Compound-nucleus Formation Following Direct Interactions to Highly-excited Final States

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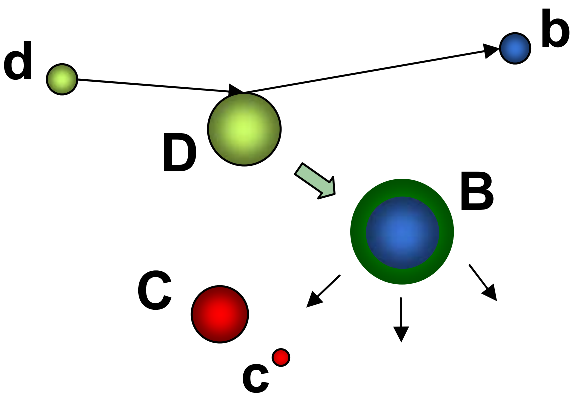
Objectives

We examine an important assumption of the surrogate reaction mechanism:

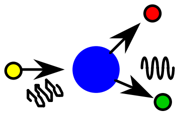
The residual nucleus B following a direct reaction is an equilibrated compound nucleus



The problem:

B can decay promptly by emitting particles into the continuum

Possible decay mechanisms need to be studied for each type of direct reaction used in surrogate experiments, such as (^{3}He,α), (α,α'),(d,p), *etc.*



Examples of prompt decays in current experiments

- **(^{3}He,α): Pickup process; creates a hole in the residual nucleus. This is may interact with other nucleons and eject a neutron or proton into the continuum (nuclear Auger effect, or rearrangement escape)**

- **(d,p): Stripping process; creates a particle (neutron) in residual nucleus, which is *unbound* in the case of surrogate reactions. The neutron may then be emitted into the continuum (direct escape)**

- **(α,α'): Inelastic scattering; creates coherent superpositions of particle-hole pairs. Both rearrangement escape and direct escape need to be considered**

(d,p) is particularly important for reverse-kinematics experiments at RIB facilities; current tests at ORNL, LBL

Here we examine escape effects quantitatively in a closely related reaction: direct neutron capture, (n,γ)

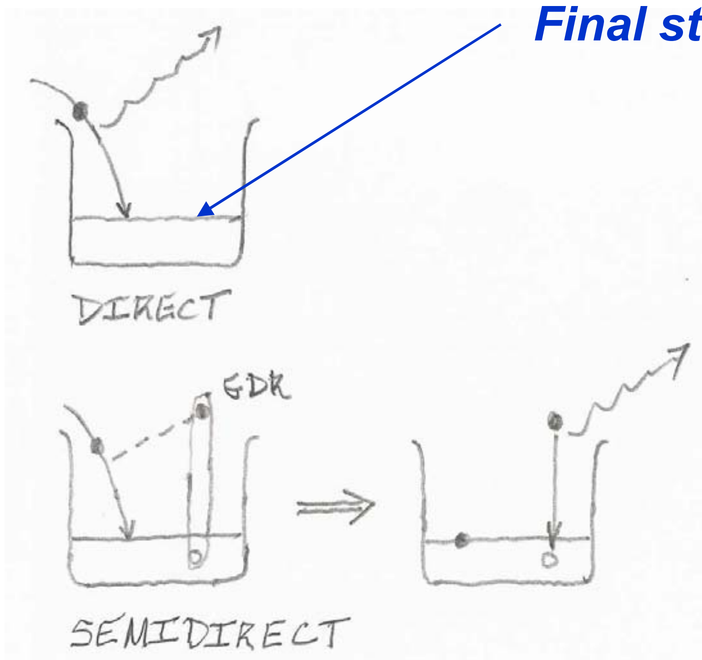
$$d + X \rightarrow (X + n) + p$$

$$n + X \rightarrow (X + n) + \gamma$$

Just erase the proton! Theory for final-state decay is the same for both reactions

2 interfering terms in direct-semidirect capture, which is DWBA theory for nucleon radiative capture

Final state may be unbound!



