Study of the surrogate-reaction method applied to neutron-induced capture cross sections

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Gamma-decay probabilities of $^{173}$Yb and $^{176}$Lu have been measured using the surrogate reactions $^{174}$Yb$(^3$He,$^3$He$\gamma$)$^{173}$Yb$^*$ and $^{174}$Yb$(^3$He,$p\gamma$)$^{176}$Lu$^*$, respectively. For the first time, the gamma-decay probabilities have been obtained with two independent experimental methods based on the use of C$_6$D$_6$ scintillators and Germanium detectors. Our results for the radiator-capture cross sections are several times higher than the corresponding neutron-induced data. To explain these differences, we have used our gamma-decay probabilities to extract rather direct information on the spin distributions populated in the transfer reactions used. They are about two times wider and the mean values are 3 to 4 h higher than the ones populated in the neutron-induced reactions. As a consequence, in the transfer reactions neutron emission to the ground and first excited states of the residual nucleus is strongly suppressed and gamma-decay is considerably enhanced.

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1. Introduction

Neutron-induced radiative-capture cross sections of short-lived nuclei are crucial for fundamental nuclear physics and also for applications such as reactor physics and astrophysics. In particular, these data are important for nuclear-waste transmutation using fast neutrons and for understanding element nucleosynthesis related to the s- and r-processes. However, very often the high radioactivity of the samples makes the direct measurement of these cross sections extremely difficult. The surrogate-reaction method is an indirect way of determining cross sections for compound-nucleus reactions. This method was first proposed by J.D. Cramer and H.C. Britt [1] in the seventies and is schematically represented in Fig. 1. The left part of Fig. 1 illustrates a neutron-induced reaction on target A – 1, which leads to the nucleus $A^*$ at an excitation energy $E^*$. The nucleus $A^*$ can decay through different exit channels: fission, gamma-decay, neutron emission, etc. On the right part of Fig. 1, in the surrogate-reaction method, the same compound nucleus $A^*$ is produced by a transfer reaction between a projectile $Y$ (a light nucleus) and a target X. The transfer reaction $(Y + X \rightarrow A + W)$ leads to the heavy recoil nucleus $A^*$ and an ejectile $W$. The identification of the ejectile permits to determine the mass $A$ and charge $Z$ of the decaying nucleus. In addition, we can deduce the excitation energy $E^*$ of the nucleus $A$ by measuring the kinetic energy and the emission angle of the ejectile. The measurement of the number of coincidences between the ejectiles and the decay products normalized to the total number of detected ejectiles allows one to extract the decay probability $P_{\text{decay}}^{A\text{exp}}$ for the corresponding decay channel. According to the surrogate-reaction method, the neutron-induced cross section for the nucleus $A – 1$ is then given by the equation:

$$\sigma_{\text{decay}}^{A-1}(E_n) \cong \sigma_{\text{CN}}^{A}(E_n) \cdot P_{\text{decay}}^{A\text{exp}}(E^*)$$ (1)
where \( \sigma_{\text{CN}} \) is the calculated compound-nucleus formation cross section in the desired reaction (formation of the compound nucleus \( A \) after absorption of a neutron with energy \( E_n \)), it is usually obtained using an optical model. The relation between incident neutron energy \( E_n \) and excitation energy \( E^* \) of the compound nucleus \( A \) can be written as:

\[
E^* = S_n + E_n \cdot \frac{A-1}{A}
\]

(2)

where \( S_n \) is the one-neutron separation energy in the nucleus \( A \). The benefit of the surrogate method is that in some cases the target is stable or less radioactive than the target \( A-1 \). Therefore, the surrogate-reaction method may enable cross sections to be extracted for nuclear reactions on short-lived nuclei that otherwise cannot be measured.

