Determination of (n, γ) cross sections in the rare-earth region using the surrogate ratio method

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The surrogate ratio method was used to convert experimentally determined relative γ-decay probabilities for excited ^{171}Yb and ^{161}Dy nuclei, populated using (^{3}He, ^{3}He$'$) and (^{3}He, α) reactions, into neutron-induced γ-decay cross sections in an equivalent neutron energy range of 165–465 keV. The relative γ-decay probabilities were measured using the CACTUS array at the Oslo Cyclotron Laboratory and were found to agree with the ratio of neutron-induced γ-decay cross sections for the same compound nuclei over the range of excitation energies measured. No significant entrance-channel effects on the extracted (n, γ) cross sections were observed. The cross sections obtained using the surrogate ratio method were compared to directly measured neutron-capture cross sections and found to agree within the total estimated uncertainty over the range of equivalent neutron energies measured.

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I. INTRODUCTION

Neutron-capture cross sections are important for the study of astrophysical nucleosynthesis of heavy elements, advanced nuclear reactor performance calculations, and feasibility studies for accelerator partitioning and transmutation systems for radioactive waste management. Many (n, γ) cross sections are difficult to measure directly due to the low intensity of available monoenergetic neutron beams and/or background and fabrication issues on account of the radioactive decay of the target. The absolute surrogate method (ASM) was developed as an indirect means for determining neutron-induced reaction cross sections, whereby a light-ion induced "surrogate" reaction is used to access the same compound nucleus formed in the neutron-induced reaction [1]. The residual nucleus produced by the light-ion induced reaction is assumed to damp into the compound nucleus of interest and the relevant decay probability is measured. To extract the neutron-induced cross section, the compound nuclear decay probability is multiplied by an independently obtained neutron-induced formation cross section, calculated using an optical-model formalism. Recently, Boyer *et al.* reported the first use of the ASM in obtaining an (n, γ) cross section [2]. The ^{232}Th(^{3}He, p) transfer reaction was employed to extract the ^{233}Pa(n, γ) cross section at equivalent neutron energies up to 1 MeV. The surrogate ^{233}Pa(n, γ) cross section determined by Boyer *et al.* agreed within a factor of 2 with directly measured results.

With few exceptions [3,4], the ASM employs the Weisskopf-Ewing approximation—the assumption that the compound nuclear decay probabilities are independent of the total angular momentum, J, and parity, π, of the populated states [5]. A recent study by Lyles *et al.* showcased a breakdown of the Weisskopf-Ewing approximation in extraction of the ^{236}U(n, f) cross section via the ASM at excitation energies just above the neutron separation energy [6]. It is in this energy range, where the angular momentum and parity of discrete states are experimentally resolvable, where γ-decay probabilities are most likely J^π dependent.

The surrogate ratio method (SRM) is a variation on the ASM in which the same surrogate direct reaction is performed on two different target nuclei to deduce an unknown neutron-induced reaction cross section relative to one that is well measured. The SRM is also carried out in the Weisskopf-Ewing limit but has the advantage that errors due to target contamination are obviated, pre-equilibrium effects are diminished, and correlated errors are minimized [7,8]. The indirect determination of neutron-induced fission cross sections on both stable and short-lived radioactive nuclei in the actinide region has recently been accomplished using the SRM in the range of 0 to 20 MeV incident neutron energy with less than 10% systematic uncertainty [6–10].

To test the viability of the SRM for deducing (n, γ) cross sections, we compare the ratio of directly measured neutron-induced γ-decay cross sections to the experimentally determined surrogate ratio of γ-decay probabilities. Surrogate measurements were performed using both the (^{3}He, ^{3}He$'$) and (^{3}He, α) direct reaction mechanisms to explore the effect of entrance channel on the extracted surrogate cross sections. We consider the following sets of reactions:

$$^{171}\text{Yb}(^3\text{He}, {}^3\text{He}') \longrightarrow {}^{171}\text{Yb}^* \longleftarrow {}^{170}\text{Yb} + n$$
$$^{161}\text{Dy}(^3\text{He}, {}^3\text{He}') \longrightarrow {}^{161}\text{Dy}^* \longleftarrow {}^{160}\text{Dy} + n$$

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and

$$^{172}\mathrm{Yb}(^3\mathrm{He},\alpha) \longrightarrow {}^{171}\mathrm{Yb}^* \longleftarrow {}^{170}\mathrm{Yb} + n$$
$$^{162}\mathrm{Dy}(^3\mathrm{He},\alpha) \longrightarrow {}^{161}\mathrm{Dy}^* \longleftarrow {}^{160}\mathrm{Dy} + n,$$

where the surrogate reaction is on the left and the desired reaction is on the right. We report the first use of the SRM in the indirect determination of (n,γ) cross sections using both the $(^3\mathrm{He}, ^3\mathrm{He}')$ and $(^3\mathrm{He},\alpha)$ surrogate reactions in an equivalent neutron energy range of 165 to 465 keV.

