Investigation of Weisskopf-Ewing approximation for the determination of (*n*, *p*) cross sections using the surrogate reaction technique

Aman Sharma,* A. Gandhi, and A. Kumar†
Department of Physics, Banaras Hindu University, Varanasi 221005, India

(Received 19 June 2021; accepted 18 January 2022; published 25 January 2022)

The present study explores the limitations of the surrogate reaction method for determining the (n, p) cross sections for the target nuclei in the mass region $A \approx 50$ for the neutron energies 1–20 MeV. In the past few years there have been several experimental attempts for determining the (n, p) and (n, xp) cross sections using the surrogate reaction method. But this method has not been benchmarked with the experimentally well-known (n, p) cross sections. The surrogate reaction method with Weisskopf-Ewing approximation may help in providing good constraints for the cross-section data, but this approximation has not been validated yet for (n, p) reactions. In this paper, we have examined the validity of the Weisskopf-Ewing approximation for the (n, p) reactions and also check the sensitivity of the surrogate reaction results with respect to the compound nucleus spin distribution. We have simulated the cross sections obtained through the surrogate reaction method for $n + {}^{48}$Ti, $n + {}^{53}$Cr, $n + {}^{56}$Fe, and $n + {}^{59}$Co reactions for the different schematic spin distributions of the compound nucleus and studied the effect of assuming the validity of the Weisskopf-Ewing approximation. It has been observed that the proton decay probabilities of the compound nucleus for the (n, p) channel are strongly spin dependent, therefore the Weisskopf-Ewing approximation is violated. We have also observed that the cross sections obtained using the Weisskopf-Ewing approximation show clear dependence on the spin distribution of the compound nucleus. It has also been observed that, due to the large pre-equilibrium contributions in the (n, p) reactions at higher neutron energies, the use of the surrogate reaction method for the neutron energies greater than ≈15 MeV may not be suitable. It is concluded that the surrogate reaction method relying solely on the Weisskopf-Ewing approximation is not sufficient for determining the (n, p) cross sections for the target nuclei in mass range $A \approx 50$ and further development and exploration of the surrogate technique is required.

DOI: 10.1103/PhysRevC.105.014624

I. INTRODUCTION

Reaction cross sections of the neutron-induced reactions for a large number of stable as well as unstable nuclei over a wide range of energy are highly important in different applications. Accurate measurement and determination of these cross sections has been of great importance since the discovery of neutron-induced nuclear reactions. When a neutron is incident on a nucleus, different decay channels [e.g., (n, p), (n, γ), (n, α)] can open up depending on the neutron's energy. Cross sections of these exit channels are necessary for the development of the future nuclear technologies. Accurate measurement of the cross sections is a difficult task and it further imposes many challenges whenever cross sections of a short-lived nucleus has to be measured because the process of the target acquisition and preparation becomes very difficult due to the short half-life of the target. Direct methods which involves incident neutrons and the stable target combinations are generally used for the cross-section measurements but, in case of the short-lived nuclei, indirect approaches have to be used for determining or constraining the cross sections, which involves performing experiments as well as reaction model calculations. Different indirect techniques have been developed over the time, e.g., the surrogate reaction method, the Trojan Horse method, Coulomb dissociation, asymptotic normalization coefficient, and Oslo and β-Oslo methods [1–7]. In the present study we have focused on the surrogate reaction method and this study is motivated by the recent attempts to measure the (n, p) and (n, xp) cross sections using the surrogate reaction method [8–10]. In these studies the surrogate ratio method has been used to extract the (n, p) and (n, xp) cross sections. As pointed out in these studies, (n, p) cross sections for neutron energies around 14 MeV for the short-lived nuclei produced by the activation of structural material of the upcoming fusion reactors are important because (n, p) and (n, xp) reactions are the primary cause of the hydrogen production in the structural materials which can deteriorate their mechanical and structural properties over time [8]. Also, (n, p) cross sections are important in determining the astrophysical reaction rates to be used in the stellar nucleosynthesis studies [11]. Although some surrogate ratio measurements have been performed to measure (n, p) [8] and (n, xp) [9,10] cross sections for a few short-lived nuclei, but the surrogate method has never been bench-marked by measuring well-known (n, p) cross sections using the surrogate reaction method. The surrogate reaction method has

*aman.marley1314@gmail.com
†ajaytyagi@bhu.ac.in

been successfully used in the past for determining the (n, f) cross sections at fast neutron energies for various short-lived nuclei [12–15]. Although this technique was originally developed in 1970s [1], there has been a renewed interest in this method for the last two decades. A number of experimental and theoretical studies have been carried out to explore the use of the surrogate reaction method for determining the cross sections of various decay channels, e.g., (n, f), (n, γ), (n, p), (n, xp), (p, f), and $(n, 2n)$ [8–10,12,13,16–36]. The surrogate reaction method assumes that the reaction takes place through the compound nucleus mechanism only, but at high projectile energies pre-equilibrium and direct reaction mechanisms also compete with the compound nucleus mechanisms. Also, approximations like the Weisskopf-Ewing approximation and the surrogate ratio approximation are generally used to simplify the application of surrogate method. But it has been observed that Weisskopf-Ewing approximation does not always provide the cross sections with desirable accuracy [32,33], and it depends on the reaction type and the energy region of interest. Therefore, it becomes crucial to study the validity of the above-mentioned assumptions and approximations before using Weisskopf-Ewing approximation for a particular exit channel and energy range [35]. Different studies regarding the validity of the Weisskopf-Ewing approximation for (n, f), (n, γ), (n, n'), and $(n, 2n)$ reactions are well documented [32–34], but there has not been any study about the validity of the Weisskopf-Ewing approximation for (n, p) reactions. In the present study, we have tried to address this problem by studying the Weisskopf-Ewing approximation in the context of (n, p) reaction cross-section determination by using the surrogate reaction method. The objective of the present study is to check the validity of Weisskopf-Ewing approximation for (n, p) reactions for the target nuclei in mass region $A \approx 50$. This mass region has been chosen for the study because elements in this mass region are the main constituents of the stainless-steel (e.g., Fe, Cr, Ni) which will be an important structural material in the upcoming fusion reactors. We have used even-even target nuclei (^{48}Ti and ^{56}Fe), an even-odd nucleus (^{53}Cr), and an odd-even nucleus (^{59}Co) to cover the mass region A $\approx$ 50 for the present study. In Sec. II, we have described the surrogate reaction method and the Weisskopf-Ewing approximation briefly. In Sec. III, we have presented the methodology used in this study. Results and conclusions are presented in the Secs. IV and V, respectively.