Eq. (1) is based on the hypothesis that the excited nucleus is a compound nucleus whose decay is independent of the formation. In the region of excitation energy close to \( S_n \) (\( \approx 6-8 \) MeV in the rare-earth and actinide regions), this hypothesis is reasonable due to the high degree of configuration mixing that appears at a high nuclear level density. In addition, a significant uncertainty in the use of the surrogate-reaction method lies in the spin \( J \) and parity \( \pi \) population differences between the compound-nuclei produced in the neutron- and transfer-induced reactions. Since the decay probability strongly depends on \( J \) and \( \pi \), the spin–parity mismatch can lead to important deviations between the neutron-induced results and the ones obtained with the surrogate method [4]. Assuming that the nucleus \( A^* \) is in a compound state, the decay probabilities are given by:

\[
P_{\text{n}}^{\text{decay}}(E^*) = \sum_{J^\pi} F_n(E^*, J^\pi) \cdot G_{\text{decay}}(E^*, J^\pi),
\]

(3)

\[
P_{\text{t}}^{\text{decay}}(E^*) = \sum_{J^\pi} F_t(E^*, J^\pi) \cdot G_{\text{decay}}(E^*, J^\pi)
\]

(4)

where the indices \( n \) and \( t \) stand for neutron and transfer reactions, respectively. \( F_n(E^*, J^\pi) \) and \( F_t(E^*, J^\pi) \) correspond to the probabilities that the compound nucleus is formed in the state \( J^\pi \) by the neutron-induced and the transfer reaction, respectively. \( G_{\text{decay}}(E^*, J^\pi) \) is the decay probability for a given compound nucleus state \( J^\pi \). The two decay probabilities \( p_{\text{decay}} \) of Eqs. (3) and (4) are similar in two limiting cases:

1) The \( J^\pi \) distributions populated in both reactions are similar:

\[
F_n(E^*, J^\pi) \approx F_t(E^*, J^\pi).
\]

(5)

Unfortunately, the theoretical determination of the angular momentum and the parity populated in transfer reactions represents a big challenge. As discussed in a very recent review on the surrogate method [5], new theory development is needed to describe the formation of an excited nucleus in an unbound state by a direct reaction and its damping to a compound state. This requires detailed information on the target structure and rather complex reaction models that describe the interaction between the different reaction constituents. A focussed effort involving theoreticians and experimentalists should be performed to determine these distributions. We will see below how the present work can provide valuable information on this issue.

2) The decay probabilities \( G_{\text{decay}}(E^*, J^\pi) \) are independent of \( J^\pi \):

\[
G_{\text{decay}}(E^*, J^\pi) = G_{\text{decay}}(E^*).
\]

(6)

The quantities \( G_{\text{decay}}(E^*) \) can be then taken out of the summation signs in Eqs. (3) and (4) and since \( \sum_{J^\pi} F_n(E^*, J^\pi) = 1 \),

\[
P_{n}^{\text{decay}}(E^*) \approx p_1^{\text{decay}}(E^*)
\]

and the cross section for the desired reaction takes on the simple product form of Eq. (1). This second hypothesis is known as the Weisskopf–Ewing approximation [6] and is justified for high excitation energies where the decay of the compound nucleus is dominated by statistical level densities. At lower excitation energies, the decay probabilities strongly depend on the \( J^\pi \) of discrete states, whose population depends on the reaction mechanism used to produce the compound nucleus \( A^* \).