II. THEORY

In the Weisskopf-Ewing limit, the expression for the excitation-energy dependent neutron-induced γ-decay cross section in terms of the surrogate reaction γ-decay probability is given by

$$\sigma_{(n,\gamma)}(E^*) = \sigma_n^{\mathrm{CN}}(E^*)P_{\beta\gamma}(E^*), \tag{1}$$

where $\sigma_n^{\mathrm{CN}}(E^*)$ is the excitation-energy dependent, neutron-induced compound nuclear formation cross section. $P_{\beta\gamma}(E^*)$ is the γ-decay probability for the compound nucleus formed via the surrogate reaction, labeled β with $\beta = (^3\mathrm{He}, ^3\mathrm{He}')$ or $(^3\mathrm{He},\alpha)$ here, and can be written as

$$P_{\beta\gamma}(E^*) = \frac{N^0_{\beta\gamma}(E^*)}{N^0_\beta(E^*)}, \tag{2}$$

where $N^0_{\beta\gamma}(E^*)$ is the number of γ-ray counts in coincidence with the surrogate reaction ejectile, $N^0_\beta(E^*)$ is the number of surrogate reaction events, both a function of excitation energy, E^*, and the superscript 0 denotes the actual number of events. The detected number of surrogate-γ coincident events, $N_{\beta\gamma}(E^*)$, is related to the actual number of events, $N^0_{\beta\gamma}(E^*)$, for example, by

$$N_{\beta\gamma}(E^*) = N^0_{\beta\gamma}(E^*)\epsilon(E^*). \tag{3}$$

Here, $\epsilon(E^*)$ represents the absolute efficiency of the detector array. Neutron-induced reaction cross sections involving two different nuclei, but the same exit channel (in this case, γ decay) can be measured relative to one another using a technique known as the surrogate ratio method, described below in the Weisskopf-Ewing limit:

$$\frac{\sigma^1_{(n,\gamma)}(E^*)}{\sigma^2_{(n,\gamma)}(E^*)} = \frac{\sigma^1_n(E^*)P^1_{\beta\gamma}(E^*)}{\sigma^2_n(E^*)P^2_{\beta\gamma}(E^*)}. \tag{4}$$

The superscripts 1 and 2 denote the two different compound nuclei. We assume that the neutron-induced formation cross sections for the two compound nuclei formed in the ratio are sufficiently similar over the excitation energy range considered for the measurement such that they cancel in the ratio with negligible uncertainty. This assumption is valid in the limit that the properties of individual nuclear states can be neglected and is expected to be inapplicable if effects from discrete states for the two nuclei are manifest at low energies. Equation (4) is then simplified as

$$\frac{\sigma^1_{(n,\gamma)}(E^*)}{\sigma^2_{(n,\gamma)}(E^*)} = \frac{P^1_{\beta\gamma}(E^*)}{P^2_{\beta\gamma}(E^*)}. \tag{5}$$

In the compound nuclei formed via the surrogate reactions, at an excitation energy just below the neutron separation energy, the only open decay channel is γ-ray emission and the γ-decay probability is defined to be 1 at this point. More formally,

$$P_{\beta\gamma}(E^*_A) = \frac{N^0_{\beta\gamma}(E^*_A)}{N^0_\beta(E^*_A)} = \frac{N_{\beta\gamma}(E^*_A)}{\epsilon(E^*_A)I\rho\sigma_\beta(E^*_A)\Delta t} = 1, \tag{6}$$

where I is the beam intensity in particles per unit time, ρ is the areal density of the target, Δt is the length of time over which the data were collected, $\sigma_\beta(E^*_A)$ is the cross section for forming the compound nucleus via the surrogate reaction, $\epsilon(E^*_A)$ is the efficiency of the CACTUS detector array and $E^*_A = B_n - \delta$, where B_n is the neutron separation energy in the compound nucleus and δ is the amount of energy needed to ensure that the total excitation energy, E^*_A, is sufficiently below the neutron separation energy such that the only open decay channel is γ-decay. From Eq. (6),

$$I\rho\Delta t = \frac{N_\beta(E^*_A)}{\epsilon(E^*_A)\sigma_\beta(E^*_A)}, \tag{7}$$

and therefore

$$N^0_\beta(E^*) = I\rho\sigma_\beta(E^*)\Delta t = \frac{N_\beta(E^*_A)\sigma_\beta(E^*)}{\epsilon(E^*_A)\sigma_\beta(E^*_A)}. \tag{8}$$