II. SURROGATE REACTION TECHNIQUE AND THE WEISSKOPF-EWING APPROXIMATION

According to the Bohr's hypothesis a nuclear reaction involving a fast neutron and a heavy nucleus is a two step process, with each step being independent of the other [37]. The first step is the formation of the compound nucleus in which all the constituents share the incident energy among themselves. The second step is the disintegration of the compound nucleus, which depends on the spin, parity, and the excitation energy of the compound nucleus. Consider a reaction, where $a + A$ is the entrance channel α and $c + C$ is the exit channel χ of the reaction and let B^* be the intermediate compound nucleus. In the surrogate reaction technique we assume the validity of the Bohr hypothesis. In the surrogate reaction technique the same compound nucleus B^* is populated through a surrogate reaction $d + D \rightarrow B^* + b \rightarrow c + C + b$ because, for the short-lived target nucleus, the direct experiments will be very difficult if not impossible. In the Hauser-Feshbach formalism [38] we can give the reaction cross section for the desired nuclear reaction as

$$\sigma_{\alpha\chi}(E_a) = \sum_{J\pi} \sigma_\alpha^{CN}(E_{ex}, J, \pi) G_\chi^{CN}(E_{ex}, J, \pi), \tag{1}$$

where E_{ex} is the excitation energy of the compound nucleus and E_a is the projectile energy. In a surrogate experiment the decay probability of the compound nucleus (B^*) for a particular exit channel χ is determined experimentally by measuring the number of coincidence counts ($N_{\delta\chi}$) between the desired exit channel particle (c) and the outgoing direct reaction particle (b) as $P_{\delta\chi}(E_{ex}) = \frac{N_{\delta\chi}}{N_\delta}$, where N_δ is the total number of surrogate events and δ is used to represent the entrance channel of the surrogate reaction. Let $F_\delta^{CN}(E_{ex}, J, \pi)$ be the probability of the formation of the compound nucleus with excitation energy E_{ex} in a specific spin-parity state (J, π) in the surrogate reaction and $G_\chi^{CN}(E_{ex}, J, \pi)$ be the decay probability of the compound nucleus in that state. Then the decay probability of the desired compound nucleus formed in a surrogate reaction into the exit channel χ can be given as

$$P_{\delta\chi}(E_{ex}) = \sum_{J\pi} F_\delta^{CN}(E_{ex}, J, \pi) G_\chi^{CN}(E_{ex}, J, \pi). \tag{2}$$

Now assuming that the spin and parity of the compound nucleus has no effect on the decay probabilities of the compound nucleus (Weisskopf-Ewing approximation) which means $G_\chi^{CN}(E_{ex}, J, \pi)$ is independent to the spin-parity, then Eq. (2) is greatly simplified as $P_{\delta\chi}(E_{ex}) = G_\chi^{CN}(E_{ex})$, because $\sum_{J\pi} F_\delta^{CN}(E_{ex}, J, \pi) = 1$. The Weisskopf-Ewing approximation implies that, for a compound nucleus, the probability of decay in to a particular channel is a function of the excitation energy only and not of the spin and parity of the compound nucleus [39,40]. Using the Weisskopf-Ewing approximation one can calculate the desired cross sections as

$$\sigma_{\alpha\chi}(E_{ex}) = \sigma_\alpha^{CN}(E_{ex}) P_{\delta\chi}^{CN}(E_{ex}). \tag{3}$$

The cross sections with desirable accuracy can be obtained by using the surrogate reaction method with Weisskopf-Ewing approximation, if any of the following conditions [32] is fulfilled:

(a) The compound nucleus formed in the surrogate reaction is approximately populated with the same spin-parity distribution as in the desired reaction (serendipitous matching).
(b) The desired decay probabilities are nearly independent to the spin and parity of the compound nucleus.

More details on the surrogate reaction method can be found in Ref. [35].

III. METHODOLOGY

A surrogate experiment is mostly concerned about experimentally determining the particular decay probability of a

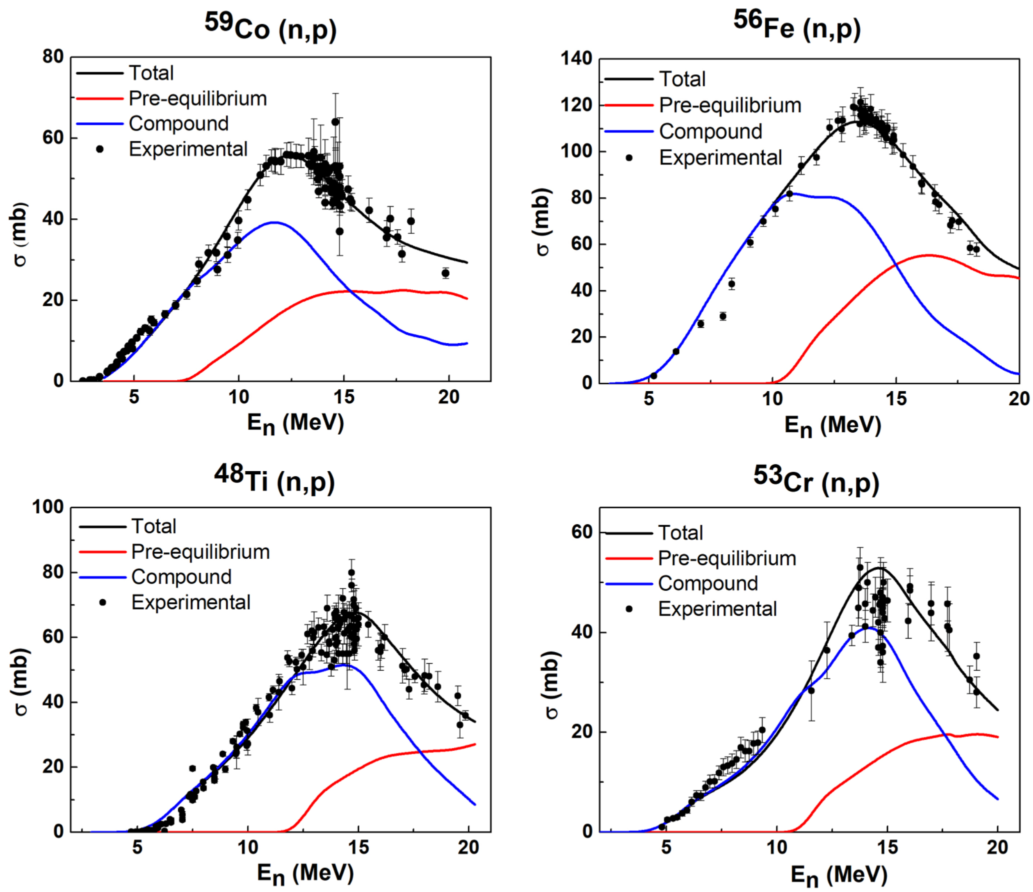

FIG. 1. Reaction cross sections for ^{59}Co(n, p), ^{56}Fe(n, p), ^{48}Ti(n, p), and ^{53}Cr(n, p) with contributions from compound nucleus and pre-equilibrium mechanisms.