Projectile radiates and is captured in well

1) **Projectile excites giant dipole resonance and is captured;**
2) **Giant dipole collapses and emits the gamma ray**

Effective radial electromagnetic operator:

$$Q_L = q_L r^L + \left(\frac{1}{E_\gamma - E_{res} + i\Gamma/2} - \frac{1}{E_\gamma + E_{res}} \right) h_L'(r)$$

direct **semidirect**

Theory ca. 1995 for capture to unbound final states exhibited both compound formation and direct escape of captured nucleon

PHYSICAL REVIEW C VOLUME 52, NUMBER 1 JULY 1995

Fluctuation effects in radiative capture to unstable final states: A test via the $^{89}\mathrm{Y}(\vec{p},\gamma)$ reaction at $E_p = 19.6$ MeV

W.E. Parker *et al.*

Compound formation

Direct escape

$$\frac{d\sigma}{dE_\gamma \, d\Omega_\gamma} = \sigma_1 + \sigma_2$$

Absorption at **r** by imaginary potential ***W***

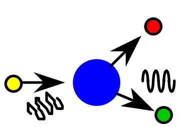
propagator

$$\sigma_1 = -\frac{1}{\phi_{inc}} \frac{2}{\hbar} \left(\frac{1}{\hbar c}\right)^3 E_\gamma^2 \int d^3\mathbf{r}\, W(\mathbf{r}) \left| \left\langle \mathbf{r} \middle| G^{(+)} H_\gamma \middle| \overline{\Psi}_i^{(+)} \right\rangle \right|^2$$

$$\sigma_2 = \frac{1}{\phi_{inc}} \frac{2\pi}{\hbar} \left(\frac{1}{\hbar c}\right)^3 E_\gamma^2 \sum_{\mathbf{p}} \left| \left\langle \tilde{\chi}_{\mathbf{p}}^{(-)} \middle| H_\gamma \middle| \overline{\Psi}_i^{(+)} \right\rangle \right|^2 \delta(E - E_p)$$

Similar to calculation for bound final state

See also Kerman & McVoy, Ann. Phys. 122, 197 (1979)



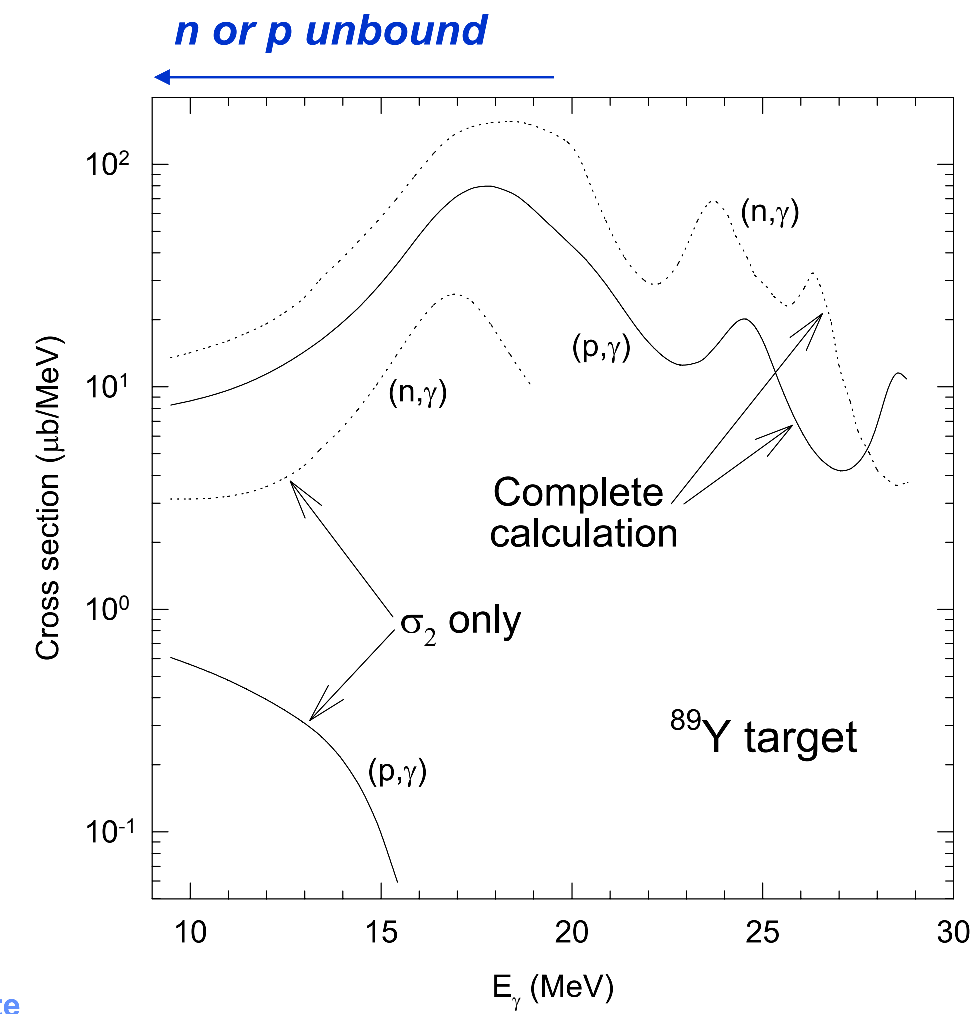
Calculations of ^{89}Y(p,γ) and (n,γ) show compound formation is dominant but escape also happens

