Surrogate Reactions: Indirect Determination of Cross Sections on Unstable Targets

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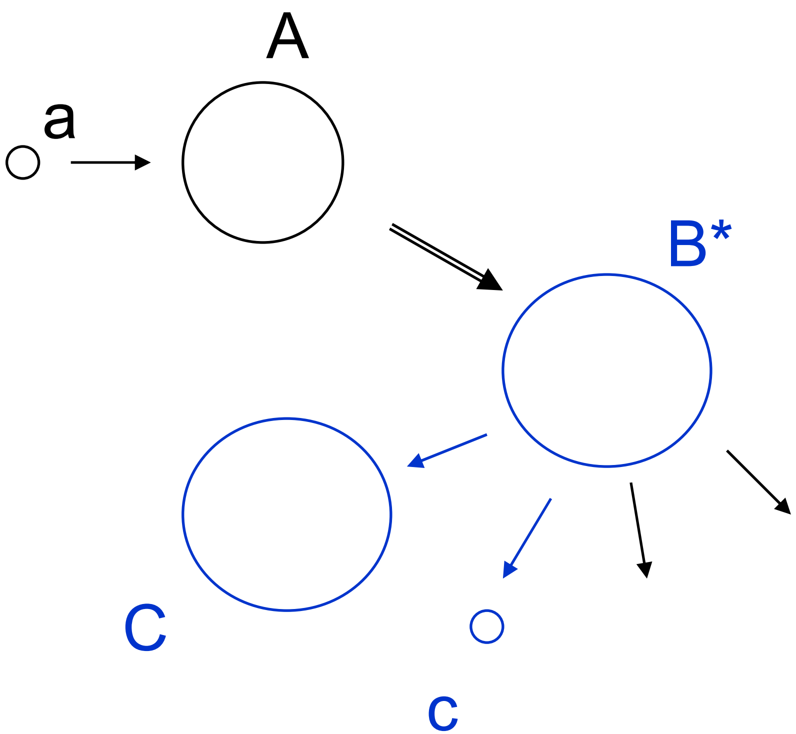
Outline

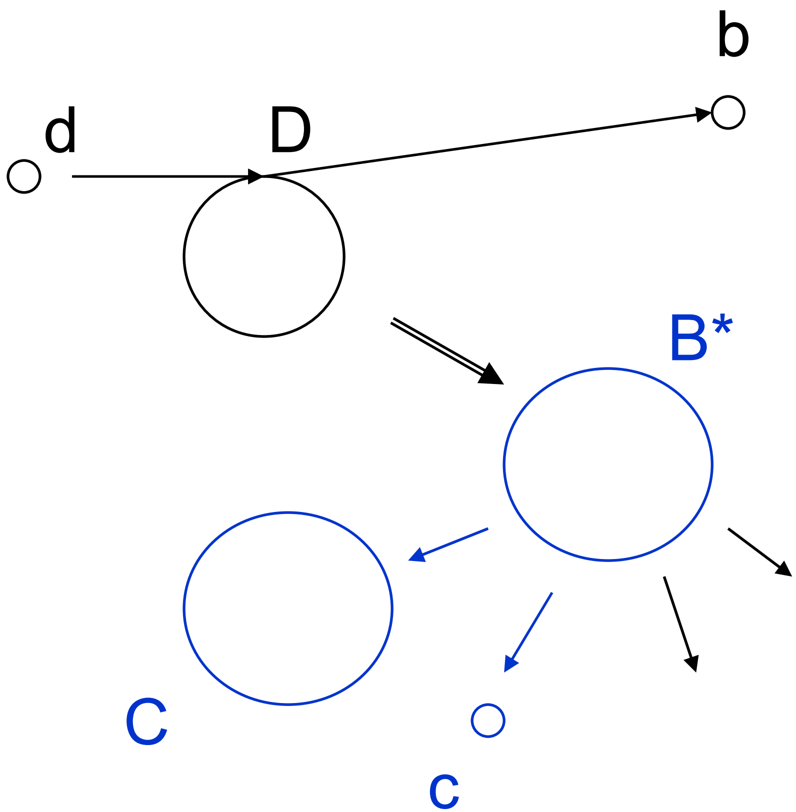
- Outline of Theory and various approximations
- Successes of the Surrogate Method
- Proposed theoretical improvements

Schematic Diagram of Surrogate Reactions

"Desired" reaction, e.g. (n,γ)



Surrogate reaction, e.g. (t,p)



Vastly different time scales of the direct part of the surrogate reaction and the compound reaction;
"b" is a spectator.

