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Compound-Nucleus Formation Following Direct Interactions to Highly-Excited Final States

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Compound-Nucleus Formation Following Direct Interactions to Highly-Excited Final States

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Abstract. When direct reactions populate highly excited, unbound configurations in the residual nucleus, the nucleus may further evolve into a compound nucleus. Alternatively, the residual system may decay by emitting particles into the continuum. Understanding the relative weights of these two processes as a function of the angular momentum and parity deposited in the nucleus is important for the surrogate-reaction technique. A particularly interesting case is compound-nucleus formation via the (d,p) reaction, which may be a useful tool for forming compound nuclei off the valley of stability in inverse-kinematics experiments. We present here a study of the compound formation probability for a closely-related direct reaction, direct-semidirect radiative neutron capture.

Keywords: direct reactions, compound nuclear reactions, fluctuations, direct-semidirect radiative capture
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INTRODUCTION

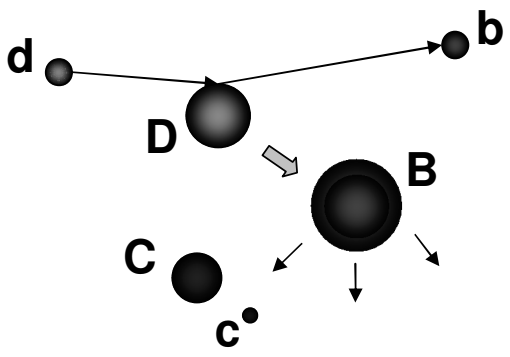

FIGURE 1. Schematic picture of the formation of a residual nucleus B via a direct reaction $D(d,b)B$, followed by the decay $B \rightarrow C+c$.

The surrogate nuclear reaction technique for indirect determination of compound-nucleus cross sections, discussed in several presentations at this conference, involves the production of a highly-excited residual nucleus in a direct reaction, followed by the the detection of the decay products of this residual system. This process is indicated schematically in Fig. 1, in which the residual nucleus B is formed in the direct reaction $D(d,b)B$, followed by the decay $B \rightarrow C+c$. In this presentation we examine an important assumption of the surrogate reaction mechanism, namely that the residual nucleus B is an equilibrated compound nucleus.

The potential difficulty with this assumption is that B may decay promptly by emitting particles into the continuum before a compound nucleus is formed. Estimating the probability that such decays actually occur must be carried out for all relevant spins and parities of the residual system. This problem is closely related to those of preequilibrium emission and incomplete fusion in direct reactions. Possible prompt decay mechanisms need to be studied for each type of direct reaction used in surrogate experiments. Here we give examples of prompt decay processes that may play a role in several direct reactions that have been used in surrogate-reaction measurements:

- $(^3\mathrm{He},\alpha)$: Pickup process, which creates a hole in the residual nucleus. This may interact with the remaining nucleons and eject a nucleon (nuclear Auger effect, or rearrangement escape).
- (d,p): Stripping process that deposits a particle (neutron) in the residual nucleus, which is unbound in the case of surrogate reactions. The nucleon may then leak into the continuum (direct escape).
- (α,α'): Inelastic scattering, which creates coherent superpositions of particle-hole pairs in the residual system. Both rearrangement and direct escape need to be considered.

In principle, theories need to be implemented for each relevant type of direct interaction, suitable for calculating the compound-nucleus formation probabilities for each spin-parity combination of the residual nucleus.

A particularly important case is (d,p), since this is a potentially useful reaction for studying unstable nuclei in reverse-kinematics experiments at radioactive beam facilities. Here we carry out calculations of the compound formation probabilities in a closely-related reaction, radiative neutron capture (n,γ). For kinematics relevant to the surrogate mechanism, both reactions insert a neutron

in an unbound state around the target nucleus X:

$$d+X \rightarrow (X+n)+p, \quad (1)$$
$$n+X \rightarrow (X+n)+\gamma. \quad (2)$$

We study the radiative capture reaction because a suitable reaction theory has been implemented for nucleon capture to unbound states, including the evolution of the final state into its compound-nucleus and escape parts [1]. The only difference in the reactions is the manner in which the neutron is captured onto the target; the theory for the decay of the configuration $(X+n)$ is the same in both cases. Thus we can use calculations of compound formation probabilities in the radiative capture reaction as a prototype for what should be expected in the stripping reaction.

RADIATIVE CAPTURE

The theory of direct-semidirect fast-nucleon radiative capture to bound final states is well known, and its extension to unbound states has been treated in detail by Parker *et al.* [1]. In that work the theory was developed and shown to reproduce a wide variety of experimental data on ^{89}Y(p,γ) at 19.6 MeV incident energy; here we carry out the same calculations for ^{89}Y(n,γ), also at 19.6 MeV.