For proton capture, escape is unimportant – suppressed by Coulomb barrier

For neutron capture, escape contributes at ~15% level

For both reactions, we see effects of giant-dipole resonance as well as single-particle spectroscopy contained in optical potential for final state

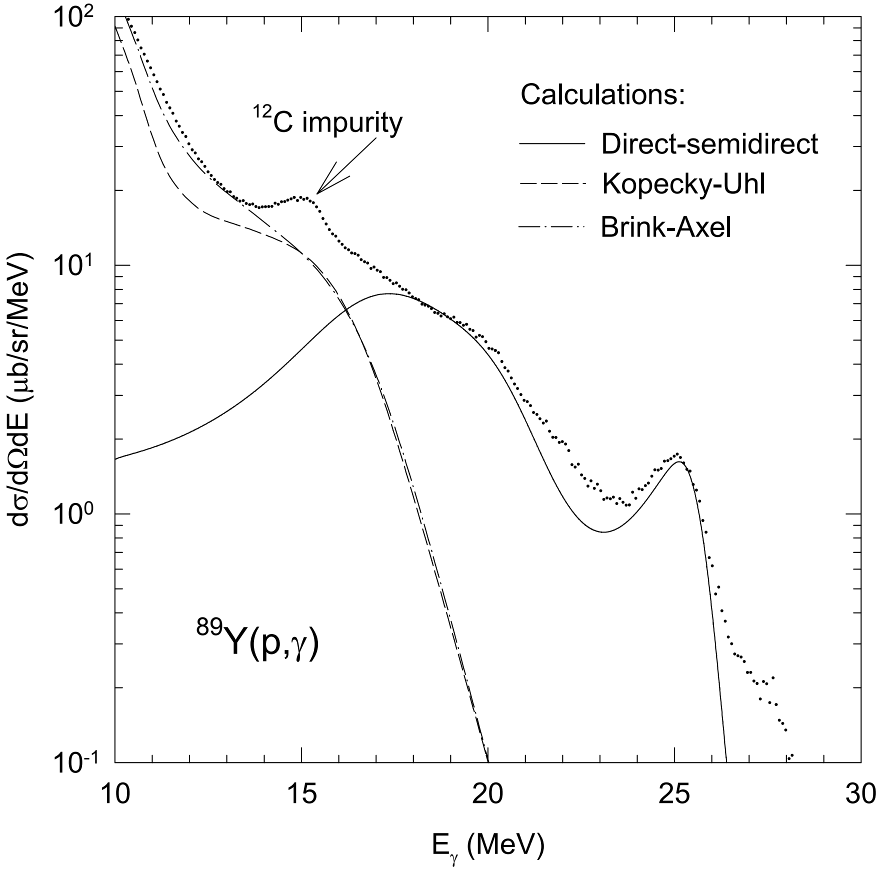
Incident energy: 19.6 MeV



Extended DSD theory, supplemented by compound capture, well described $^{89}Y(p,\gamma)$ experiment