In Ref. [7], we showed that our results for the fission cross sections of \( ^{242,243}\text{Cm} \) and \( ^{244}\text{Am} \) obtained with the surrogate method are in very good agreement with the corresponding neutron-induced data at low excitation energies. However, in a recent experiment [8] the radiative-capture cross sections obtained using the reactions \( ^{156,158}\text{Gd}(p, p') \) are up to a factor 4 higher than the corresponding \( ^{155}\text{Gd}(n, \gamma) \) and \( ^{157}\text{Gd}(n, \gamma) \) cross sections. These important discrepancies have been attributed to the spin–parity mismatch. To understand such large deviations, one should also take into account that radiative-capture cross sections are expected to decrease very rapidly with energy. In the energy region where the gamma-decay probability represents only a few percent of the total decay, any absolute variation of a few percent of the gamma-decay probability due to the spin–parity mismatch results in a large relative change. The objective of this work is to further investigate to which extent the surrogate method can be applied to infer neutron-induced capture cross sections. In the case of actinides, one may need to distinguish between gamma rays originating from the fission fragments and the radiative-decay gamma rays. This can make radiative-decay measurements extremely complicated and more difficult to interpret. Therefore, as a first step, we have chosen to investigate radiative-capture reactions on deformed rare-earth nuclei. In particular, our aim is to study the transfer reactions \( ^{174}\text{Yb}(^3\text{He},^4\text{He})^{173}\text{Yb} \) and \( ^{174}\text{Yb}(^3\text{He},\gamma)^{176}\text{Yb} \) as surrogates for the \( ^{172}\text{Yb}(n, \gamma) \) and \( ^{176}\text{Lu}(n, \gamma) \) reactions, respectively. We have considered the \( ^{172}\text{Yb}(n, \gamma) \) and \( ^{176}\text{Lu}(n, \gamma) \) cross sections because they present the advantage to be very well known, see for example [9–12].

2. Experiment

The measurement was performed at the Tandem accelerator of the IPN Orsay. We used an incident \(^3\text{He}\) beam with an energy of 24 MeV. The beam intensity was 10 pA. The stable \(^{174}\text{Yb}\) target was fabricated at the SIDONIE facility of the CNSM laboratory. The \(^{174}\text{Yb}\) sample had a thickness of 250 µg/cm\(^2\) and was deposited onto a natural C foil with a thickness of 40 µg/cm\(^2\). Fig. 2 illustrates schematically our experimental set up. To infer the gamma-decay probability, gamma rays were detected in coincidence with the ejectiles. The latter were fully identified by two large-area \( \Delta E-E \) telescopes placed symmetrically at 130° with respect to the \(^3\text{He}\) beam. The \( \Delta E \) detectors were two 300 µm thick double-sided silicon strip detectors with an active area of 50 × 50 mm\(^2\), whose
The use of C6D6 liquid scintillators has the important advantage with one of the C6D6 detectors, an angular coverage ranging from 108° to 152°. We shielded these detectors from delta electrons coming from the target with a thin Mylar(Al) foil biased to −300 V. The E detectors were two Si(Li) detectors of 3 mm thickness. Four C6D6 liquid scintillators were used for counting gamma rays with energies up to 10 MeV. The C6D6 detectors were placed symmetrically with respect to the beam line at an angle of 45° to the horizontal beam-line plane. The use of C6D6 liquid scintillators has the important advantage that the coupling of these detectors to a pulse-shape discriminator allows one to distinguish between photons and neutrons interacting within the scintillators.

The 3He-induced transfer reactions on the 174Yb target lead to the production of various heavy residues. As mentioned before, here we consider only the (3He,p) and (3He,4He) channels. The experimental gamma-decay probability \( P_\gamma(E^*) \) can be obtained in the following way:

\[
P_\gamma(E^*) = \frac{N_{\text{coinc}}(E^*)}{N_{\text{singles}}(E^*) \cdot \varepsilon(E^*)}
\]