desired compound nucleus formed in a surrogate reaction. In the present study we have simulated the experimental results of a surrogate experiment under different circumstances. To simulate the experimental decay probabilities of a surrogate experiment one needs to know the spin-parity-dependent branching ratio [$G_{\beta}^{CN}(E_{ex}, J, \pi)$] of the compound nucleus for the desired decay channel and the spin-parity distribution of the compound nucleus formed in a surrogate reaction over the desired excitation energy range [$F_{\delta}(E_{ex}, J, \pi)$]. Although difficult to calculate, spin-dependent branching ratios can be calculated from the statistical calculations if all the model parameters are well optimized to reproduce the experimental data related to the decaying nucleus and detailed information on the structure of the decaying nucleus is available [33,34]. Also the calculations for the $F_{\delta}(E_{ex}, J, \pi)$ of a compound nucleus populated through a surrogate reaction not only depend on the spin distribution of the level densities but also depend on the reaction mechanism of the formation of the compound nucleus in a direct (surrogate) reaction, which makes it difficult to address this problem [32,34]. In this paper we have studied the (n, p) reactions, so we have calculated the spin-dependent branching ratios for the proton decay of ^{49}Ti, ^{54}Cr, ^{57}Fe, and ^{60}Co compound nuclei in the excitation energy range 11–28 MeV. We can calculate the decay probability of the compound nucleus formed in a surrogate reaction for different schematic spin distributions by using Eq. (2). Applying these decay probabilities in Eq. (3), we calculated the (n, p) cross sections for the desired reactions.

A. Spin-parity-dependent branching ratios

Spin-dependent proton decay probabilities have been calculated using TALYS nuclear reaction code [41]. Level densities were calculated by using the backshifted Fermi gas model [42], and the optical model parameters of Koning and Delaroche were used [43] in the calculations. These parameters were fine tuned to reproduce the available experimental data by using the adjusted parameters from the code's structure directory (talys/structure/best) [44], which sufficiently reproduces the experimental trends. The calculations of TALYS for the ^{48}Ti(n, p), ^{53}Cr(n, p), ^{56}Fe(n, p), and ^{59}Co(n, p) reactions using the best set of parameters are presented in the Fig. 1 along with the experimental data from the EXFOR data library [45]. We have also calculated the contributions from compound and pre-equilibrium reaction mechanisms in the reaction, TALYS predictions are consistent with the experimental data. TALYS allows us to start the decay calculations from an initial population of the excited compound nucleus. Users can define the population of the compound nucleus in desired energy and spin-parity states. We started our calculations by populating the compound nucleus in a single spin-parity state of specific excitation energy and then calculated the

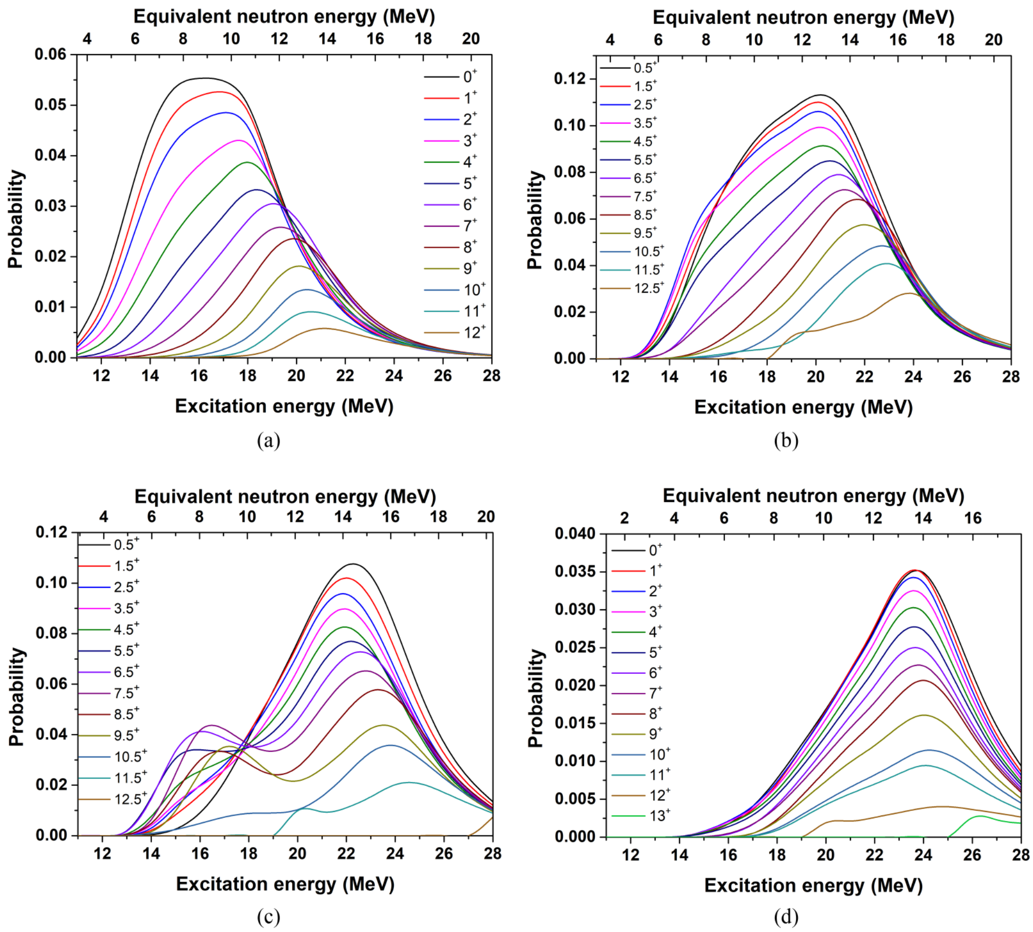

FIG. 2. Spin-dependent proton decay probabilities as a function of compound nucleus excitation energy or the corresponding equivalent neutron energies for (a) ^{60}Co, (b) ^{57}Fe, (c) ^{49}Ti, and (d) ^{54}Cr compound nuclei for positive parity states..

production cross sections for the desired residual nucleus. The ratio of the final population (of the reaction residue) to the initial population of the compound nucleus gives the desired decay probability of that specific state. We have excluded the contributions from the main competing channel $(n, n'p)$ by using the population of the desired residual nucleus instead of proton production cross sections. We have used only the compound nucleus calculations and contributions from the pre-equilibrium has not been included in the calculations. $G_{\beta}^{CN}(E_{ex}, J, \pi)$ for ^{49}Ti, ^{54}Cr, ^{57}Fe, and ^{60}Co over an excitation energy range 11 to 28 MeV have been calculated and presented in the Figs. 2 and 3.