We assume that the outgoing gamma ray is observed at a given energy and angle, and sum over all (unobserved) final nuclear states. The resulting double-differential cross section for this inclusive reaction can, as shown in Ref. [1], be divided into two components: σ_1, in which the nucleus evolves into a compound nucleus; and σ_2, in which the captured projectile escapes into the continuum.

$$\frac{d\sigma}{dE_\gamma\, d\Omega_\gamma} = \sigma_1 + \sigma_2, \quad (3)$$

where

$$\sigma_1 = -\frac{1}{\phi_{inc}}\frac{2}{\hbar}\left(\frac{1}{\hbar c}\right)^3 E_\gamma^2 \times \int d^3\mathbf{r}\, W(\mathbf{r}) \left|\left\langle \mathbf{r}\left| G^{(+)}\, H_\gamma \right| \bar{\Psi}_i^{(+)}\right\rangle\right|^2, \quad (4)$$

and

$$\sigma_2 = \frac{1}{\phi_{inc}}\frac{2\pi}{\hbar}\left(\frac{1}{\hbar c}\right)^3 E_\gamma^2 \times \sum_{\mathbf{p}} \left|\left\langle \tilde{\chi}_{\mathbf{p}}^{(-)}\left| H_\gamma \right| \bar{\Psi}_i^{(+)}\right\rangle\right|^2 \delta(E-E_p). \quad (5)$$

We can interpret the compound contribution σ_1 as follows: the electromagnetic operator H_γ causes a transition of the incident nucleon from its initial continuum state $\bar{\Psi}_i^{(+)}$ at energy E_i, approximated by an optical-model wave function, to an intermediate configuration in which the nucleon is at a spatial position $\mathbf{r}'$, at energy $E_f = E_i - E_\gamma$, where E_γ is the energy carried off by the emitted gamma. The nucleon is then propagated in the field of the target nucleus from $\mathbf{r}'$ to $\mathbf{r}$ by the optical-model Green's function $G^{(+)}(\mathbf{r},\mathbf{r}')$, where it is absorbed by the imaginary part of the optical potential $W(\mathbf{r})$. ϕ_{inc} is the flux in the incident channel.

The escape contribution, σ_2, is close to the standard expression for direct-semidirect capture to bound final states. Here, the bound final state wave function is replaced by the optical-model wave function $\tilde{\chi}_{\mathbf{p}}^{(-)}$ for the final-state nucleon, with appropriate boundary conditions. The summation represents an integration over all final-state 3-momenta of the unobserved outgoing nucleon, and the delta function guarantees energy conservation.

The electromagnetic operator for E1 radiation, including both direct and semidirect (giant dipole formation) terms, is approximately

$$H_\gamma \sim q_1\, r + \left(\frac{1}{E_\gamma - E_{res} + i\Gamma/2} - \frac{1}{E_\gamma + E_{res}}\right) h_1'(r), \quad (6)$$

where q_1 is an effective charge factor, E_{res} and Γ are the energy and width of the giant dipole resonance, and $h_1'(r)$ is a form factor for exciting the giant resonance; notation and details are as in Ref. [1].

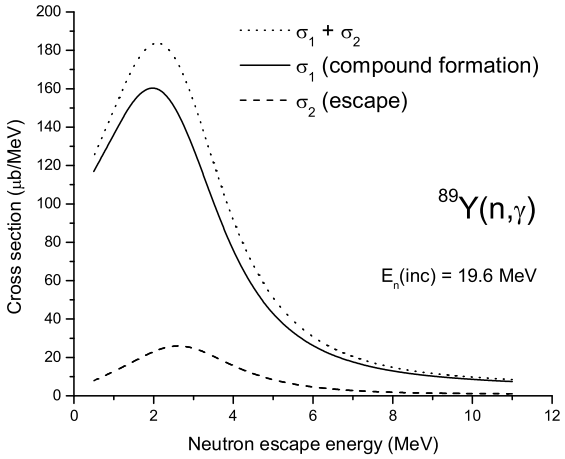

FIGURE 2. Angle-integrated cross section for ^{89}Y(n,γ) as a function of final-state neutron energy E_f.