where \( N_{\text{coinc}}(E^*) \) is the number of ejectiles detected in coincidence with one of the C6D6 detectors, \( N_{\text{singles}}(E^*) \) the total number of ejectiles, i.e., the total number of decaying nuclei formed, and \( \varepsilon(E^*) \) represents the gamma-cascade detection efficiency. The identification of the ejectiles and the determination of their energy and scattering angle were achieved using the Si telescopes. With this information and the associated Q-values, the excitation energy \( E^* \) of the corresponding decaying nuclei was obtained. The left panel of Fig. 3 illustrates the identification achieved in one of the telescopes through the conventional energy-loss vs. residual-energy plot. By selecting one type of light particle, for example alphas, the spectrum represented by the solid line on the right of Fig. 3, the so-called “singles” spectrum \( N_{\text{singles}}(E^*) \), is obtained. It represents the number of alphas, i.e., the number of 173Yb nuclei, as a function of their excitation energy. By selecting the alphas detected in coincidence with a gamma event in one of the C6D6 detectors, the spectrum associated with the number of 173Yb that have undergone gamma-emission, \( N_{\text{coinc}}(E^*) \), is obtained (see dashed line in the right panel of Fig. 3). The coincidence spectrum first increases with \( E^* \) and then shows a steep decrease at \( E^* = S_n \) indicating a drastic reduction of gamma decay due to the competition with neutron emission. The \( S_n \)-values found experimentally are in good agreement with the tabulated values for all the compound nuclei investigated. \( N_{\text{coinc}} \) contains also the \((n\gamma)\) contribution, i.e. the gamma rays emitted after neutron emission by the residual nucleus 172Yb. For the \( E^* \) region of interest in this work (from \( S_n \) to \( S_n + 1 \) MeV), these events have been removed from \( N_{\text{coinc}} \) by applying a threshold to the detected gamma energy in the C6D6 detectors that ranges from 200 to 400 keV. This threshold does not totally suppress the \((n\gamma)\) contribution at higher \( E^* \), as illustrated by the increase of the \( N_{\text{coinc}} \) spectrum. Note that for the \((3\text{He},p)\) transfer channel, the \( N_{\text{singles}}(E^*) \) and \( N_{\text{coinc}}(E^*) \) spectra had to be slightly corrected for the ejectiles coming from transfer reactions between the \(^3\text{He} \) beam and the carbon backing.

To determine the gamma-cascade detection efficiency in this work we have developed a new method that is thoroughly discussed in Refs. [13,15]. Here we will only present the main conclusions. Since the compound nuclei are formed by a transfer reaction, it is possible to extend our investigation below the neutron separation energy \( S_n \) where only gamma rays can be emitted and consequently the measured gamma-decay probability should be 1. Therefore, below \( S_n \) the ratio \( N_{\text{coinc}}(E^*)/N_{\text{singles}}(E^*) \) gives the total efficiency of the C6D6 detectors for detecting a gamma cascade. Our data show that this ratio remains essentially constant from \( E^* = S_n - 1 \) MeV to \( S_n \). Since there is no physical reason for a sudden change of efficiency above \( S_n \), we have assumed

![Fig. 2](image-url) (Color online.) Schematic representation of the experimental set-up for gamma-decay probability measurements. The four C6D6 liquid scintillators were placed at forward angles with respect to the beam direction, whereas the two Si telescopes and the six germanium detectors were placed at backward angles. More details are given in [13,14].

16 x 16 X-Y strips provided the angle of the detected particle with an angular coverage ranging from 108° to 152°. We shielded these detectors from delta electrons coming from the target with a thin Mylar(Al) foil biased to −300 V. The E detectors were two Si(Li) detectors of 3 mm thickness. Four C6D6 liquid scintillators were used for counting gamma rays with energies up to 10 MeV. The C6D6 detectors were placed symmetrically with respect to the beam line at an angle of 45° to the horizontal beam-line plane. The use of C6D6 liquid scintillators has the important advantage that the coupling of these detectors to a pulse-shape discriminator allows one to distinguish between photons and neutrons interacting within the scintillators.

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![Fig. 3](image-url) (Color online.) Left: Energy loss \( \Delta E \) versus residual energy \( E \) in one of the telescopes at 130°. Right: Number of alphas (in coincidence or not with gammas in one of the C6D6 scintillators) as a function of the 173Yb excitation energy.
the same efficiency also from $E^* = S_n$ to $S_n + 1$ MeV. The constancy of the efficiency is confirmed by TALYS calculations [16] that show that the multiplicity of the gamma cascade and the average gamma energy vary only very weakly in the continuum region right above $S_n$. In addition, the independence of the gamma-cascade detection efficiency from the excitation energy and its absolute value have been confirmed by using the total-energy detection principle in combination with the pulse-height weighting technique [17,18]. Once the detection efficiency is determined, we apply Eq. (7) to determine the gamma-decay probability of the desired excited nucleus as a function of its $E^*$.