B. Schematic spin distributions

Since calculations for the energy-dependent spin-parity population of the compound nucleus require the knowledge of reaction mechanisms taking place in a surrogate reaction, which makes it complex to be calculated. To study the effect of the difference in the spin-parity distribution of the compound nucleus formed in a desired reaction and surrogate reaction, we have assumed various schematic spin-parity distributions. We have also calculated the spin distributions of the compound nucleus formed in the ^{48}Ti(n, p), ^{53}Cr(n, p), ^{56}Fe(n, p), and ^{59}Co(n, p) reactions at neutron energies 5, 10, 15, and 20 MeV which are presented in the Fig. 4. In this study we have used the even-even target nuclei ^{48}Ti and ^{56}Fe with ground state spin 0^+, the even-odd nucleus ^{53}Cr with spin $3/2^-$, and the odd-even nucleus ^{59}Co with spin $7/2^-$. Spin distribution $[F_{CN}(E_{ex}, J, \pi)]$ for the neutron-induced reactions are calculated by using optical model calculations as $F_{CN}(E_{ex}, J, \pi) = \sigma_{CN}(E_{ex}, J, \pi)/\sum_{J'\pi'} \sigma_{CN}(E_{ex}, J', \pi')$, where $\sigma_{CN}(E_{ex}, J, \pi)$ is the compound nucleus formation cross section in that state.

It is clear from Fig. 4 that the mean spin value of the distribution increases with increasing neutron energies and also the spread of the distribution increases as the energy increases because of the contributions from higher partial waves at higher energies. It can be clearly observed from these figures that the compound nucleus is populated within $J \approx 10\,\hbar$ for all the reactions studied here for the neutron energies 5–20 MeV. In a surrogate reaction compound nucleus can be populated with spin-parity distribution centered at low spin values or at high J values [20,34,35]. Therefore, in this study we have assumed that the compound nucleus formed in a surrogate reaction does not match the compound nucleus spin-parity distributions of the desired reaction. We have taken five different schematic spin distributions, namely, a, b, c, d, and e as presented in Fig. 5. To keep the calculations simple the schematic spin distributions are considered to be independent of energy. The mean spin of the a, b, c, d, and e distributions for the

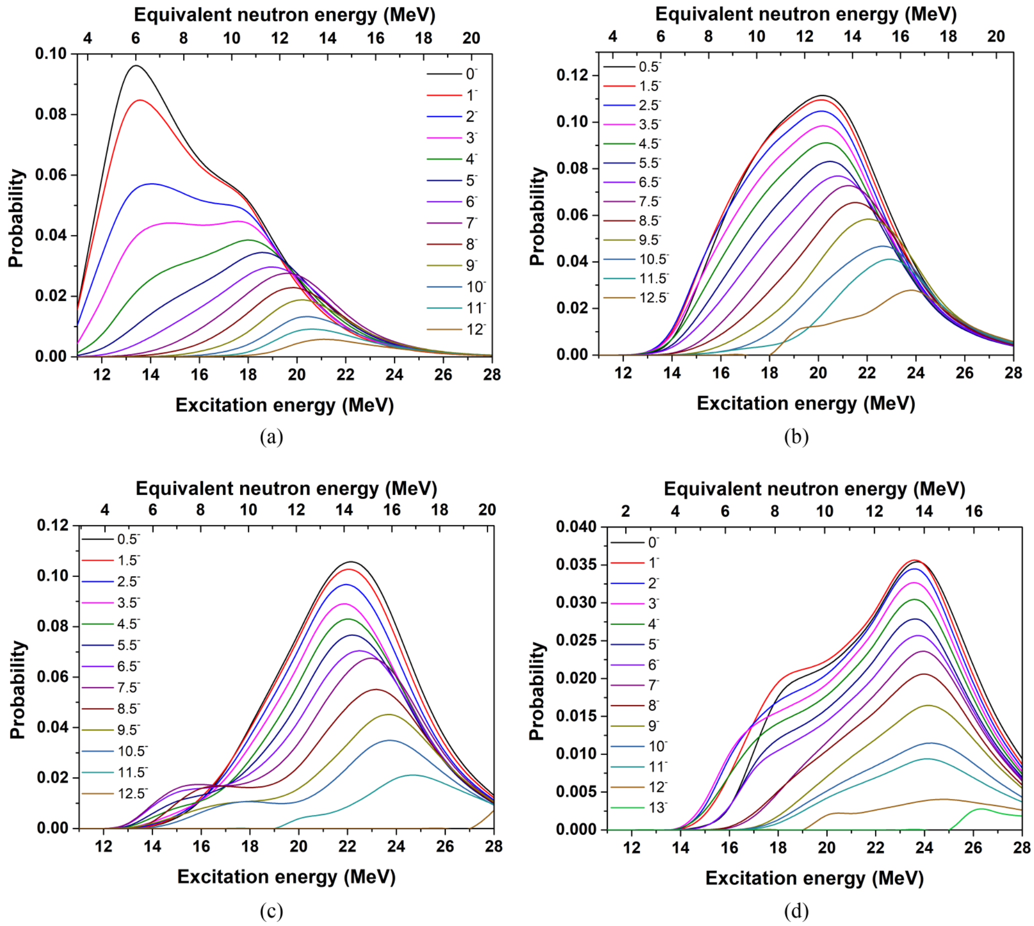

FIG. 3. Spin-dependent proton decay probabilities as a function of compound nucleus excitation energy or the corresponding equivalent neutron energies for (a) ^{60}Co, (b) ^{57}Fe, (c) ^{49}Ti, and (d) ^{54}Cr compound nuclei for negative parity states.

compound nucleus corresponding to even-even target nuclei (^{48}Ti and ^{56}Fe) are at 1.5, 3.5, 5.5, 7.5, and 9.5, respectively, while variance for these distributions were set equal to the mean. For the compound nucleus corresponding to the odd-even and even-odd target nuclei (^{53}Cr and ^{59}Co) mean spin of the same distributions were assumed at 1, 3, 5, 7, and 9 for distributions a, b, c, d, and e, respectively. These schematic distributions are normalized Gaussians and we have assumed that the spin distributions are same for positive-parity and negative-parity states. The surrogate results for each schematic distribution has been calculated individually and we have studied the effect of difference in the spin-parity distribution of the compound nucleus.