RESULTS FOR ^{89}Y(n,γ)

Fig. 2 shows the cross section for ^{89}Y(n,γ) integrated over all outgoing gamma-ray angles at an incident neutron energy $E_i = 19.6$ MeV, plotted as a function of the

final-state neutron escape energy $E_f = E_i - E_\gamma$. Both the compound and escape contributions are shown, together with their sum. The peak just above $E_f = 2$ MeV is due to the semidirect contribution, corresponding to a giant-dipole resonance energy of 16.7 MeV. The details of the calculation are exactly as described for $^{89}\mathrm{Y}(p,\gamma)$ in Ref. [1], except that the initial- and final-state neutron wave functions were generated from the global optical potential of Koning and Delaroche [2], and only E1 radiation was considered.

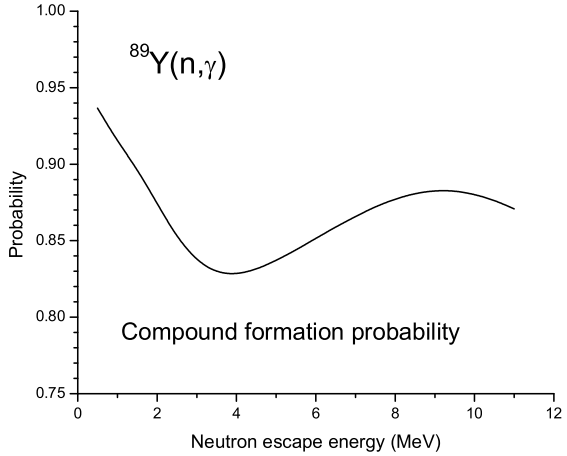

FIGURE 3. Compound formation probability as a function of neutron escape energy, calculated from results shown in Fig. 2.

It is evident from Fig. 2 that a significant part of the capture cross section corresponds to leakage of the final-state neutron rather than compound nucleus formation. This is very different from the $^{89}\mathrm{Y}(p,\gamma)$ case [1], since at corresponding escape energies the final-state proton is held in by a large Coulomb barrier. The compound formation probability for neutrons is shown in Fig. 3. This probability is calculated from the results in Fig. 2 by the expression $\sigma_1/(\sigma_1+\sigma_2)$, again using quantities integrated over outgoing gamma angles. Clearly 10–15% of the capture reactions fail to form a compound nucleus, and this would have to be taken into account if the capture reaction were used to prepare a compound system in a surrogate-reaction experiment.

We next investigate the spin-parity distributions of the compound nuclei that survive the escape process. Although these values are available as by-products of the calculations described above, it is more instructive for present purposes to look at the cross sections (angle-integrated $\sigma_1+\sigma_2$) and the compound formation probabilities as a function of L, the orbital angular momentum of the outgoing neutron in the final state. These quantities are shown in Fig. 4 for three values of the final-state neutron escape energy, E_f =1, 2, and 5 MeV (E_f is referred to as $\mathrm{E_n(esc)}$ in the figure).

There are two particularly striking features in the results shown in Fig. 4. The first is the alternation of high and low values of the cross section with L; the second is the behavior of the compound formation probability, which is lowest for small values of L and tends toward unity for high values. Both of these features have simple physical interpretations.

The even-odd behavior of the cross sections is a consequence of the single-particle structure in the real part of the optical potential describing the final-state neutron. For bound states, there is an alternation between predominantly even and predominantly odd states as the energy increases by a harmonic-oscillator spacing (about 9 MeV here), and this behavior continues as the energy extends into the continuum. It is most pronounced for low energies; at E_f =1 MeV the cross sections for odd L are much larger than for the neighboring even values. This effect is related to the fact that in the A=90–100 region the s-wave neutron strength function is near a minimum and the p-wave is near a maximum. Note that the effect is less pronounced at E_f =5 MeV, and at 11 Mev there is some evidence that the effect has reversed, so that the even partial waves are stronger.

The behavior of the compound-nucleus formation probability is simply accounted for by the angular momentum barrier, which restricts neutron emission above a characteristic L value that should increase approximately as the square root of the neutron energy. For the lowest L values only about half the cross section is associated with compound formation at 1 MeV, and this value rises to about 0.75 at 11 MeV. The transition to full compound formation varies with energy roughly as expected. It is important to note that while only about 15% of the cross section leads to escape on average (Fig. 3), the low partial waves show a much larger effect, and thus the spin-parity population of a compound nucleus formed in a surrogate reaction can be significantly distorted by the partial-wave effect shown here.