The $^{174}$Yb target was also surrounded by six high-volume (70% efficiency) high-purity germanium detectors (see Fig. 2). They were located symmetrically at $70^\circ$ degrees with respect to the beam line. In a similar way as was done in [8], they were used to determine the gamma-decay probability by measuring low-lying $\gamma$-ray transition intensities associated with the decaying nucleus of interest as a function of the excitation energy. We determined the ratio between several selected transition intensities of $^{173}$Yb and $^{176}$Lu and the corresponding number of detected ejectiles in $E^*$ steps of 200 keV. The gamma-decay probability was obtained by normalizing this ratio to the value of the ratio below $S_n$. Additional details are given in [13] and in a further publication [14].

3. Neutron-induced capture cross sections

We have used Eq. (1) to determine the neutron-induced capture cross sections of $^{172}$Yb and $^{175}$Lu. We have considered the gamma-decay probabilities obtained with the C$_6$D$_6$ detectors and the compound-nucleus formation cross sections calculated with the phenomenological optical model from TALYS [16]. Our results are compared with existing neutron-induced data, with the available evaluations [19–21] and TALYS calculations [16] in Fig. 4. Our surrogate data present large discrepancies (by a factor 10 at the lowest energies for $^{172}$Yb and by a factor 3 to 4 for $^{175}$Lu) with respect to the neutron-induced data. In the next two sections we use the measured gamma-decay probabilities to investigate the origin of these discrepancies.

4. Study of the $^{174}$Yb($^3$He,$^4$He) $^{173}$Yb$^*$ reaction

In Fig. 5, the gamma-decay probabilities of $^{173}$Yb obtained using the C$_6$D$_6$ and the Germanium detectors are shown. Good agreement was found between the two methods. This shows that there is no contaminant issue or severe systematic error in the experiment and that the ($n\gamma$) channel has been well subtracted in the C$_6$D$_6$ analysis. These results are compared with the TALYS calculation for the neutron-induced capture probability of $^{173}$Yb. The parameters of the TALYS code have been tuned to closely reproduce the experimental data for the $^{172}$Yb($n,\gamma$) cross sections, see Fig. 4. In Fig. 5, the neutron-induced capture probability shows clear changes of slope at $S_n$ and at an energy that corresponds to the first excited state of $^{172}$Yb. They indicate the reduction of the gamma-decay probability caused by the onset of neutron emission leaving the residual nucleus $^{172}$Yb in the ground state and in the first excited state. These changes in slope can also be observed at similar energies for the $^{174}$Yb($^3$He,$^4$He)$^{173}$Yb reaction although in this case the changes due to higher excited states are also observed. Note that the excitation-energy resolution for these data is 80 keV.

Fig. 6 shows TALYS calculations for the gamma-decay probabilities for various spin/parity states as a function of the excitation energy of $^{173}$Yb. The sensitivity of gamma-decay probabilities $G_{\gamma}(E^*,J^\pi)$ to the $J^\pi$ of the decaying compound state is clearly illustrated. Due to the low level density in the residual even–even nucleus $^{172}$Yb below the pairing gap, the onset of the neutron
Decay to each state corresponds clearly to a break of slope. The drop at $S_{\pi}$ corresponds to the opening of neutron emission to the ground state of $^{172}$Yb that is only observed for spin values close to $1/2 \hbar$ and is particularly strong for positive parity. Also neutron emission to the first excited states is considerably hindered for spins higher than $3/2 \hbar$. Due to the high spin selectivity of neutron decay, the gamma-decay probabilities are strongly influenced by the structure of the low-lying states of the residual nucleus after neutron emission. In view of the high sensitivity of gamma decay to $J^\pi$, we investigated a method to extract rather direct information on the populated $J^\pi$ distribution from a fit to the experimental decay probability using the gamma-decay probabilities $G_{\gamma}(E^*, J^\pi)$ calculated by TALYS.

