First spectroscopy of the r-process nucleus $^{135}\text{Sn}$

Thorsten Kröll$^1$ / Kathrin Wimmer$^2$

$^1$TU Darmstadt, Germany; $^2$Univ. of Tokyo, Japan; $^3$TU München, Germany; $^4$IEM CSIC, Madrid, Spain; $^5$Lunds Univ., Sweden; $^6$Univ. of Guelph, Canada; $^7$Univ. zu Köln, Germany; $^8$CERN, Genève, Switzerland; $^9$CSNSM, Orsay, France; $^{10}$Univ. of Sofia, Bulgaria; $^{11}$Univ. of the West of Scotland, Paisley, UK; $^{12}$Univ. of Jyväskylä, Finland; $^{13}$Helsinki Institute of Physics, Finland; $^{14}$KU Leuven, Belgium; $^{15}$Univ. of Manchester, UK; $^{16}$UC Madrid, Spain

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Region of Interest

Nuclei around doubly-magic shell closure in $^{132}$Sn
- Letter of Intent: CERN-INTC-2010-045; INTC-I-111
- Approved Proposals: IS548, IS549, IS551 ... all Coulex (beam time 2016)

Higher energies from HIE-ISOLDE: first nucleon transfer $^{134}$Sn(d,p)$^{135}$Sn
\(^{135}\text{Sn} – \text{r-process nucleus}\)

- r-process passes region around \(^{132}\text{Sn}\)
- abundance pattern depends on both nuclear structure \((m, \beta-T_{1/2}, \sigma(n), \text{etc.})\) and astrophysical conditions
  ... August 2017: neutron star merger identified as (one) astrophysical site
- \((d,p)\) is surrogate reaction for \((n,\gamma)\)

Neutron capture rates can change average abundances by up to 43%

\(^{134}\text{Sn}(n,\gamma)\) has no impact (\(^{134}\text{Sb}(n,\gamma)\) has!!!)
... but transfer to an even-even nucleus is theoretically easier
... contributes to the overall understanding of \((d,p)\) in this region

\[\begin{array}{cccccccc}
  130 & 131 & 132 & 133 & 134 & 135 & 136 & 137 \\
  \text{Te} & \text{Te} & \text{Te} & \text{Te} & \text{Te} & \text{Te} & \text{Te} & \text{Te} \\
  129 & 130 & 131 & 132 & 133 & 134 & 135 & 136 \\
  \text{Sb} & \text{Sb} & \text{Sb} & \text{Sb} & \text{Sb} & \text{Sb} & \text{Sb} & \text{Sb} \\
  128 & 129 & 130 & 131 & 132 & 133 & 134 & 135 \\
  \text{Sn} & \text{Sn} & \text{Sn} & \text{Sn} & \text{Sn} & \text{Sn} & \text{Sn} & \text{Sn} \\
  127 & 126 & 126 & 126 & 126 & 126 & 126 & 126 \\
  \text{In} & \text{In} & \text{In} & \text{In} & \text{In} & \text{In} & \text{In} & \text{In} \\
  126 & 127 & 126 & 126 & 126 & 126 & 126 & 126 \\
  \text{Cd} & \text{Cd} & \text{Cd} & \text{Cd} & \text{Cd} & \text{Cd} & \text{Cd} & \text{Cd} \\
\end{array}\]

$^{133}\text{Sn} \ldots$ what has been done?

$^{132}\text{Sn}(d,p) @ 4.77 \text{ MeV/u}$

- particle spectroscopy only
- transferred $\Delta \ell$ determined (angular distributions are quite similar)
- SFs extracted

$^{133}\text{Sn} \ldots$ what has been done?