IV. RESULTS

Since the surrogate reaction method only accounts for the compound nucleus contributions therefore it becomes necessary to check the pre-equilibrium contributions in the desired reactions i.e., (n, p) reaction for this study. The cross sections for ^{48}Ti(n, p), ^{53}Cr(n, p), ^{56}Fe(n, p), and ^{59}Co(n, p) reactions along with the contributions from the compound as well as pre-equilibrium mechanisms have been calculated by using the TALYS nuclear reaction code, and the results are presented in Fig. 1. We have used two-component exciton model [46] for the pre-equilibrium calculations and well-optimized parameters from the "best" directory in the TALYS code have been used for the calculations [44]. It is observed from Fig. 1 that for neutron energies <12 MeV pre-equilibrium contributions are very small relative to the compound nucleus contributions in all reactions under consideration. In the cases studied, the contribution from compound-nuclear processes peaks at around 14–15 MeV. At higher energies, the contribution from pre-equilibrium processes becomes stronger and surpasses the compound-nucleus contribution. Hence it may be acceptable to apply the surrogate reaction method for (n, p) reactions for equivalent neutron energies below ≈15 MeV, but for energies greater than ≈15 MeV the surrogate reaction method with the Weisskopf-Ewing approximation may not provide cross sections with the desirable accuracy.

To check the validity of the Weisskopf-Ewing approximation we have calculated the spin-parity-dependent proton decay probabilities for the compound nuclei under consideration, which are presented in Figs. 2 and 3. It is clear from these figures that the decay probabilities around excitation energies corresponding to 14 MeV neutron energy show a strong spin dependence and the dependence on parity is not drastic. The large variation in the decay probabilities with respect to the spin can be attributed to the proton transmission coefficients and the shell structure of the low-energy residual nucleus.

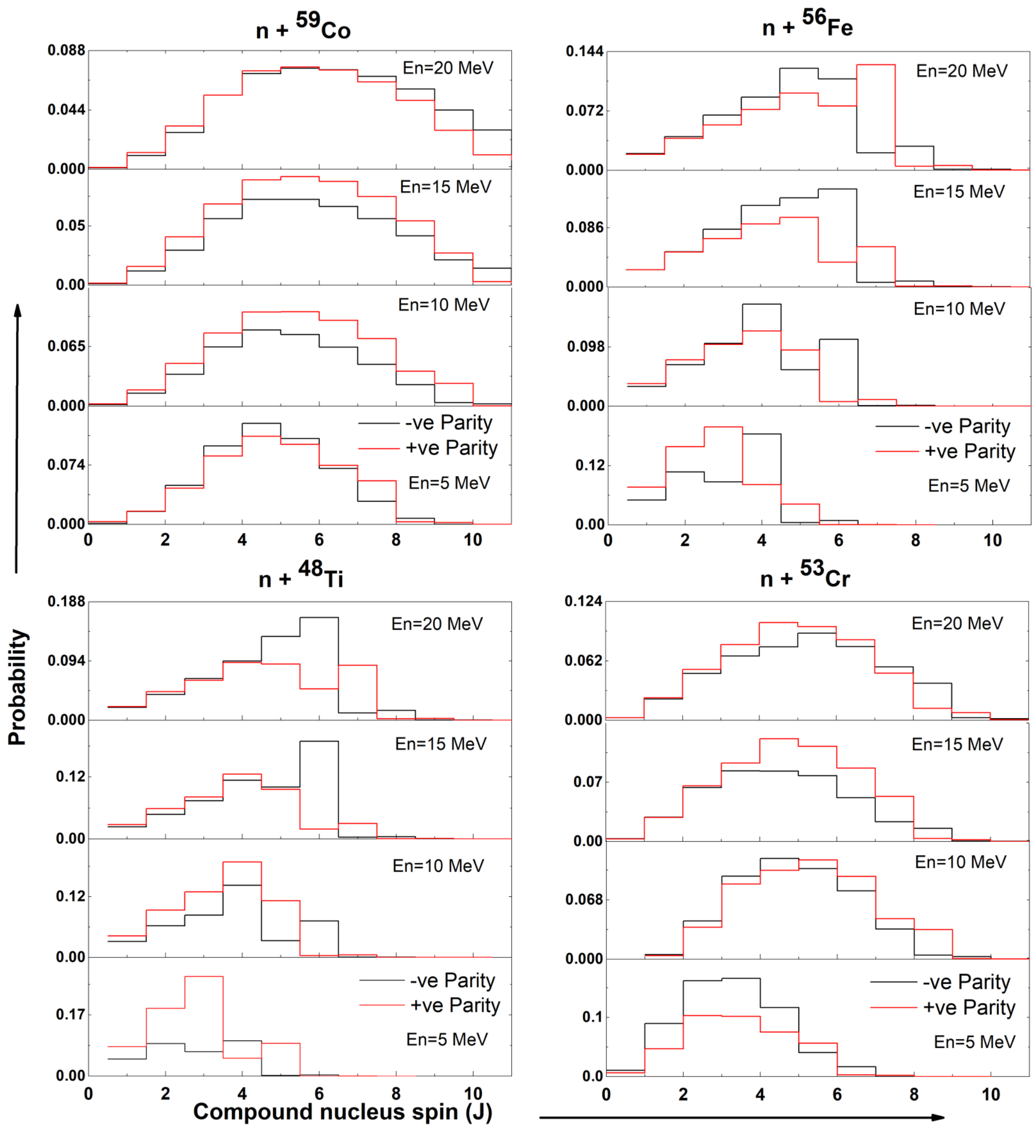

FIG. 4. Spin distributions of the compound nuclei formed in the ^{48}Ti(n, p), ^{53}Cr(n, p), ^{56}Fe(n, p), and ^{59}Co(n, p) reactions for neutron energies 5–20 MeV.