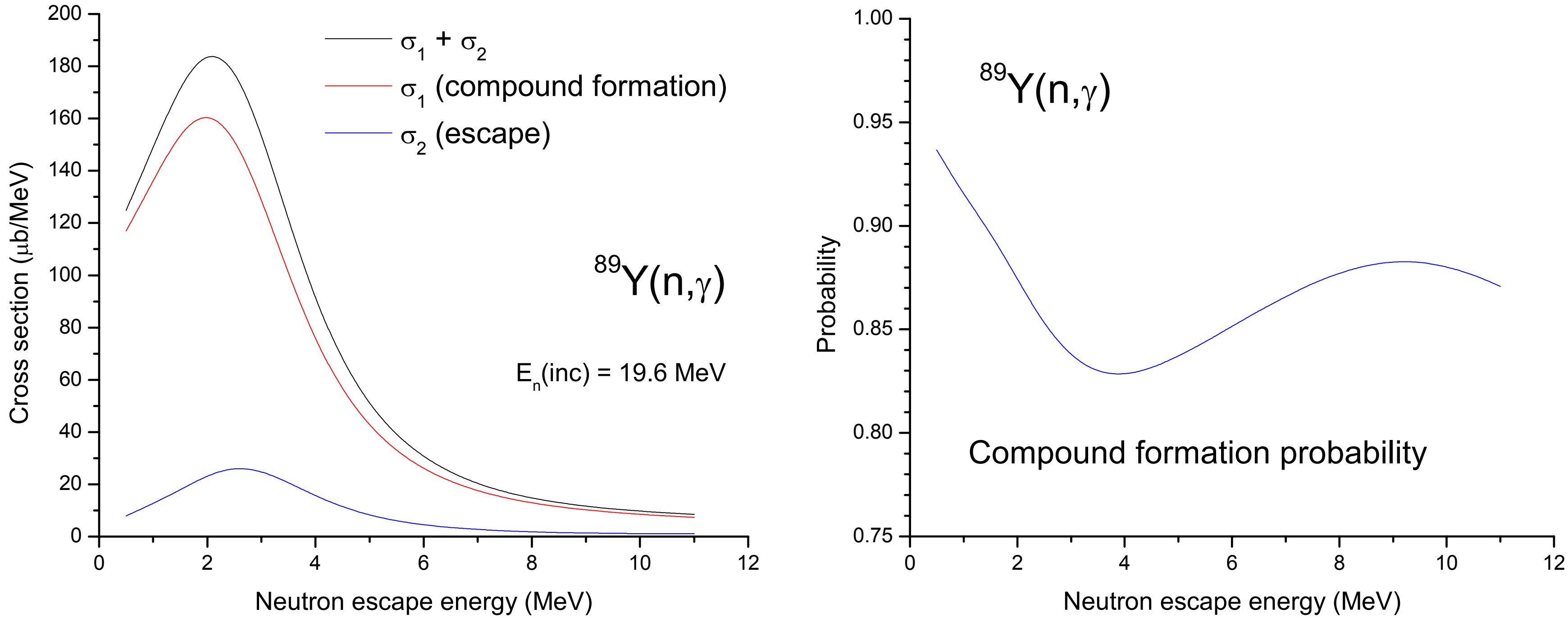
The theory also well predicted angular distributions and analyzing powers of the gammas observed in the polarized-beam experiment reported in Parker *et al.*