Using Eqs. (3) and (8), Eq. (2) can be rewritten as

$$P_{\beta\gamma}(E^*) = \frac{N_{\beta\gamma}(E^*)}{N_{\beta\gamma}(E^*_A)}\frac{\epsilon(E^*_A)}{\epsilon(E^*)}\frac{\sigma_\beta(E^*_A)}{\sigma_\beta(E^*)}. \tag{9}$$

Here, the number of surrogate reaction events that would normally appear in the denominator of the γ-decay probability is approximated by the number of particle-gamma coincident events just below the neutron separation energy. Using the following assumptions, a ratio of excitation energy dependent surrogate reaction γ-decay probabilities can be extracted from the γ-ray count distribution:

(i) The cross sections for the direct reactions to form the compound nuclei for the two surrogate reactions employed in the ratio are equal at and near the neutron separation energy. This is a reasonable assumption for the data presented here because the target pairs are both even-even nuclei or both even-odd nuclei, with similar deformations and mass.

(ii) The $(n, n'\gamma)$ channel, where photons are emitted after neutron evaporation, is insignificant in the excitation energy range relevant for the measurement (in this case, up to 500 keV above the neutron separation energy) or sufficiently similar for the two nuclei employed in the ratio such that contributions from this decay channel cancel in the ratio. In this analysis, a γ-ray energy gate of 1.5 MeV or greater ensures that contributions from the $(n, n'\gamma)$ channel are excluded in the particle-gamma coincidence spectra for excitation energies up to 1.5 MeV above the neutron binding energy.

(iii) The statistical γ-ray multiplicity scales similarly with excitation energy for the two nuclei employed in the ratio. This assumption should be borne out given that experimental data in the rare-earth region exhibit statistical

γ-ray multiplicities that do not differ much for even-odd nuclei at or above the neutron separation energy and depend weakly on mass number [11].

Using Eqs. (5) and (9), the ratio of surrogate reaction induced γ-decay probabilities for two different compound nuclei can then be written as

$$R(E^*) = \frac{P^1_{\beta\gamma}(E^*)}{P^2_{\beta\gamma}(E^*)} = \frac{N^1_{\beta\gamma}(E^*)N^2_{\beta\gamma}(E^*_A)}{N^2_{\beta\gamma}(E^*)N^1_{\beta\gamma}(E^*_A)}. \quad (10)$$

The absolute efficiency of the CACTUS detector array, $\epsilon(E^*)$, as a function of excitation energy is the same for the two compound nuclei and thus cancels in the ratio. Because $E^*_A = B_n - \delta$ and the neutron separation energy differs for the two compound nuclei ($B_n = 6.454$ MeV and 6.615 MeV for ^{161}Dy and ^{171}Yb, respectively), δ is chosen to ensure that E^*_A is taken at the same excitation energy for the two compound nuclei employed in the ratio. (In this analysis, $\delta \approx 150$–375 keV. See Sec. IV for further discussion.) Because $N^1_{\beta\gamma}(E^*_A)$ and $N^2_{\beta\gamma}(E^*_A)$ are constants, Eq. (10) is simplified as

$$R = \frac{P^1_{\beta\gamma}(E^*)}{P^2_{\beta\gamma}(E^*)} = A\frac{N^1_{\beta\gamma}(E^*)}{N^2_{\beta\gamma}(E^*)}, \quad (11)$$

where

$$A = \frac{N^2_{\beta\gamma}\left(E^*_A = B^2_n - \delta^2\right)}{N^1_{\beta\gamma}\left(E^*_A = B^1_n - \delta^1\right)}. \quad (12)$$

The A parameter is an energy-independent scale factor that takes into account the integrated beam current and number of target atoms for the two reactions of interest.