Figures 2 and 3 present a clear violation of condition (b) for the Weisskopf-Ewing approximation listed in Sec. II. Therefore, the Weisskopf-Ewing approximation cannot be used unless condition (a) holds, namely, the condition that the compound nucleus populated in a surrogate reaction has the same spin distribution as that of the desired reaction. We have simulated the cross sections obtained thorough a surrogate reaction corresponding to the different schematic spin distributions (a, b, c, d, and e as presented in Fig. 5) to study the sensitivity of the surrogate results on the spin distribution of the compound nucleus. The cross sections for ^{48}Ti(n, p), ^{53}Cr(n, p), ^{56}Fe(n, p), and ^{59}Co(n, p) reactions were derived for different schematic distributions by using Eq. (3) and are presented in Fig. 6 along with the experimental data from the EXFOR data library and the evaluated data from ENDF/B-VIII for comparison. It is clear from Fig. 6 that the derived (n, p) cross sections are very sensitive to the spin distribution of the compound nucleus populated in the surrogate reaction.

In the ^{48}Ti(n, p) reaction for neutron energies <14 MeV, the average difference in the simulated cross sections corresponding to the distribution b with respect to a; c with respect to b; d with respect to c; and e with respect to d is around 10%, 15%, 20%, and 30%, respectively. Similarly for the reaction ^{53}Cr(n, p), the average difference of 5%, 15%, 25%, and 35% is observed for the results of distribution b with respect to a; c with respect to b; d with respect to c; and e with respect to d, respectively, for incident energies <14 MeV. For the reaction ^{56}Fe(n, p), the simulated results from the distribution b with respect to a; c with respect to b; d with respect to c; and e with respect to d for neutron energies <14 MeV are observed to differ on average by around 5%, 20%, 30%, and 40%, respectively. Finally, for reaction ^{59}Co(n, p), the average difference of about 20%, 30%, 40%, and 50% between the results corresponding to the distribution b with respect to a; c with respect to b; d with respect to c; and e with respect to d, respectively, is observed for energies <14 MeV. For incident

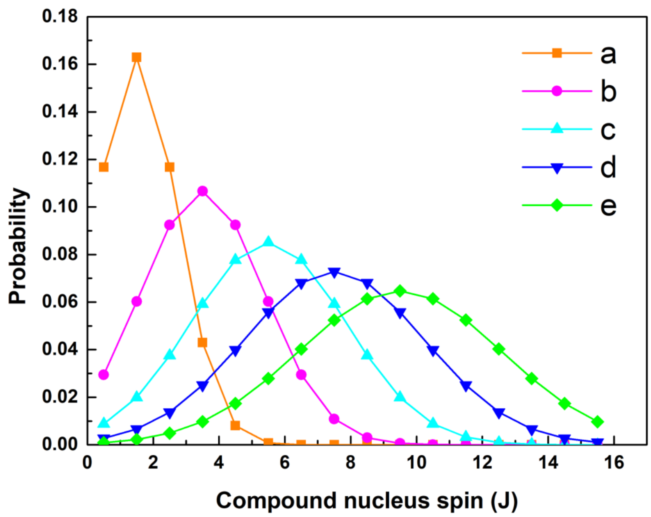

FIG. 5. Energy-independent schematic spin distributions used in the present work.

neutron energies >14 MeV, the average difference between the results corresponding to various schematic spin distributions is $\lesssim$10%. It is also observed from Fig. 6 that the trend of the results from the surrogate reaction method is similar to the trend of the desired results for neutron energies <14 MeV, but for neutron energies >14 MeV the trend of the simulated results is different than the desired cross sections. From these observations it is clear that the (n, p) cross sections derived by surrogate reaction method are very sensitive to the mean value and shape of the spin distribution of the compound nucleus for neutron energies <14 MeV. For neutron energies >14 MeV the results of the surrogate method are less sensitive to the spin distribution of the compound nucleus.

V. CONCLUSIONS

It is observed in this study that proton decay probabilities are highly spin dependent and the Weisskopf-Ewing approximation is violated for the (n, p) reactions. Therefore, (n, p) cross sections derived through the surrogate reaction method assuming the validity of the Weisskopf-Ewing approximation will not be reliable. It is clear from this study that the Weisskopf-Ewing approximation is not sufficient for deriving the (n, p) cross sections for target nucleus in the mass region $A \approx 50$. It is also concluded from this study that due to the large pre-equilibrium contributions for neutron energies greater than ≈15 MeV, the surrogate reaction method with Weisskopf-Ewing approximation may not be suitable to extract the (n, p) cross sections. The present study recommends