Surrogate method for fission of actinides

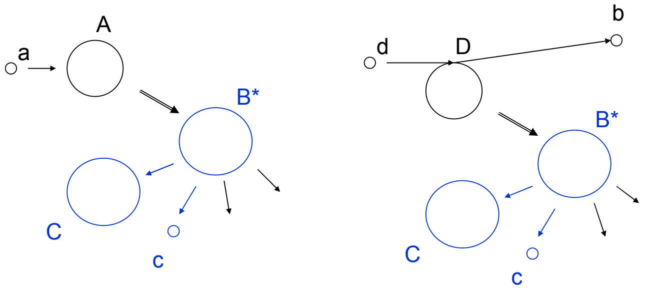
- **Used in 1970's to extract (n,fission) on unstable actinides by transfer reactions on neighboring stable isotopes using tritium and ^{3}He projectile, e.g.:**
  - **Desired:** ^{237}U(n,fission)
  - **Surrogate:** ^{236}U(t,p)^{238}U → fission
  - **Compound:** ^{238}U
- **More recently Petit *et al.* (2004)** (Protactinium)
  - **Desired:** ^{233}Pa(n,fission)
  - **Surrogate:** ^{232}Th(^{3}He,p)^{234}Pa → fission
  - **Compound:** ^{234}Pa
  - **+ several others Pa isotopes**
- **Escher and Dietrich recently applied it to (n,gamma)**

Surrogate Method

Desired reaction cross-section:

$$\frac{d\sigma_{\alpha\gamma}^{\mathrm{HF}}(E_\alpha)}{dE_\chi} = \sum_{J\pi} \sigma_\alpha^{\mathrm{CN}}(E_{\mathrm{ex}}, J, \pi)\, G_\chi^{\mathrm{CN}}(E_{\mathrm{ex}}, J, \pi)\;\; W$$

$$\alpha = (a + A)$$
$$\chi = (c + C)$$
$$\delta = (d + D)$$
$$E_{\mathrm{ex}} = S_a(B) + E_\alpha = S_c(B) + E_\chi$$



Surrogate reaction probability:

$$P_{\delta\gamma}(E_{\mathrm{Ex}}) = \sum_{J\pi} F_\delta(E_{\mathrm{ex}}, J, \pi)\, G_\chi^{\mathrm{CN}}(E_{\mathrm{ex}}, J, \pi)$$

Jπ distributions are likely different for the two reactions: complicates calculations and requires more surrogate data

J. Escher, F. Dietrich, Phys. Rev. C74, 054601 (2006)

Weiskopf-Ewing Limit

Desired reaction cross section

$$\frac{d\sigma^{\mathrm{HF}}_{\alpha\gamma}(E_\alpha)}{dE_\chi} = \sigma^{\mathrm{CN}}_\alpha(E_{\mathrm{ex}})\, G^{\mathrm{CN}}_\chi(E_{\mathrm{ex}})$$

$$\sigma^{\mathrm{CN}}_\alpha(E_{\mathrm{ex}}) = \sum_{J\pi} \sigma^{\mathrm{CN}}_\alpha(E_{\mathrm{ex}}, J, \pi)$$

$$= \pi \lambda\!\!\!^{-2}_\alpha \sum_{l=0}^{\infty} (2l+1) T_{\alpha 1}(E_\alpha)$$