According to Eq. (4), the experimental gamma-decay probability $P_{\gamma}(E^*)$ can be written as:

$$P_{\gamma}(E^*) = \sum_{J^\pi} \left[ \frac{1}{2\pi \sqrt{2}} e^{-\frac{(J^\pi - \bar{J^\pi})^2}{2\sigma^2}} \right] \cdot G_{\gamma}(E^*, J^\pi)$$

(8)

where the unknown angular momentum distribution $F_{\pi}(J^\pi)$ has been approximated by a Gaussian distribution without dependence on the excitation energy. The two parities are assumed to be equally populated. The two unknown parameters $\bar{J}$ and $\sigma$ correspond to the average value and the standard deviation of the spin distribution, respectively. These quantities are obtained by fitting the experimental gamma-decay probability with Eq. (8) using the calculated $G_{\gamma}(E^*, J^\pi)$ of Fig. 6. The result of the fit is shown in Fig. 7 and the corresponding spin distribution is compared with the neutron-induced spin distributions obtained with TALYS in Fig. 8. Since there are enough data on the $n + ^{172}$Yb and $n + ^{175}$Lu reactions to accurately determine the parameters of the phenomenological optical-model potentials used in TALYS, the calculated neutron-induced spin distributions shown in this and next section are highly reliable. The width of the surrogate spin distribution is about two times larger and the mean value is between 2.5 and $4 \hbar$ higher than for the neutron-induced spin distributions. We would like to stress that we also investigated a more realistic approach to extract the spin distributions that does not assume equal probability for positive and negative parities. We followed the fairly simple statistical assumptions used by B. Back [22] and W. Younes [23]. This approach confirms the former spin distribution. Thus, the angular momentum induced by the $^3$He,$^4$He transfer reaction will most probably be higher than the angular momentum of the ground state and first excited states of $^{172}$Yb.

Fig. 6. (Color online.) TALYS gamma-decay probabilities $G_{\gamma}(E^*, J^\pi)$ of $^{173}$Yb for negative and positive parities. The excitation energies shown correspond to incident neutron energies from 0 to about 15 MeV.

Since at low $E^*$ the average orbital angular momentum carried by the emitted neutron is in general quite low (around $1 \hbar$), this leads to a strong suppression of neutron emission to the low lying states of the residual nucleus $^{172}$Yb. In conclusion, the differences in the populated spins and parities, and the high spin/parity selectivity of the neutron-decay channel are most likely at the origin of the large discrepancies observed between our surrogate measurement and the neutron-induced data.

5. Study of the $^{174}$Yb($^3$He,p)$^{176}$Lu* reaction

The results for the gamma-decay probability associated to the $^{174}$Yb($^3$He,p)$^{176}$Lu reaction are shown in Fig. 9. The data are compared with the TALYS calculation for the neutron-induced radiative capture probability. As before, the parameters of the code have been fixed to reproduce the existing neutron-induced data (Fig. 4). The spin distribution obtained with the fit procedure described in the previous section is defined by an average spin of $\bar{J} = 7.1 \pm 0.05 \hbar$ and a standard deviation of $\sigma = 2.3 \pm 0.1 \hbar$, and is presented in Fig. 8. The surrogate spin distribution is shifted to higher values of spin by $3 \hbar$ and is significantly larger than the neutron-induced spin distributions. As discussed in the previous section,
the strong spin selectivity of neutron emission and the spin–parity mismatch mainly explain the large discrepancies found.