The surrogate (n,γ) cross section is given by substitution of Eq. (11) into Eq. (5):

$$\sigma^1_{(n,\gamma)}(E^*) = A\frac{N^1_{\beta\gamma}(E^*)}{N^2_{\beta\gamma}(E^*)}\sigma^2_{(n,\gamma)}(E^*). \quad (13)$$

The result for $\sigma^1_{(n,\gamma)}(E^*)$ is then shifted into equivalent neutron energy, E_n, defined as the energy of the neutron in the desired reaction and related to the excitation energy of the compound nucleus, E^*, by $E_n = E^* - B^1_n$, where B^1_n is the separation energy of the neutron in the compound system. The results of such an analysis are presented in Sec. IV.

III. EXPERIMENTAL APPARATUS

The experiments were carried out with 45-MeV ^{3}He ions at the Oslo Cyclotron Laboratory and have been reported earlier [12–14]. Particle-gamma coincident events for ^{161}Dy and ^{171}Yb compound nuclei were measured with the CACTUS multidetector array [15]. Charged-particle ejectiles were detected with eight particle telescopes, each consisting of a front Si ΔE detector and a back Si(Li) E detector with thicknesses 140 and 3000 μm, respectively, placed at an angle of 45° relative to the beam direction. The intrinsic particle detector energy resolution was determined using an ^{241}Am source to be 50 keV at $E_\alpha = 5.486$ MeV. The average energy resolution of the particle detectors, dominated by the systematic uncertainty arising from determination of the recoil angle of the residual nucleus, was determined to be 200 keV over the entire particle energy region. An array of 28 NaI γ-ray detectors, which intercepted a solid angle of 15% of 4π, surrounded the target and particle detectors. The response function for the CACTUS array as a function of γ-ray energy was previously determined [16] and accounted for in the extracted particle-gamma coincidence spectra. The full width at half maximum of the detector output varies from 80 keV at a γ-ray energy of 1.33 MeV up to 250 keV at a γ-ray energy of 8 MeV. Targets were self-supporting and enriched to approximately 95% purity with thicknesses of 2 mg/cm^2. The Dy and Yb experiments were run for 8 weeks with beam currents of 2 and 1.5 nA, respectively. The experimental extraction procedure and the assumptions made are described in Refs. [16,17], and the references therein.

IV. DATA ANALYSIS AND RESULTS

A two-dimensional, particle-gated matrix of γ-ray energy and compound nuclear excitation energy, E^* (as determined by the ejectile energy), was recorded for each reaction of interest [12,13]. The γ-ray spectra covered an energy range of 100 keV to approximately 6 MeV. Each γ-ray spectrum was summed over γ-ray energies greater than 1.5 MeV for each 120-keV bin of compound nuclear excitation energy to form the particle-gamma coincidence spectra. The lower limit of 1.5 MeV for γ-ray energies was applied to exclude γ-rays depopulating the lowest-lying excited states in the residual nucleus from the analysis. This limit also ensures that contributions from the $(n,n'\gamma)$ channel are omitted in the particle-gamma coincidence spectra for the excitation energies relevant for the surrogate measurement (E^* between B_n and $B_n + 1.5$ MeV).

For each compound nucleus employed in the surrogate ratio measurement, the scale factor, A, as outlined in Eq. (12), was determined by identifying a point in excitation energy where the only open decay channel is γ-ray emission. The particle-gamma coincidence spectrum for the ^{161}Dy(^{3}He, ^{3}He$'$) inelastic-scattering reaction is illustrated in Fig. 1. The normalization parameter, $N^2_{\beta\gamma}(E^* = B^2_n - \delta^2)$ in Eq. (12) was determined to be 44,917 ± 212 counts at an excitation energy of 6240 keV (indicated by the arrow in Fig. 1). This point lay approximately $\delta = 214$ keV below the neutron separation energy in ^{161}Dy($B^2_n = 6454.4$ keV). The normalization parameters for the other entrance channels employed in this analysis were extracted in a similar fashion. For $\beta = (^3\text{He}, ^3\text{He}')$ and $(^3\text{He}, \alpha)$, the A parameter in Eq. (12) was determined to be 1.90 ± 0.02 and 1.98 ± 0.03, respectively. A sensitivity study of the effect of δ on the A parameter indicates that for $\delta \pm 120$ keV, the A parameter is shifted by as much as 4.0% and 10.9%, for $\beta = (^3\text{He}, ^3\text{He}')$ and $(^3\text{He}, \alpha)$, respectively.