SUMMARY AND IMPLICATIONS FOR SURROGATE REACTIONS

We have studied the process of forming a compound nucleus as a final state in a direct reaction, using radiative capture as a test case since the necessary computational tools were available. The results for the dependence of the cross section and the compound-nucleus formation probability on orbital angular momentum are readily understandable as effects of single-particle structure and the angular-momentum barrier. These results show that the angular-momentum and parity distribution of the compound system cannot be approximated by simple models, but must be calculated carefully using an appropriate

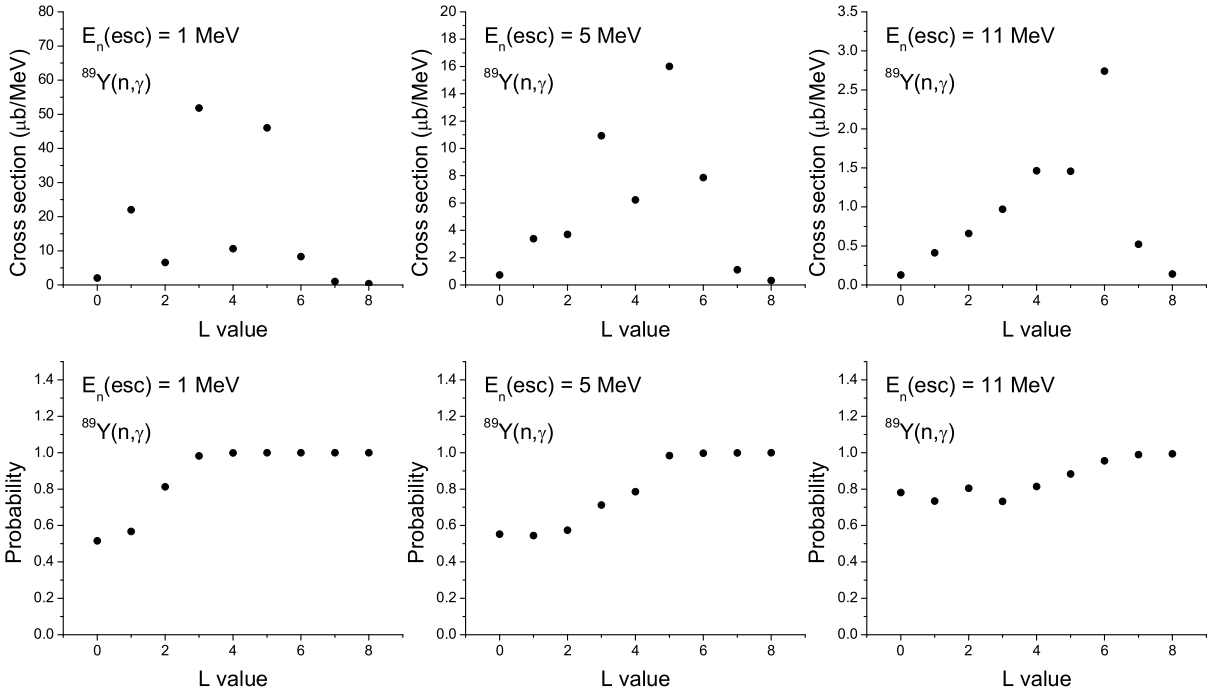

FIGURE 4. Cross section and compound-nucleus formation probability for radiative capture to unbound final states in the $^{89}\mathrm{Y}(n,\gamma)$ reaction at 19.6 MeV incident energy, as a function of the orbital angular momentum of the neutron following capture. Results are shown for final-state neutron escape energies of 1, 5, and 11 MeV. The upper graphs show the cross sections, which are the angle-integrated values calculated from Eqs. 3–5.

theory for each type of direct interaction used in a surrogate reaction.

The calculations shown here provide guidance for understanding compound nucleus formation via the (d,p) reaction, since as noted earlier this reaction produces the same neutron-plus-core final state as the (n,γ) reaction. We therefore expect the results to be qualitatively similar for the two reactions. To modify the theory of Parker *et al.* [1] for (d,p), it suffices to replace the electromagnetic operator H_γ in Eqs. 3–5 by V_{pn}, the appropriate interaction for DWBA calculation of the stripping process, and also replace the incident neutron distorted wave by one for the deuteron.

Kerman and McVoy [3] developed a very detailed theory of the statistical properties of nuclei following direct reactions. In Ref. [1] a closure relation was used to sum over final nuclear states, which avoided the need to deal explicitly with the statistical properties of the final states. However, if it becomes necessary to calculate correlation effects in the formation and decay of the final states, a more detailed treatment such as that of Ref. [3] will be required.

Finally, we note that the cases discussed here are probably the most likely to exhibit decay before a compound nucleus is formed, because the single neutron left by the direct process may escape into the continuum directly, with no inhibition by a Coulomb barrier. Other reactions requiring rearrangement in the escape mechanism, such as a $(^3\mathrm{He},\alpha)$ reaction, may have a significantly greater chance of avoiding premature decay. However, detailed calculations will be necessary to verify this conjecture.

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