Neutron-induced cross-sections via the surrogate method

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Nucleosynthesis or origin of the nuclei in the Universe

Production of nuclei above $^{56}$Fe in the explosion of massive stars

Need of $\sigma(n,\gamma)$

Very difficult to measure – Short-lived nuclei!

Nuclear energy
- Minor-actinide incineration
- $^{232}$Th/$^{233}$U cycle

$\sigma(n,f)$ and $\sigma(n,\gamma)$ needed in the energy range $1 \text{ keV} < E_n < 10 \text{ MeV}$
NEUTRON-INDUCED REACTION

\[ \sigma_A^{(n,\chi)}(E_n) = \sigma_n^{CN}(E_n) \]

\[ P^{CN}_\chi(E^*) \]

**SURROGATE REACTIONS**

**Spin-parity mismatch?**

The validity of the surrogate method need to be discussed...
\[ P_\chi (E^*) = \sum_{J^\pi} P_{\text{form}}^{CN} (E^*, J^{\pi}) \cdot G_\chi (E^*, J^{\pi}) \]

- Probability that the CN is formed in the state \( \{E^*, J^\pi\} \)
- Branching ratios for the decay channel \( \chi \)
\[ P_{\chi}(E^*) = \sum_{J^\pi} P^{CN}_{form}(E^*, J^\pi) \cdot G_{\chi}(E^*, J^\pi) \]

Neutron-induced reaction

Very difficult to model!

s-wave neutron \( \ell = \frac{1}{2}\hbar \)

\[ <\ell> \approx 1\hbar \]

TALYS angular momentum distribution calculation

\[ <\ell> \approx 4\hbar \]

DWBA angular momentum distribution calculation

\[ \theta = 90^\circ \]

\[ ^{240}\text{Pu} \]

J.P. Delaroche et al., 2002
\[ P_\chi (E^*) = \sum_{J^\pi} P_{\text{form}}^{\text{CN}} (E^*, J^\pi) \cdot G_\chi (E^*, J^\pi) \]

\( G_\chi (E^*, J^\pi) = G_\chi (E^*) \)

Weisskopf-Ewing hypothesis

\[ \rightarrow \text{Valid at excitation energies where most of the decay is dominated by the level density!} \]

\[ \rightarrow \text{Strong mixing of } J\pi \text{ states} \]

\[ \rightarrow \text{Discrete levels} \rightarrow \text{high } J\pi \text{ selectivity} \]

\[ \rightarrow \text{Measurements that test the validity of the surrogate method are needed!} \]
SURROGATE METHOD APPLIED TO FISSION

$^{243}\text{Am}(^{3}\text{He},\alpha)^{242}\text{Am}^*$

$^{243}\text{Am}(^{3}\text{He},\alpha f)^{243}\text{Cm}^*$

$^{241}\text{Am}(n,f)$  
$T_{1/2}=432$ y

$^{242}\text{Cm}(n,f)$  
$T_{1/2}=163$ d

Nice agreement even at low neutron energy!

SURROGATE METHOD APPLIED TO CAPTURE

Capture probability:

\[ P_\gamma (E^*) = \frac{N_{ej-\gamma} (E^*)}{N_{ej} (E^*) \cdot \varepsilon_\gamma (E^*)} \]
RESULTS FOR $^{174}\text{Yb}(^{3}\text{He},p)^{176}\text{Lu}$ AS SURROGATE FOR $^{175}\text{Lu}(n,\gamma)$

Over-estimation by a factor 3
\[ P_\chi (E^*) = \sum_{J^\pi} P_{\text{form}}^{\text{CN}} (E^*, J^\pi) \cdot G_\chi (E^*, J^\pi) \]

**Gaussian independent of** \(E^*\)

\[
\frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(J-J_\chi)^2}{2\sigma^2}}
\]

**Branching ratios calculated with TALYS**

Two free parameters: \(<J>\) and \(\sigma\)

\(\chi^2 / \text{ndf} = 44.4 / 21\)

- \(p0 = 7.096 \pm 0.055\)
- \(p1 = 2.304 \pm 0.116\)

\(<\ell> = 7 \hbar\)

\(\sigma = 2.3 \hbar\)

**174Yb(\(^3\)He,p)\(^{176}\)Lu***
\( S_n = 6.27 \text{MeV} \)

\( E^* \)

\( (n, \gamma) \) competes with \((n,n)\)

\( \langle \ell \rangle = 1/2 \hbar \) is exactly the \( \ell \) carried away by the neutron in the compound elastic \((n,n)\) reaction \( \rightarrow \) dominant decay!