In Figs. 2 and 3, the scaled ratios of particle-gamma coincident events [described in Eq. (11)] are given as a function of excitation energy for $\beta = (^3\text{He}, ^3\text{He}')$ and $(^3\text{He}, \alpha)$, respectively, denoted by open circles. The reference data (filled squares) are generated using a ratio of directly measured ^{170}Yb(n,γ) cross section data from M. V. Bokhovko *et al.* [18] to an evaluated ^{160}Dy(n,γ) cross section obtained from

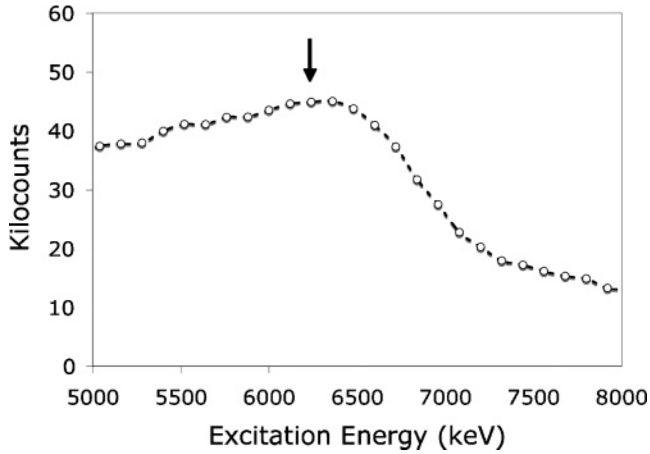

FIG. 1. Number of γ rays in coincidence with the scattered ^{3}He ejectile resulting from the ^{161}Dy(^{3}He, ^{3}He$'$) inelastic-scattering reaction as a function of excitation energy in the compound nucleus, ^{161}Dy*. The neutron separation energy in ^{161}Dy is at 6454.4 keV and the arrow distinguishes the data point identified as being at an excitation energy such that the only open decay channel is γ-ray emission.

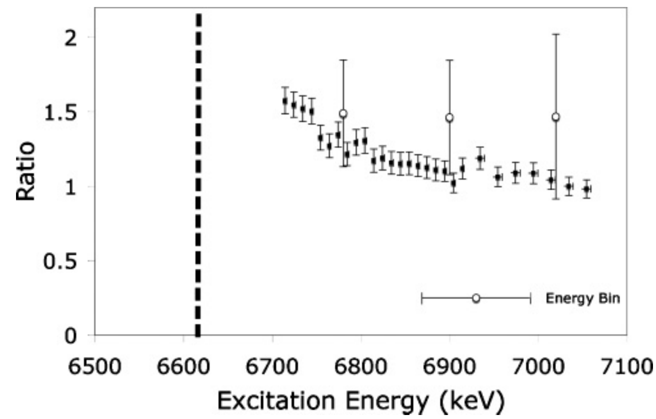

FIG. 3. Dimensionless ratio of the γ-decay probability of ^{171}Yb relative to ^{161}Dy as a function of excitation energy obtained via the (^{3}He, α) reaction on ^{172}Yb and ^{162}Dy, respectively (open circles), and through directly determined cross-section data (filled squares). The dashed line corresponds to zero equivalent neutron energy for $n + {}^{170}$Yb. The error bars represent both the statistical and systematic uncertainty. Note the zero-suppressed abscissa.

the Evaluated Nuclear Data File B-VII (ENDF/B-VII) [19]. The dashed vertical line at the neutron separation energy of the ^{171}Yb compound nucleus corresponds to zero equivalent neutron energy. Data for excitation energies at or below 6734.5 keV were not plotted because the 120-keV energy bin overlaps with negative equivalent neutron energy for $n + {}^{170}$Yb. In both cases, the surrogate data agree with the directly measured values within the total estimated uncertainty over the excitation energy range of 6780 to 7080 keV.

The sources of systematic uncertainty in the surrogate ratio measurement include the energy identified as the normalization point for the γ-decay probability [E_A in Eq. (6)],