6. Discussion

This work provides valuable information on the angular momentum transferred in the studied transfer reactions. Very recently, the authors of Ref. [24] have proposed several experimental quantities to infer the spin distribution in surrogate reactions such as the evaporated neutron energy spectrum and gamma-ray energy spectrum or the fission-fragment mass distributions. However, our work shows that the determination of the gamma-decay probability in absolute surrogate experiments is probably the most sensitive observable and the most direct way to extract experimental information on the populated spin–parity distribution. The sensitivity of the gamma-decay probability to $J^\pi$ decreases as the number of states in the residual nucleus after neutron emission increases. For this reason, one expects a better agreement between neutron-induced and surrogate data for actinides [5]. Interestingly, the present work helped us to reinterpret the good agreement found at low $E^*$ for fission in Ref. [7]. Assuming that the transferred angular momenta do not depend too much on the mass of the target nuclei, we may also expect a difference of few $\hbar$ between the spins populated in the transfer reactions used in Ref. [7] and the corresponding neutron-induced reactions. However, in this case the level densities after neutron emission and on top of the fission barrier are high enough to considerably attenuate the effect of such spin differences even near the fission threshold.

7. Conclusion and perspectives

We have performed an experiment to study the validity of the surrogate method for extracting neutron-induced capture probabilities. We have used the well known $^{172}\text{Yb}(n,\gamma)$ and $^{172}\text{Lu}(n,\gamma)$ cross sections to study the $^{174}\text{Yb}(^3\text{He},^4\text{He}\gamma)$ and $^{174}\text{Yb}(^3\text{He},p\gamma)^{176}\text{Lu}$ surrogate reactions. For the first time, the gamma-decay probabilities have been obtained using CdD$_6$ and Ge detectors in the same experiment. The results obtained with these two different methods are in good agreement, demonstrating the quality of our results. Our surrogate data present large discrepancies with respect to the neutron-induced data. Since the gamma-decay probabilities are very sensitive to $J^\pi$, we have extracted rather direct information on the populated angular-momentum distributions from a fit to the experimental decay probability using the gamma-decay probabilities for a given spin/parity state $G_\gamma(E^*, J^\pi)$ calculated by TALYS. The spin distributions obtained for the transfer reactions investigated in this work are about two times wider and the average spins are 3 to 4 $\hbar$ higher than in the neutron-induced reactions. Right above Sn, neutron emission to the ground state and to the first excited states of the residual nucleus is the dominant way of deexcitation for a neutron-induced reaction, whereas in the transfer reactions used, gamma-decay is favored because of the strong hindrance of the neutron-decay channel. For the nuclei we have considered, the Weisskopf–Ewing approximation cannot be applied at low neutron energies. We believe that an important effort involving theoreticians and experimentalists needs to be performed to determine the angular-momentum distributions populated in the surrogate reactions. A crucial point to be investigated is to which extent the obtained angular-momentum distribution can be extrapolated to heavier target nuclei (e.g. actinides). More precisely, one needs to study the influence of the single-particle structure of the target nucleus on the angular-momentum distribution populated in a surrogate reaction. If progress is made on this issue, we could use decay probabilities measured with the surrogate method together with experimental or theoretical spin distributions to fix key parameters of the statistical model. The latter can then be used in combination with the optical model to provide reliable predictions of neutron-induced cross sections for unstable nuclei that cannot be directly measured. In this sense, the surrogate method in combination with radioactive ion beams (RIB) can help explore regions of
the chart of nuclei that cannot be studied with surrogate reactions using direct kinematics. Very interesting opportunities for surrogate studies in inverse kinematics open up with new RIB facilities such as HIE-ISOLDE or SPIRAL2. In the long term, unprecedented surrogate experiments on fission will become possible thanks to the ELISE e⁻-ion collider at FAIR [25]. The fissioning nucleus will be fully characterized in \((A, Z, E^*, J)\) and a complete set of fission observables will be precisely measured as a function of \(E^*\).

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