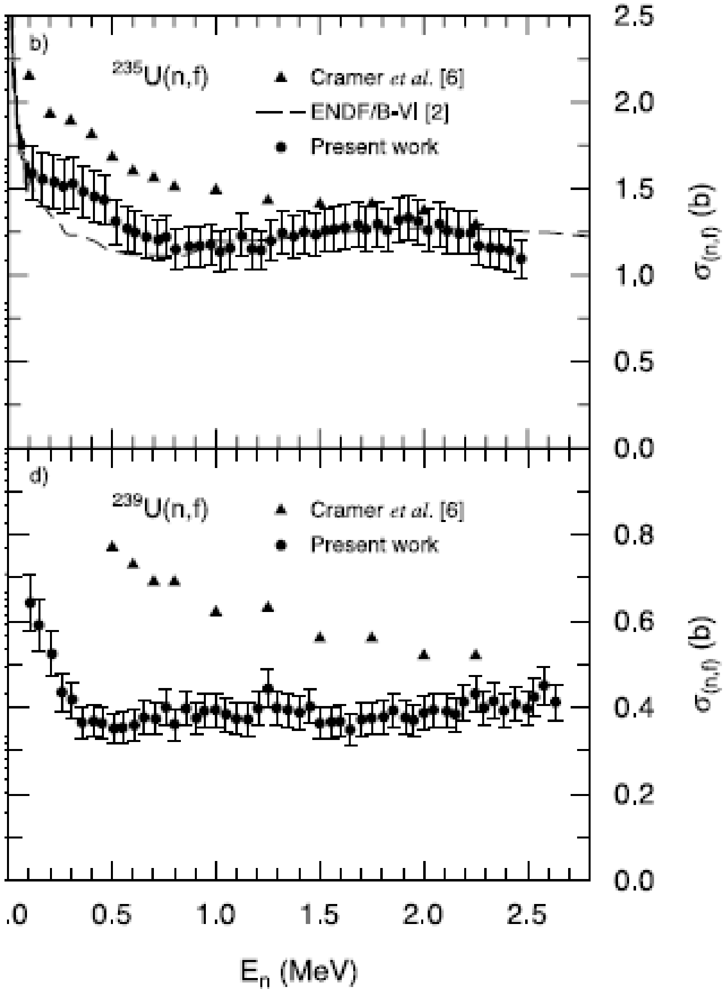
Surrogate reaction probability:

$$P_{\delta\chi}(E_{\mathrm{Ex}}) = \sum_{J\pi} F^{CN}_\delta(E_{\mathrm{ex}}, J, \pi)\, G^{\mathrm{CN}}_\chi(E_{\mathrm{ex}}, J, \pi)$$

$$= G^{\mathrm{CN}}_\chi(E_{\mathrm{ex}})$$

- **Branching ratios are independent of Jπ when:**
  - **Compound energy is high**
  - **Width-fluctuations small**
  - **Transmission coeff.'s small**
  - **Level densities ~(2I'+1)**
    - **True for I'<σ_{cutoff}~6-7**

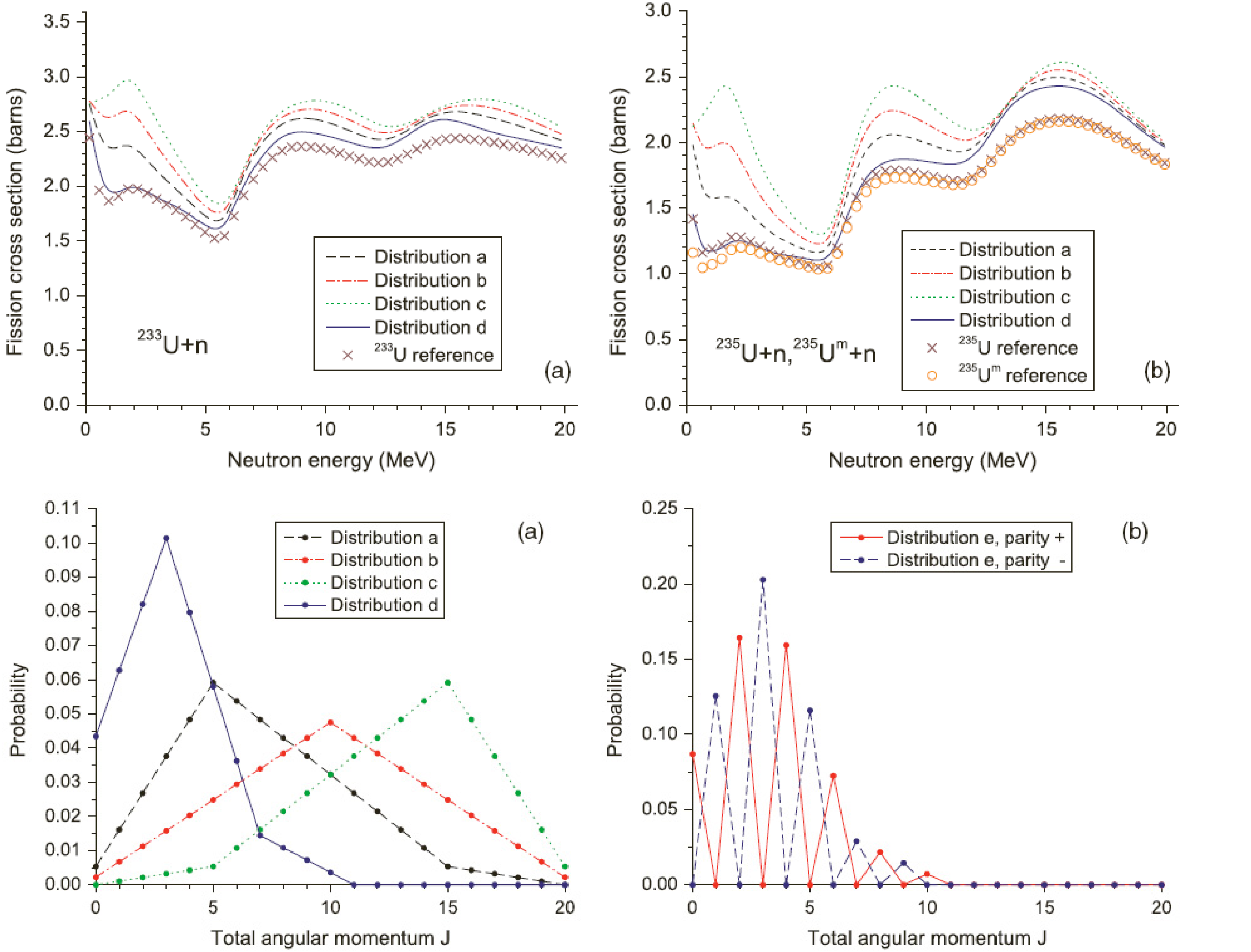
The effect of mismatched Jπ distributions