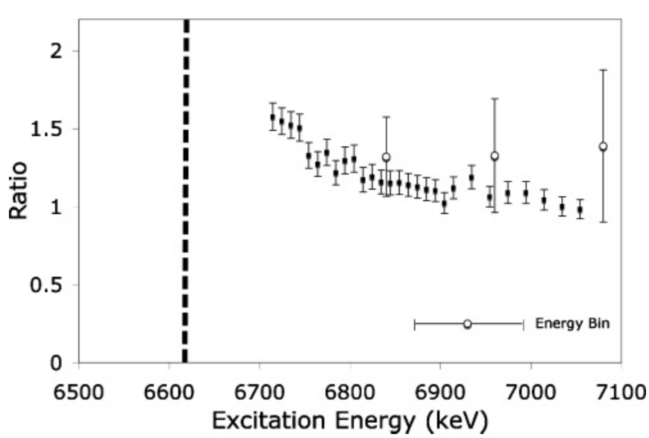

FIG. 2. Dimensionless ratio of the γ-decay probability of ^{171}Yb relative to ^{161}Dy as a function of excitation energy obtained via the (^{3}He, ^{3}He$'$) inelastic-scattering reaction on ^{171}Yb and ^{161}Dy, respectively (open circles), and through directly determined cross-section data (filled squares). The dashed line corresponds to zero equivalent neutron energy for $n + {}^{170}$Yb. The error bars represent both the statistical and systematic uncertainty. Note the zero-suppressed abscissa.

the choice of 1.5 MeV as the lower limit in γ-ray energy, and the contributions to the particle-gamma spectra due to target contaminants. As previously discussed, the systematic uncertainty associated with the choice of E_A was explored via a sensitivity study of the impact of δ on the A parameter and determined to be a 4.0% and 11% effect, for $\beta =$ (^{3}He, ^{3}He$'$) and (^{3}He, α), respectively. To determine the effect of the γ-ray energy gate on the extracted surrogate ratio, the analysis was performed using an ungated γ-ray energy spectrum. An excitation-energy-dependent percentage change of the (^{3}He, ^{3}He$'$) and (^{3}He, α) surrogate ratios was determined, with maxima of 20% and 36%, respectively, over the reported excitation energy range. Isotopic contamination in the target is less than approximately 5% of the total target composition. For both the (^{3}He, ^{3}He$'$) and (^{3}He, α) measurements, the relevant residual nuclei resulting from reactions on contaminants are ^{160}Dy and ^{162}Dy for the desired ^{161}Dy compound nucleus and ^{170}Yb and ^{172}Yb for the desired ^{171}Yb compound nucleus. For the purpose of obtaining a quantitative estimate for the contaminant spectrum, it was assumed that the shape of the particle-gamma count spectrum is the same for a pure target as for the contaminants. To quantify the effect of contaminants on the desired particle-gamma spectra, the count spectrum was shifted in energy to result in a threshold at the neutron binding energy of the relevant contaminant nucleus and scaled using the target composition. To account for a possible enhancement in the (^{3}He, α) direct reaction cross section on the even-odd contaminants, target contamination was scaled to 25% in these cases, representing a conservative estimate. The background-subtracted count spectrum was compared to the raw count spectrum and an excitation-energy-dependent percentage change for the (^{3}He, ^{3}He$'$) and (^{3}He, α) surrogate ratios was determined, with maxima of 29.0% and 6.0%, respectively, over the reported excitation energy range. The maximum systematic uncertainty for the (^{3}He, ^{3}He$'$) and

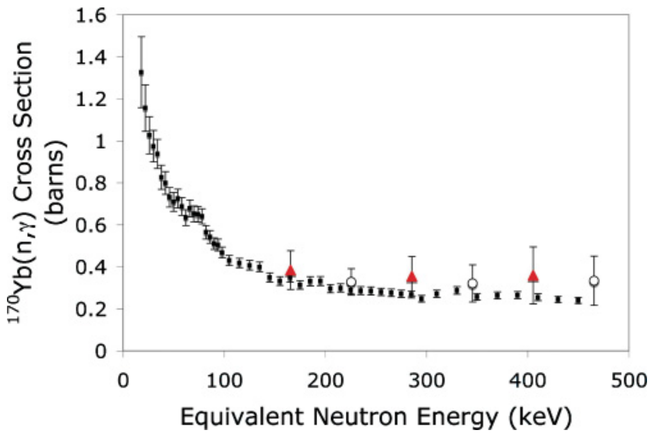

FIG. 4. (Color online) The ^{170}Yb(n,γ) cross section extracted using the SRM relative to the evaluated ^{160}Dy(n,γ) cross section obtained from ENDF/B-VII as a function of equivalent neutron energy obtained via the (^{3}He, ^{3}He$'$) inelastic-scattering reaction (open circles) and the (^{3}He, α) pickup reaction (filled red triangles). The error bars represent both the statistical and systematic uncertainty. For comparison, the directly measured ^{170}Yb(n,γ) cross section from M. V. Bokhovko *et al.* [18] is denoted by filled squares.

(^{3}He, α) surrogate ratios over the excitation energy range of 6780 keV to 7080 keV was 49% and 55%, respectively.