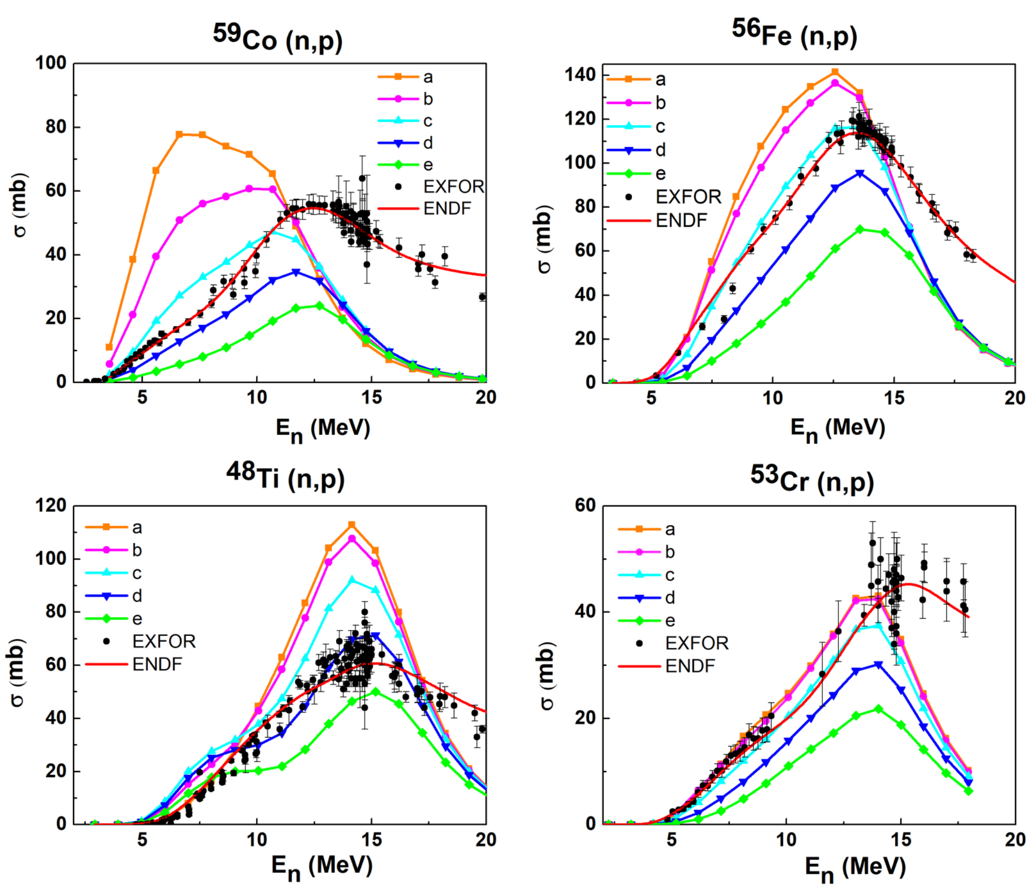

FIG. 6. ^{48}Ti(n, p), ^{53}Cr(n, p), ^{56}Fe(n, p), and ^{59}Co(n, p) cross sections corresponding to different schematic distributions derived by assuming the validity of the Weisskopf-Ewing approximation.

that the surrogate reaction method with the Weisskopf-Ewing approximation is not appropriate to obtain or constrain the (n, p) cross sections for neutron energies around 14 MeV. In light of the present study it is suggested that other variants of the surrogate reaction method like the surrogate ratio method [31] or the modeling approach [25,26,29,35] should be explored theoretically as well as experimentally for constraining the (n, p) cross sections.

ACKNOWLEDGMENTS

One of the authors (A. Kumar) thanks the SERB-DST, Government of India (Sanction No. CRG/2019/000360), UGC-DAE Consortium for scientific research (Sanction No. UGC-DAE-CSR-KC/CRS/19/NP03/0913) and Institutions of Eminence (IoE) BHU (Grant No. 6031) for financial support for this work.

[1] J. D. Cramer and H. C. Britt, Nucl. Sci. Eng. **41**, 177 (2017).
[2] G. Baur, C. A. Bertulani, and H. Rebel, Nucl. Phys. A **458**, 188 (1986).
[3] G. Baur, Phys. Lett. B **178**, 135 (1986).
[4] H. M. Xu, C. A. Gagliardi, R. E. Tribble, A. M. Mukhamedzhanov, and N. K. Timofeyuk, Phys. Rev. Lett. **73**, 2027 (1994).
[5] M. Guttormsen, T. Ramsøy, and J. Rekstad, Nucl. Instrum. Methods Phys. Res., Sect. A **255**, 518 (1987).
[6] A. Schiller, L. Bergholt, M. Guttormsen, E. Melby, J. Rekstad, and S. Siem, Nucl. Instrum. Methods Phys. Res., Sect. A **447**, 498 (2000).
[7] A. Spyrou, S. N. Liddick, A. C. Larsen, M. Guttormsen, K. Cooper, A. C. Dombos, D. J. Morrissey, F. Naqvi, G. Perdikakis, S. J. Quinn, T. Renstrøm, J. A. Rodriguez, A. Simon, C. S. Sumithrarachchi, and R. G. T. Zegers, Phys. Rev. Lett. **113**, 232502 (2014).
[8] B. Pandey, V. V. Desai, S. V. Suryanarayana, B. K. Nayak, A. Saxena, E. T. Mirgule, S. Santra, K. Mahata, R. Makawana, M. Abhangi, T. K. Basu, C. V. S. Rao, S. Jakhar, S. Vala, B. Sarkar, H. M. Agrawal, G. Kaur, P. M. Prajapati, A. Pal, D. Sarkar, and A. Kundu, Phys. Rev. C **93**, 021602(R) (2016).
[9] J. Pandey, B. Pandey, A. Pal, S. V. Suryanarayana, S. Santra, B. K. Nayak, E. T. Mirgule, A. Saxena, D. Chattopadhyay, A. Kundu, V. V. Desai, A. Parihari, G. Mohanto, D. Sarkar, P. C. Rout, B. Srinivasan, K. Mahata, B. J. Roy, S. De, and H. M. Agrawal, Phys. Rev. C **99**, 014611 (2019).
[10] R. Gandhi, B. K. Nayak, S. V. Suryanarayana, A. Pal, G. Mohanto, S. De, A. Parihari, A. Kundu, P. C. Rout, S. Santra, K. Mahata, B. Srinivasan, E. T. Mirgule, and J. Pandey, Phys. Rev. C **100**, 054613 (2019).
[11] P. E. Koehler, F. Kaeppeler, H. Schatz, Yu. M. Glednov, Yu. P. Popov, J. A. Harvey, N. W. Hill, M. Weischer, R. W. Kavanagh, and R. B. Vogelaar, *Proceedings of 8th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics, Fribourg, Switzerland, 20–24 September 1993*, Technical Report No. LA-UR-93-2418; CONF-9309173-1, Los Alamos National Laboratory (United States, 1993).
[12] R. J. Casperson, J. T. Burke, N. D. Scielzo, J. E. Escher, E. McCleskey, M. McCleskey, A. Saastamoinen, A. Spiridon, A. Ratkiewicz, A. Blanc, M. Kurokawa, and R. G. Pizzone, Phys. Rev. C **90**, 034601 (2014).
[13] B. K. Nayak, A. Saxena, D. C. Biswas, E. T. Mirgule, B. V. John, S. Santra, R. P. Vind, R. K. Choudhury, and S. Ganesan, Phys. Rev. C **78**, 061602(R) (2008).
[14] V. V. Desai, B. K. Nayak, A. Saxena, E. T. Mirgule, and S. V. Suryanarayana, Phys. Rev. C **88**, 014613 (2013).
[15] A. Czeszumska, C. T. Angell, J. T. Burke, N. D. Scielzo, E. B. Norman, R. A. E. Austin, G. Boutoux, R. J. Casperson, P. Chodash, R. O. Hughes, C. M. Mattoon, V. Meot, J. Munson, L. Phair, J. J. Ressler, O. Roig, T. J. Ross, E. Swanberg, and B. Wang, Phys. Rev. C **87**, 034613 (2013).
[16] M. Petit, M. Aiche, G. Barreau, S. Boyer, N. Carjan, S. Czajkowski, D. Dassié, C. Grosjean, A. Guiral, B. Haas *et al.*, Nucl. Phys. A **735**, 345 (2004).
[17] J. J. Ressler, J. T. Burke, J. E. Escher, C. T. Angell, M. S. Basunia, C. W. Beausang, L. A. Bernstein, D. L. Bleuel, R. J. Casperson, B. L. Goldblum, J. Gostic, R. Hatarik, R. Henderson, R. O. Hughes, J. Munson, L. W. Phair, T. J. Ross, N. D. Scielzo, E. Swanberg, I. J. Thompson, and M. Wiedeking, Phys. Rev. C **83**, 054610 (2011).
[18] S. R. Lesher, J. T. Burke, L. A. Bernstein, H. Ai, C. W. Beausang, D. L. Bleuel, R. M. Clark, F. S. Dietrich, J. E. Escher, P. Fallon, J. Gibelin, B. L. Goldblum, I. Y. Lee, A. O. Macchiavelli, M. A. McMahan, K. J. Moody, E. B. Norman, L. Phair, E. Rodriguez-Vieitez, N. D. Scielzo, and M. Wiedeking, Phys. Rev. C **79**, 044609 (2009).
[19] R. O. Hughes, C. W. Beausang, T. J. Ross, J. T. Burke, R. J. Casperson, N. Cooper, J. E. Escher, K. Gell, E. Good, P. Humby, M. McCleskey, A. Saastimoinen, T. D. Tarlow, and I. J. Thompson, Phys. Rev. C **90**, 014304 (2014).
[20] N. D. Scielzo, J. E. Escher, J. M. Allmond, M. S. Basunia, C. W. Beausang, L. A. Bernstein, D. L. Bleuel, J. T. Burke, R. M. Clark, F. S. Dietrich, P. Fallon, J. Gibelin, B. L. Goldblum, S. R. Lesher, M. A. McMahan, E. B. Norman, L. Phair, E. Rodriquez-Vieitez, S. A. Sheets, I. J. Thompson, and M. Wiedeking, Phys. Rev. C **81**, 034608 (2010).
[21] B. L. Goldblum, S. G. Prussin, L. A. Bernstein, W. Younes, M. Guttormsen, and H. T. Nyhus, Phys. Rev. C **81**, 054606 (2010).
[22] R. Hatarik, L. A. Bernstein, J. A. Cizewski, D. L. Bleuel, J. T. Burke, J. E. Escher, J. Gibelin, B. L. Goldblum, A. M. Hatarik, S. R. Lesher, P. D. OMalley, L. Phair, E. Rodriguez-Vieitez, T. Swan, and M. Wiedeking, Phys. Rev. C **81**, 011602(R) (2010).
[23] A. Ratkiewicz, J. A. Cizewski, J. E. Escher, G. Potel, J. T. Burke, R. J. Casperson, M. McCleskey, R. A. E. Austin, S. Burcher, R. O. Hughes, B. Manning, S. D. Pain, W. A. Peters, S. Rice, T. J. Ross, N. D. Scielzo, C. Shand, and K. Smith, Phys. Rev. Lett. **122**, 052502 (2019).
[24] R. Perez Sanchez, B. Jurado, V. Meot, O. Roig, M. Dupuis, O. Bouland, D. Denis-Petit, P. Marini, L. Mathieu, I. Tsekhanovich, M. Aiche, L. Audouin, C. Cannes, S. Czajkowski, S. Delpech, A. Gorgen, M. Guttormsen, A. Henriques, G. Kessedjian, K. Nishio *et al.*, Phys. Rev. Lett. **125**, 122502 (2020).
[25] W. Younes and H. C. Britt, Phys. Rev. C **67**, 024610 (2003).
[26] W. Younes and H. C. Britt, Phys. Rev. C **68**, 034610 (2003).