$^{132}\text{Sn}(^9\text{Be},^8\text{Be}) @ 3 \text{ MeV/u}$

- particle($2\alpha$)-$\gamma$ coincidences
- $\gamma\gamma$-coincidences, $\gamma$-branchings

Our approach: combine the best of both light-particle and $\gamma$-ray spectroscopy!!!
Set-up: MINIBALL and T-REX

**T-REX**
- large solid angle
  - $8^\circ - 78^\circ$ and $102^\circ - 172^\circ$
- position sensitive
- PID ($\Delta E$-$E$)

**MINIBALL**
- 24 HPGe
- $\epsilon \approx 3\% @ 1.3$ MeV

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Shell model predictions

$^{135}\text{Sn}$

E(level) | $J^\pi$ | $T_{1/2}$ | $T_{1/2}$
--- | --- | --- | ---
0 | (7/2$^-$) | 515 ms | 5

7/2$^-$ | cwg | 0 | 7/2$^-$ | cw5082 | 0 | 7/2$^-$ | jj56pna | 0
Comparison 7.5 MeV/u and 10 MeV/u

- **7.5 MeV/u**
  - mostly larger cross section
  - less pronounced angular distributions
  - smaller energies of protons to be detected

- **10 MeV/u**
Simulation (backward direction)

\[^{134}\text{Sn}(d,p) \at 7.5 \text{ MeV/u, 1 mg/cm}^2 \text{ CD}_2 \text{ target}
\]

\[Q_0 = 45.2 \text{ keV, first 4 levels in } ^{135}\text{Sn}\]

- Energies are well above experimental trigger threshold (≈500 keV @ 3 MeV/u and A=80 ... we have to see at 7.5 or 10 MeV/u and A=140)
- Levels are not sufficiently separated .... most likely we need \(\gamma\)-rays!!!
Physics aims

- Particle spectroscopy, particle-γ(γ) coincidences
  ➔ identify excited states in $^{135}$Sn for the first time

- (γ-gated) particle angular distributions
  ➔ determine orbital angular momentum transfer

- γ-decay branching (and guidance by theory)
  ➔ assign (tentatively) total angular momentum

- cross sections
  ➔ extract spectroscopic factors

➔ Comparison with shell model

Note: shell model needs interaction matrix elements AND single-particle energies around $^{132}$Sn, i.e. $^{133}$Sn and $^{133}$Sb
... predictive power can be evaluated only by studying nuclei beyond!!
Beam / rate estimate

MINIBALL + T-REX (maybe modified configuration in backward direction)

- Beam
  - molecular beam $^{134}$Sn$^{34}$S$^+$ from ISOLDE
  - beam energy from HIE-ISOLDE: 7.8 MeV/u (or whatever is reachable)
  - intensity on target $10^4$/s
  - highly contaminated by $^{134}$Sb (A=168 contaminations?)

- Rate (1 mg/cm$^2$ CD$_2$ target)
  - 650 protons/day (per 1 mb)
  - 2-8 mb per state, 6-10 angular bins $\Rightarrow \approx 300$ counts / bin / day
    $\Rightarrow$ 2% statistical error
  - $\gamma$-gated: factor 10-30 less $\Rightarrow \approx 150$ counts / bin / week
    $\Rightarrow$ 10% statistical error
  - particle-integrated $\gamma$-rate per state $\Rightarrow \approx 350$ / mb / week
    $\Rightarrow$ the excitation energy can be determined even for very low cross sections

We request 24 shifts (8 days) of beam time
Simulation (forward direction)

Because of high energies, many p and d punch through both $\Delta E$ and $E$ detectors.
Simulation

\[ ^{134}\text{Sn}(d,p) @ 7.5 \text{ MeV/u} \]
\[ Q_0 = 45.2 \text{ keV} \]

\[ ^{134}\text{Sb}(d,p) @ 7.5 \text{ MeV/u} \]
\[ Q_0 = 1516.5 \text{ keV} \]

- States at high excitation energy in \(^{135}\text{Sb}^*\) partially overlap with states at low excitation energy in \(^{135}\text{Sn}\)
- States at higher excitation energy are likely to emit \(\gamma\)-rays in coincidence (which are, of course, not detected with 100% efficiency)!

* For simplicity, the same excitation energies as in Sn have been assumed