectroscopy

- @LeRibbs: purified sample implanted into tape in the centre of experimental set-up
  - movable tape periodically removed long-lived activity
  - 2 plastic scintillators and 4 clovers for $\beta$ and $\gamma$ detection
  - decay radiation measured during beam-on (grown-in) and beam-deflected-away (decay)
  - digital DAQ
**Exp \( T_{1/2} \) —>> model verification —>> r-process modelling**

**Half-life measurement of Fe and Co isotopes**

Time distribution of βs

Fit function:

\[
f(t) = A \cdot e^{-\lambda t} + A \cdot \frac{\lambda_d}{\lambda_d - \lambda} \cdot (e^{-\lambda t} - e^{-\lambda_d t}) + B \cdot e^{-\lambda_{bkg} t}
\]

**TABLE I:** For each isotope the number of ions implanted in ms [ms]

<table>
<thead>
<tr>
<th>Isotope</th>
<th>N</th>
<th>T_{1/2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe 70</td>
<td>125</td>
<td>9.0(1) ns</td>
</tr>
<tr>
<td>Fe 71</td>
<td>160</td>
<td>30(1) ns</td>
</tr>
<tr>
<td>Fe 72</td>
<td>10</td>
<td>19±4 ms</td>
</tr>
<tr>
<td>Co 71</td>
<td>400</td>
<td>8.0(5) ms</td>
</tr>
<tr>
<td>Co 72</td>
<td>200</td>
<td>1.5(1) ms</td>
</tr>
<tr>
<td>Co 73</td>
<td>40</td>
<td>0.9(2) ms</td>
</tr>
<tr>
<td>Co 74</td>
<td>40</td>
<td>0.5(1) ms</td>
</tr>
</tbody>
</table>

C.M. et al., PRC 88 (2013) 064320
Exp $T_{1/2}$ —>> model verification —>> r-process modelling

Half-life measurement of Fe and Co isotopes

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Exp $T_{1/2}$ —>> model verification —>> r-process modelling

Half-lives & the weak r-process

✓ potential impact on r-process:
  - astrophysical site(s) of r-process are still unknown
  - astrophysical conditions that produce lighter nuclei ($A \sim 80$) are rather uncertain

- **weak r-process calculations:**
  - parametrised neutrino wind that reasonably reproduces solar r-process abundance

- FRDM+QRPA calculations:
  - off by at least factor 5
  - uncertainty in rates —>> *uncertainty in final abundance pattern*

Exp $T_{1/2} \rightarrow$ model verification $\rightarrow$ r-process modelling

Half-lives & the weak r-process

final abundance $Y(A)$
- final abund. with $T_{1/2}(\text{th})$ increased x5 [$Y_{\text{incr}}(A)$]
- final abund. with $T_{1/2}(\text{th})$ decreased x5 [$Y_{\text{decr}}(A)$]
- final abund. with $T_{1/2}(\text{exp})$
- scaled solar abund. [+]

uncertainty in the predictions of r-process abundances

weak r-process simulation
[entropy = 10·$k_B$, timescale= 0.1 s, initial e$^-$ fraction $Y_{\text{e}}=0.31$]

Exp $T_{1/2} \rightarrow$ model verification $\rightarrow$ r-process modelling

Half-lives & the weak r-process

final abundance $Y(A)$
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- final abund. with $T_{1/2}(\text{th})$ decreased x5 [$Y_{\text{decr}}(A)$]
- final abund. with $T_{1/2}(\text{exp})$
  - scaled solar abund. [+]

$$100 \cdot \frac{Y_{\text{decr}}(A) - Y_{\text{incr}}(A)}{\left[ Y_{\text{decr}}(A) + Y_{\text{incr}}(A) \right]/2}$$

reduction of the uncertainty in the predictions of r-process abundances

weak r-process simulation
- [entropy = 10·$k_B$, timescale= 0.1 s, initial e$^-$ fraction $Y_e=0.31$]

Exp $T_{1/2} \rightarrow \text{model verification} \rightarrow \text{r-process modelling}$