To obtain the ^{170}Yb(n,γ) cross section, the ratio data were multiplied by the ENDF/B-VII ^{160}Dy(n,γ) cross section matched at excitation energy as described in Eq. (13). The result was then shifted into equivalent neutron energy by subtracting the neutron separation energy in the ^{171}Yb compound nucleus from the excitation energy. The surrogate ^{170}Yb(n,γ) cross section obtained using the (^{3}He, ^{3}He$'$) surrogate reaction (open circles) and (^{3}He, α) surrogate reaction (filled red triangles, color online) is shown in Fig. 4. The surrogate data agree within the total estimated uncertainty with the directly measured ^{170}Yb(n,γ) cross-section data from M. V. Bokhovko *et al.* (filled squares) over the equivalent neutron energy range of 165 to 465 keV.

Given that the SRM is predicated on the Weisskopf-Ewing approximation, discrepancies in the surrogate γ-ray production cross section and the directly measured (n,γ) cross section arising from disparities in the compound nuclear angular momentum population distributions are expected at low energies. The type of reaction used in the surrogate entrance channel is expected to modulate the resulting total angular momentum population distributions in the compound nucleus and thus affect the extracted surrogate cross sections. The inelastic-scattering mode [$\beta =$ (^{3}He, ^{3}He$'$)] has a tendency to populate low-lying collective states (such as the ground state rotational band) and compound nuclear resonances, whereas single nucleon pickup processes [$\beta =$ (^{3}He, α)] tend to populate states via particle-hole excitations with a wide range of spins [20].

Because the angular momentum transferred by the particle in the surrogate reaction can couple to the ground-state angular momentum of the target, the target ground-state spin is also expected to affect the angular-momentum population distribution in the compound nucleus. The (^{3}He, ^{3}He$'$) surrogate reaction is performed on even Z, odd N targets of ^{171}Yb and ^{161}Dy with ground-state spin and parity of $1/2^-$ and $5/2^+$, respectively. To study the effect of angular momentum, the same set of compound nuclei were formed via the (^{3}He, α) direct reaction performed on even Z, even N targets with ground-state spin and parity of 0^+. For targets in which the ground-state spin and parity is not equal to 0^+, the angular momentum probability distribution tends to be broadened and shifted toward higher total-angular-momentum values.

Figure 4 shows that in the equivalent neutron energy range from 165 to 465 keV, the surrogate cross section extracted using the (^{3}He, ^{3}He$'$) reaction overlaps within systematic error with the cross section extracted using the (^{3}He, α) reaction, indicating no significant entrance-channel effects. Despite the expected disparities in the compound nuclear angular momentum distributions outlined above, no statistically significant discrepancies exist between the ^{170}Yb(n,γ) cross section extracted using the (^{3}He, ^{3}He$'$) and (^{3}He, α) surrogate reactions and the directly measured cross section. Because the γ-decay probabilities are almost certainly dependent on angular momentum at low energy [21], the success of the SRM in the rare-earth region for equivalent neutron energies as low as 165 keV may not be attributable to the validity of the Weisskopf-Ewing approximation in this region. As noted in the Introduction, use of the SRM tends to lessen the effects of *correlated* errors [22], thus if a deviation from the Weisskopf-Ewing approximation is similar for the two quantities in the ratio, then a partial cancellation of these effects is expected.

V. CONCLUSIONS

We have indirectly measured the ^{170}Yb(n,γ) cross section using the SRM over an equivalent neutron energy range of 165 to 465 keV. The ^{170}Yb(n,γ) cross sections extracted using the (^{3}He, ^{3}He$'$) and (^{3}He, α) surrogate reactions were consistent over the range of equivalent neutron energies probed and agreed with the directly measured cross section within the total estimated uncertainty. Good agreement of the surrogate cross sections with directly measured data suggests that the assumptions of identical reaction channel cross sections in the excitation energy range relevant for the measurement for the two direct reactions and similar statistical γ-ray multiplicities for the two compound nuclei employed in the ratio are borne out. Furthermore, the agreement strongly suggests that any residual dependence of the γ-decay probabilities on angular momentum are at least partially canceled in the surrogate ratio analysis. The results presented here represent an extension of the SRM beyond actinide nuclei to a lower-mass region and suggest promising use of the SRM to extract (n,γ) cross sections on radioactive nuclei in the rare-earth region.

