Investigation of the $^{238}\text{U}(d, p)$ surrogate reaction via the simultaneous measurement of $\gamma$-decay and fission probabilities


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Need for neutron-induced cross sections of short-lived nuclei: element nucleosynthesis
Neutron-induced fission and capture cross sections of short-lived nuclei needed. Very difficult or even impossible to measure!
Surrogate-reaction method

Cramer and Britt (Los Alamos 1970...!!)

Neutron-induced reaction

\[ n + A \rightarrow (A+1)^* \]

Surrogate reaction

Transfer

\[ X + Y \]

\[ \sigma_{n,\text{decay}}^A (E^*) = \sigma_{CN}^{A+1} (E^*) \cdot P_{\text{surro}}^{\text{decay}} (E^*) \]

Theory

Optical model

Experiment
Validity of the surrogate method

\[ \sigma^A_{n,\text{decay}}(E^*) = \sigma^{A+1}_{\text{CN}}(E^*) \cdot P^\text{surro}_\text{decay}(E^*) \]

Neutron-induced and surrogate reaction must lead to the formation of a compound nucleus:
Decay only depends on \( E^*, J \) and \( \pi !! \)

\[ P^\text{surro}_\text{decay}(E^*) = P^n_\text{decay}(E^*) \]

Populated \( J \) and \( \pi \) distributions are equal
OR
Decay independent of \( J \) and \( \pi \)
(Only valid at high \( E^* \) in the Weisskopf-Ewing limit)

Not possible to say a priori if a reaction meets these conditions.
Data obtained with the surrogate method need to be compared to neutron-induced data!
Results for fission

$^{3}\text{He} + ^{243}\text{Am}(7370 \text{ y}) \rightarrow ^{4}\text{He} + ^{242}\text{Am} \leftrightarrow n + ^{241}\text{Am}(432.2 \text{ y})$

General finding: the cross sections obtained with surrogate method are in good agreement with n-induced data for fission!

Results for radiative capture

\[ 3\text{He} + {}_{174}\text{Yb} \rightarrow 4\text{He} + {}_{173}\text{Yb} \]

The cross sections obtained with surrogate method are in clear disagreement with n-induced data for capture!

Why do we obtain such discrepancies?

Strong sensitivity of neutron emission to $J^\pi$
Fission seems to be much less sensitive to spin/parity differences, why?

The top of the fission Barrier is also a region of low density of states!

First step to understand:
Simultaneous measurement of fission and gamma-decay probabilities!

Never done before!
The interest of the $^{238}\text{U}(d,p)$ reaction:

No advantage for the target half life but...

- Appears intuitively as the closest reaction to a neutron-induced reaction in inverse kinematics with RIBs

-Good-quality $n+^{238}\text{U}$ data to compare with
Impact of deuteron breakup on the fission probability

$^{238}\text{U}(d,p)$ at 18 MeV and 150°

$^{235}\text{U}(t,p)$  $^{236}\text{U}(d,p)$

$^{233}\text{U}(t,p)$  $^{234}\text{U}(d,p)$

$^{239}\text{Pu}(t,p)$  $^{240}\text{Pu}(d,p)$

Setup for simultaneous measurement of fission and $\gamma$-decay probabilities at the Oslo cyclotron

- **27 NaI scintillators for $\gamma$ detection**
- **15 MeV d Beam**
- **Position sensitive Si Telescopes (126 -140°) for ejectile detection**
- **4 PPACs for fission-fragment detection**

**Challenge:** removal of gamma rays emitted by the fission fragments!
Determination of decay probabilities

\[ P_{\text{decay}}^{\text{surro}}(E^*) = \frac{N_{p-\text{decay}}^{\text{coin}}(E^*)}{N_p^{\text{sing}}(E^*) \cdot \epsilon_{\text{decay}}(E^*)} \]

Subtraction of γ-rays from fission fragments

\[ N_{p-\gamma}^{\text{coin}}(E^*) = N_{p-\gamma}^{\text{coin,tot}}(E^*) - \frac{N_{p-f-\gamma}^{\text{coin}}(E^*)}{\epsilon_f(E^*)} \]
• Angular dependence observed
• Gamma-emission probability much higher than the n-induced data
• Fission probability below the n-induced data (up to 35% lower)
Deuteron breakup

Non elastic breakup: DWBA (IAV method)

Elastic breakup

CDCC

Inelastic breakup

Breakup fusion & direct stripping

Imaginary part of the n-238U optical potential was divided into two, one part corresponding to CN formation

\[ P_f^{\text{surro}} (E^*) = \frac{N_{p-f}^{\text{coin}} (E^*)}{N_{p}^{\text{sing}} (E^*)} \cdot \epsilon_f (E^*) \]

Jin Lei and Antonio Moro, Univ. of Sevilla, Spain

In \( E^* \leq \text{Sn} + 1.5 \) MeV the breakup fusion represents nearly 80% of the total detected protons
Above $E^*=6.3$ MeV the corrected Pf is still lower than the n-induced data, probably due to fusion of d with 16O followed by proton evaporation.
Focus on the overlap zone...

d + 238U -> p + 239U ↔ n + 238U
Can we explain these results within the framework of the statistical model?

\[
P_{\text{surro,decay}}(E^*) = \sum_{J^\pi} P_{\text{surro}}^{\text{form}}(E^*, J^\pi) \cdot G_{\text{decay}}(E^*, J^\pi)
\]
Interpretation of results

Calculated average spin of 239U

Monte-carlo Hauser Feshbach code

Perspectives: Determine full spin & parity distribution and couple it to the HF results to see if we can reproduce our data
Preliminary results!

\[ ^{3}\text{He} + ^{238}\text{U} \rightarrow ^{4}\text{He} + ^{237}\text{U} \leftrightarrow n + ^{236}\text{U} \]

The fission probability is much less sensitive to the entrance channel than the gamma-decay probability!

P. Marini et al., to be published
Conclusions...

- First simultaneous measurement of gamma-decay and fission probabilities for the $^{238}\text{U}(d,p)$ surrogate reaction

- The fission probability is lower than the n-induced one. This difference is explained by the contribution from elastic and inelastic deuteron breakup and by fusion-evaporation on oxygen.

- The fission probability corrected for breakup, is in good agreement with the n-induced data whereas the gamma-emission probability is much higher. Also observed for reactions not affected by breakup.

- The fission probability is much less sensitive to the populated angular momentum than the gamma-decay probability

- No obvious explanation yet, our data are useful to establish to which extent the surrogate method can be used to infer fission cross sections in regions where no data are available
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