Half-lives of fission fragments

Time distribution of $\beta$ys with respect to the grow-in and decay cycle

Fit function:

$$A \cdot \left(1 - e^{-\lambda t}\right) \quad \text{grow-in}$$

$$A \cdot \left(1 - e^{-\lambda t}\right) \cdot e^{-\lambda(t-t_0)} \quad \text{decay}$$
Exp $T_{1/2} \rightarrow \text{model verification} \rightarrow \text{r-process modelling}$

Half-lives of fission fragments: benchmarking theoretical predictions

**Zn & Ga**

- ✓ FRDM+QRPA:
  - longer $T_{1/2}$ than measured
- ✓ DF3a+CQRPA calculations:
  - reproduce well experimental values
  - systematically much longer than FRDM at $N=55$
  - for Ga isotopes $T_{1/2}$ stabilization for $N \geq 56$

LOG scale!
Exp $T_{1/2}$ $\rightarrow$ model verification $\rightarrow$ r-process modelling

LOG scale!

+ post r-process abundances

- simulations with Moeller's $T_{1/2}$'s
- simulations with Borzov's $T_{1/2}$'s

M. Madurga et al., PRL 109 (2012) 112501
Exp $T_{1/2}$ —>> model verification —> r-process modelling

Benchmarking theoretical predictions

- Review of the predictive power of the global models for the n-rich portion of the chart-of nuclei
  - Zn, Ga, Ge and As isotopes: FRDM(+QRPA) overestimates $T_{1/2}$ by large factors

- Study of the impact of the new $T_{1/2}$ on the r-process nucleosynthesis calculations:
  - $T_{1/2}$s influence the abundances in the 75<A<90 region & impact how the r-process proceeds for heavier nuclei
  - replacing FRDM+QRPA with DF3a+CQRPA calculations improves predictions for production of nuclei for A>140
Exp $T_{1/2} \rightarrow \text{model verification} \rightarrow \text{r-process modelling}$

Benchmarking theoretical predictions: half-life measurement of As and Ge isotopes

$^{86}\text{Ge}$: 226±21 ms

CM et al., PRC 87 (2013) 034315
Exp $T_{1/2}$ —>> model verification —> r-process modelling

Benchmarking theoretical predictions: half-life measurement of As and Ge isotopes

Ge
✓ FRDM+QRPA give longer half-lives
✓ CQRPA calculations:
  - reproduce well experimental values
  - provide robust prediction for $^{86}$Ge
  - predict $T_{1/2}$ stabilisation for $A \geq 86$, $N \geq 54$ + become systematically longer than FRDM

As
✓ FRDM+QRPA gives better agreement
✓ CQRPA calculations:
  - reproduce well new exp. value for $^{84}$As
  - predict $T_{1/2}$ stabilisation for $N \geq 54$ (systematically longer than FRDM)
  - worse agreement for $^{86,87}$As $\rightarrow$ (rapid) onset of collectivity leaving $N=50$, $Z=28$ shell closures?

$\beta$-decay of $^{86}\text{Ge}$
β-decay of $^{86}$Ge

βγ spectrum (gate 112 keV)

Counts

Energy [keV]

Counts

Energy [keV]

Counts

Energy [keV]

βγ spectrum at A=86

Counts

Energy (keV)

Counts

Energy (keV)

βγ spectrum (gate 125 keV)

Counts

Energy (keV)

Counts

Energy (keV)
\( \beta^- \) decay of \(^{86}\)Ge

\( Q_{\beta^-} = 9200(300) \) keV

\( P_n = 45(15) \% \)

\( ^{85}\)As

C.M. et al., PRC 92 (2015) 054317
B(GT) for $^{86}$Ge and $^{86}$As

Single-particle description:

✓ “Valence” neutrons cannot decay via allowed GT transitions between spin orbit partners → spectators
✓ Particle-hole excitations lead to population of high energy states
✓ Important role of forbidden transitions ($\Delta l>0$ and parity changing)

$\beta$ decay of N>50 isotopes:

✓ competition between
  forbidden transitions with large $Q_\beta$ (small strength) & allowed GT decays to highly excited states (very fragmented)
✓ exotic nuclei → GT decay dominant → large $P_n$
✓ $fpg$ neutrons → spin-orbit partner proton orbital
✓ $d_{5/2}$ and $s_{1/2}$ neutrons as spectators

Model: R. Grzywacz in M. Alshudifat, R. Grzywacz et al., PRC93 (2016) 044325
B(GT) for $^{86}$Ge and $^{86}$As

B(GT) calculations:

- Nushellx (parallel processing version) with $^{56}$Ni core
- jj44bpm interaction for fpg [Lisetskiy & Brown]
- N=50 shell gap parameter of the model
- $d_{5/2}$ neutrons “blocked” for B(GT) calculations
- s.p. energies from experimental systematics (Grawe)
- protons and neutrons in fpg orbitals allowed to scatter without restrictions
  ($f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2}$ for protons, $f_{5/2}, p_{3/2}, p_{1/2}, g_{9/2} + d_{5/2}$ for neutrons)
- good description of N<50 isotopes (empirical adjustments) and decent job for Ga isotopes
  [M. Alshudifat, R. Grzywacz et al., PRC93 (2016) 044325]
B(GT) for $^{86}$Ge and $^{86}$As

$^{86}$Ge

$^0 - 226(21)$ ms

$\beta^-$

$Q_{\beta} = 9200(300)$ keV

Model: R. Grzywacz in M. Alshudifat, R. Grzywacz et al., PRC 93 (2016) 044325

B(GT) for $^{86}$Ge and $^{86}$As

calculations: decay dominated by
$\nu p_{1/2} \rightarrow \pi p_{3/2}$ $\Rightarrow$ strongly bound $1^+$

$jj44pn$ interaction

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$jj44pn$ interaction

$jj45pn$ interaction 
[new, based on $jj44bpn$ ($^{56}$Ni core) and $jj45pna$ ($^{78}$Ni core)]
**B(GT) for $^{86}$Ge and $^{86}$As**

**jj44pn interaction**

Model: R. Grzywacz in M. Alshudifat, R. Grzywacz et al., PRC 93 (2016) 044325

**jj45pn interaction**
[new, based on jj44bpm ($^{56}$Ni core) and jj45pna ($^{78}$Ni core)]

**jj44pn interaction (based on jj44bpm) & modified T=0:**
- weaken (by 1MeV) diagonal matrix elements between $v_{d5/2}$ and $\pi_{p3/2}$ that generated strongly bound 1+ state with large B(GT) part to achieve qualitative agreement [large B(GT) above $S_n$]
- strengthening (by 0.4 MeV) of the T=1 $v_{p1/2}$ and $\pi_{f5/2}$ to generate low-lying 1+ states with weak B(GT)
B(GT) for $^{86}$Ge and $^{86}$As

jj44pn interaction and modified T=0 matrix elements:

qualitatively better agreement, quantitatively largely underestimated

important role of pn residual interaction

a set of interaction with better microscopic foundation needs to be developed

$\beta n$ spectroscopy needed to locate the position of the $1^+$ states above Sn

Model: R. Grzywacz in M. Alshudifat, R. Grzywacz et al., PRC93 (2016) 044325
Summary

Z = 28
N = 50

r-process path
Thanks! to

Experiments @ ORNL

P. Bączyk
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M. Karny
A. Korgul
M. Madurga
A.J. Mendez II
K. Miernik
D. Miller
S. Padgett
S.V. Paulauskas
K.P. Rykaczewski
A.A. Sonzogni
D.W. Stracener
M. Wolińska-Cichocka

Experiment @ NSCL

J.C. Batchelder
C.R. Bingham
I.N. Borzov
D. Fong
R. Grzywacz
J.H. Hamilton
J.K. Hwang
M. Karny
W. Królas
S.N. Liddick
P.F. Mantica
A.C. Morton
W. F. Mueller
K.P. Rykaczewski
M. Steiner
R. Surman
A. Stolz
J.A. Winger