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[1] J. D. Cramer and H. C. Britt, Nucl. Sci. Eng. **41**, 177 (1970).
[2] S. Boyer, D. Dassie, J. N. Wilson, M. Aiche, G. Barreau, S. Czajkowski, C. Grosjean, A. Guiral, B. Haas, B. Osmanov *et al*., Nucl. Phys. **A775**, 175 (2006).
[3] W. Younes and H. C. Britt, Phys. Rev. C **67**, 024610 (2003).
[4] W. Younes and H. C. Britt, Phys. Rev. C **68**, 034610 (2003).
[5] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).
[6] B. F. Lyles, L. A. Bernstein, J. T. Burke, F. S. Dietrich, J. Escher, I. Thompson, D. L. Bleuel, R. M. Clark, P. Fallon, J. Gibelin *et al*., Phys. Rev. C **76**, 014606 (2007).
[7] J. T. Burke, L. A. Bernstein, J. Escher, L. Ahle, J. A. Church, F. S. Dietrich, K. J. Moody, E. B. Norman, L. Phair, P. Fallon *et al*., Phys. Rev. C **73**, 054604 (2006).
[8] C. Plettner, H. Ai, C. W. Beausang, L. A. Bernstein, L. Ahle, H. Amro, M. Babilon, J. T. Burke, J. A. Caggiano, R. F. Casten *et al*., Phys. Rev. C **71**, 051602(R) (2005).
[9] V. M. Maslov, Phys. Rev. C **72**, 044607 (2005).
[10] C. W. Beausang, S. R. Lesher, J. T. Burke, L. A. Bernstein, L. Phair, H. Ai, G. Gurdal, L. Ahle, D. S. Brenner, M. Carpenter *et al*., Acta Phys. Pol. B **38**, 1535 (2007).
[11] R. Chankova, A. Schiller, U. Agvaanluvsan, E. Algin, L. A. Bernstein, M. Guttormsen, F. Ingebretsen, T. Lönnroth, S. Messelt, G. E. Mitchell, J. Rekstad, S. Siem, A. C. Larsen, A. Voinov, and S. Ødegård, Phys. Rev. C **73**, 034311 (2006).
[12] M. Guttormsen, A. Bagheri, R. Chankova, J. Rekstad, S. Siem, A. Schiller, and A. Voinov, Phys. Rev. C **68**, 064306 (2003).
[13] U. Agvaanluvsan, A. Schiller, J. A. Becker, L. A. Bernstein, P. E. Garrett, M. Guttormsen, G. E. Mitchell, J. Rekstad, S. Siem, A. Voinov, and W. Younes, Phys. Rev. C **70**, 054611 (2004).
[14] A. Schiller, A. Bjerve, M. Guttormsen, M. Hjorth-Jensen, F. Ingebretsen, E. Melby, S. Messelt, J. Rekstad, S. Siem, and S. W. Ødegård, Phys. Rev. C **63**, 021306(R) (2001).
[15] M. Guttormsen, A. Atac, G. Løvhøiden, S. Messelt, T. Ramsøy, J. Rekstad, T. F. Thorsteinsen, T. S. Tveter, and Z. Zelazny, Phys. Scr. **T32**, 54 (1990).
[16] L. Henden, L. Bergholt, M. Guttormsen, J. Rekstad, and T. S. Tveter, Nucl. Phys. **A589**, 249 (1995).
[17] A. Schiller, L. Bergholt, M. Guttormsen, E. Melby, J. Rekstad, and S. Siem, Nucl. Instrum. Methods Phys. Res. A **447**, 498 (2000).
[18] M. V. Bokhovko, V. N. Kononov, N. S. Rabotnov, A. A. Voevodskiy, G. N. Manturov, and V. M. Timokhov (private communication, 1996). Data retrieved from the CSISRS database, file EXFOR 41225.
[19] M. B. Chadwick, P. Oblozinsky, M. Herman, N. M. Greene, R. D. McKnight, D. L. Smith, P. G. Young, R. E. MacFarlane, G. M. Hale, S. C. Frankle *et al*., Nucl. Data Sheets **107**, 2931 (2006).
[20] G. R. Satchler, *Direct Nuclear Reactions* (Oxford University Press, New York, 1983).
[21] J. Escher and F. S. Dietrich, Lawrence Livermore National Laboratory Technical Report No. UCRL-TR-212509-DRAFT, Lawrence Livermore National Laboratory, Livermore, CA, 2005 (unpublished).
[22] J. E. Escher and F. S. Dietrich, Phys. Rev. C **74**, 054601 (2006).