\( P\gamma \) decreases very quickly!
\((^3\text{He},p)\) reaction CASE

\[ S_n = 6.27 \text{MeV} \]

\[ 176 \text{Lu}^* \rightarrow 175 \text{Lu} \]

\[ J=7 \]

\[ 7/2^+ \]

\[ 9/2^+ \]

\[ 11/2^+ \]

\( \rightarrow \) higher spins populated

\( \rightarrow \) neutron emission forbidden

\( \rightarrow \) radiative capture is the only way of deexcitation!
\[ S_n = 6.27 \text{MeV} \]

\[ \gamma \to \text{the first excited states of the residual nucleus after neutron emission may also be forbidden...} \]

The neutron emission channel does not verify the Weisskopf-Ewing approximation in the vicinity of \( S_n \)

\( \rightarrow \text{situation is reduced as one moves to heavier nuclei (with higher level densities)} \)
RESULTS FOR $^{174}\text{Yb}(^3\text{He},\alpha)^{173}\text{Yb}$ AS SURROGATE FOR $^{172}\text{Yb}(n,\gamma)$

Over-estimation by a factor 10!
\[ P_\chi(E^*) = \sum_{J^\pi} P^{CN}_{\text{form}}(E^*, J^\pi) \cdot G_\chi(E^*, J^\pi) \]

Two free parameters: \( \langle J \rangle \) and \( \sigma \)

\[ \frac{0.5}{\sqrt{2\pi}\sigma} \exp \left( -\frac{(J - \bar{J})^2}{2\sigma^2} \right) \]

FIT

Gaussian independent of \( E^* \)

Branching ratios calculated with TALYS

\( \chi^2 / \text{ndf} = 18.74 / 29 \)

\( p_0 = 3.881 \pm 0.204 \)

\( p_1 = 3.214 \pm 0.209 \)

\( \langle \ell \rangle = 4 \hbar \)

\( \sigma = 3.2 \hbar \)
CONCLUSION

Radiative capture more sensitive than fission

Excitation energies in the vicinity of Sn

$P_\gamma$ decreases very quickly! Small variation in absolute $\rightarrow$ several factors in relative

$P_\gamma$ measured in surrogate experiments over-estimated by several factors

Determination of $\ell$ distributions populated in ($^3\text{He},p$) and ($^3\text{He},\alpha$) $\rightarrow$ Higher spins populated in transfer reactions

The neutron emission channel does not verify the Weisskopf-Ewing approximation in the vicinity of $S_n$.

PERSPECTIVES: - Use more realistic spin distributions.
- Compare our results with FRESCO (I. Thompson et al.)

2012: - ($p,d\gamma$) reaction in the rare-earth region
- ($d,pf$)/($d,p\gamma$) reactions in the actinide region
WHY DOES IT WORK FOR FISSION?

$B_{f_A} = 6.32\text{MeV}$

$S_n = 5.53\text{MeV}$

$^{241}\text{Am}$

$^{243}\text{Am}(^3\text{He,}\alpha f)^{242}\text{Am}^*$

$^{241}\text{Am}(n,f)$

$J\approx 4$

$242\text{Am}^*$

242Am*
WHY DOES IT WORK FOR FISSION?

\[ S_n = 5.53 \text{ MeV} \]

\[ B_f A = 6.32 \text{ MeV} \]

\[ 11/2 \rightarrow 158 \text{ keV} \]
\[ 9/2 \rightarrow 93 \text{ keV} \]
\[ 7/2 \rightarrow 41 \text{ keV} \]

\[ J \approx 4 \]

\[ ^{243}\text{Am}(^3\text{He},\alpha f)^{242}\text{Am}^* \]

\[ ^{241}\text{Am}(n,f) \]

\[ E^* \]

\[ ^{242}\text{Am}^* \]

\[ I \]

\[ A \]

\[ B \]

\[ n' \]