Incident energy: 19.6 MeV



Spectrum at 90° for γ

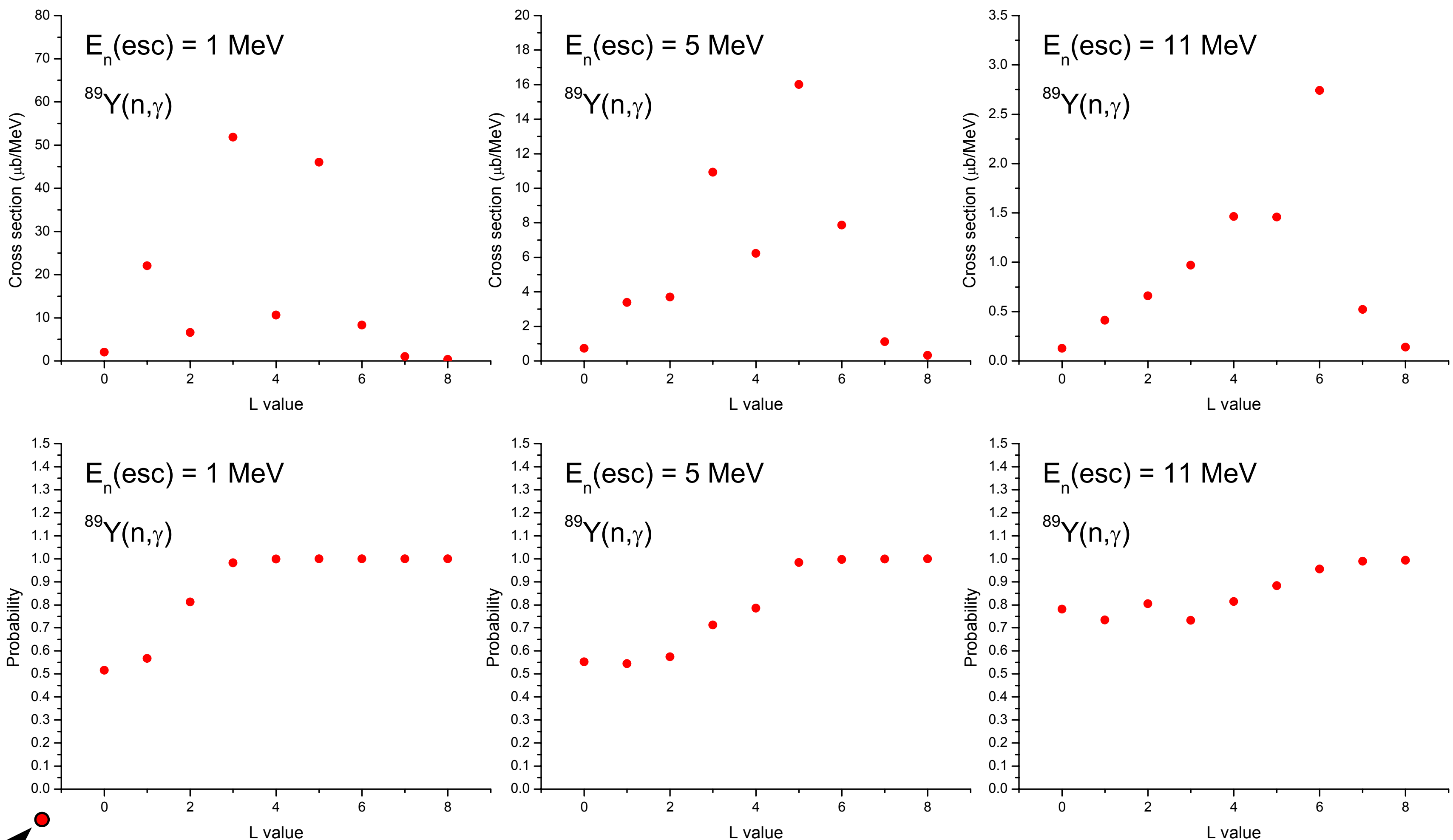
Doing similar calculation for $^{89}Y(n,\gamma)$ shows significant (~15%) probability of direct escape



What are the consequences for the spin-parity distributions of the residual nucleus? These can be calculated.

Cross sections and compound formation probabilities calculated vs. orbital angular momentum L for 3 final-state energies

Odd-even effect in cross section: single-particle spectroscopy
Compound-formation probability variation: angular-momentum barrier



Summary and conclusions

- **Calculations of final-state L distributions and compound formation probabilities have been made for $^{89}Y(n,\gamma)$**
  - *Results are understood; we find significant direct-escape probabilities that are dependent on L*
- **These calculations provide guidance for understanding compound formation in (d,p) – should be qualitatively very similar**
- **(d,p) calculations should (and can) be carried out in DWBA, using same formalism for treating unbound final states**
  - *Replace electromagnetic interaction $H\gamma$ by residual interaction Vpn*

Results suggest using single-nucleon stripping as direct interaction in surrogate experiments requires careful theoretical interpretation

Further work needs to be done on other processes involving rearrangement