Younes & Britt, Phys Rev C68, 034610 (2003)

Significant improvement obtained by using a simple model for direct part of the surrogate reaction to take into account the Jπ mismatch.

Sensitivity of method to distribution of Jπ



Proposed improvement

- Instead of HF theory, use KKM and KM theories
- KKM derives and generalizes HF
- KM applies KKM to two-step processes
  - Direct reaction + Compound reaction
  - Thus suitable for the Surrogate reaction

KKM outline

$$\mathbf{T}_{cc'} = \mathbf{T}_{cc'}^{\text{opt}} + \sum_q \frac{g_{cq} g_{c'q}}{E - \boldsymbol{E}_q}$$

Kawai, Kerman, and McVoy, Ann. of Phys. 75, 156 (1973)

$$\langle \mathbf{T}_{cc'} \rangle \approx \mathbf{T}_{cc'}^{\text{opt}}$$

$$\langle \sigma_{cc'} \rangle = \langle \mathbf{T}_{cc'} \mathbf{T}_{cc'}^{*} \rangle$$

$$\langle \sigma_{cc'} \rangle = \sigma_{cc'}^{\text{opt}} + \sigma_{cc'}^{\text{fluct}}$$

$$\sigma_{cc'}^{\text{fluct}} \sim \left\langle \sum_{qq'} \frac{g_{cq} g_{c'q}}{E - \boldsymbol{E}_q} \frac{g_{cq'}^{*} g_{c'q'}^{*}}{E - \boldsymbol{E}_{q'}} \right\rangle$$

$$\sim \langle g_{cq} g_{cq}^{*} \rangle_q \langle g_{c'q} g_{c'q}^{*} \rangle_q + \langle g_{cq} g_{c'q}^{*} \rangle_q \langle g_{c'q} g_{cq}^{*} \rangle_q$$

$$\sim X_{cc} X_{c'c'} + X_{cc'} X_{c'c}$$

$$\approx X_{cc} X_{c'c'}$$

KKM & KM applied to Surrogates

- KM deals with two-step reactions (direct + compound), just what is needed for the surrogate reaction.
- The derivation of KM is similar to KKM but it is more complicated, because of the direct-reaction step.
- The final KM result can be brought into the same overall form as the KKM

$$\sigma_{Rc'}^{\text{fluct}} \sim X_{RR} X_{c'c'} + X_{Rc'} X_{c'R}$$

$$\approx X_{RR} X_{c'c'}$$

$$\sigma_{cc'}^{\text{fluct}} \sim X_{cc} X_{c'c'} + X_{cc'} X_{c'c}$$

$$\approx X_{cc} X_{c'c'}$$