[27] G. Kessedjian, B. Jurado, M. Aiche, G. Barreau, A. Bidaud, S. Czajkowski, D. Dassié, B. Haas, L. Mathieu, L. Audouin *et al.*, Phys. Lett. B **692**, 297 (2010).

[28] R. O. Hughes, C. W. Beausang, T. J. Ross, J. T. Burke, N. D. Scielzo, M. S. Basunia, C. M. Campbell, R. J. Casperson, H. L. Crawford, J. E. Escher, J. Munson, L. W. Phair, and J. J. Ressler, Phys. Rev. C **85**, 024613 (2012).

[29] J. E. Escher, J. T. Burke, R. O. Hughes, N. D. Scielzo, R. J. Casperson, S. Ota, H. I. Park, A. Saastamoinen, and T. J. Ross, Phys. Rev. Lett. **121**, 052501 (2018).

[30] A. Sharma, A. Gandhi, N. Singh, S. V. Suryanarayana, B. K. Nayak, and A. Kumar, J. Phys. G **47**, 065106 (2020).

[31] S. Chiba and O. Iwamoto, Phys. Rev. C **81**, 044604 (2010).

[32] O. Gorton and J. Escher, arXiv:2102.03452.

[33] J. E. Escher and F. S. Dietrich, Phys. Rev. C **81**, 024612 (2010).

[34] J. E. Escher and F. S. Dietrich, Phys. Rev. C **74**, 054601 (2006).

[35] J. E. Escher, J. T. Burke, F. S. Dietrich, N. D. Scielzo, I. J. Thompson, and W. Younes, Rev. Mod. Phys. **84**, 353 (2012).

[36] G. Boutoux, B. Jurado, V. Méot, O. Roig, L. Mathieu, M. Aïche, G. Barreau, N. Capellan, I. Companis, S. Czajkowski *et al.*, Phys. Lett. B **712**, 319 (2012).

[37] N. Bohr, Nature (London) **137**, 344 (1936).

[38] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952).

[39] V. F. Weisskopf and D. H. Ewing, Phys. Rev. **57**, 472 (1940).

[40] V. Weisskopf, Phys. Rev. **52**, 295 (1937).

[41] A. J. Koning, S. Hilaire, and M. C. Duijvestijn, TALYS − 1.0, *Proceedings of the International Conference on Nuclear Data for Science and Technology, April 22-27, 2007, Nice, France*, edited by O. Bersillon, F. Gunsing, E. Bauge, R. Jacqmin, and S. Leray (EDP Sciences, 2008), pp. 211–214.

[42] W. Dilg, W. Schantl, H. Vonach, and M. Uhl, Nucl. Phys. A **217**, 269 (1973).

[43] A. J. Koning and J. P. Delaroche, Nucl. Phys. A **713**, 231 (2003).

[44] A. J. Koning, D. Rochman, J.-Ch. Sublet, N. Dzysiuk, M. Fleming, and S. van der Marck, Nucl. Data Sheets **155**, 1 (2019).

[45] N. Otuka, E. Dupont, V. Semkova, B. Pritychenko, A. I. Blokhin, M. Aikawa, S. Babykina, M. Bossant, G. Chen, S. Dunaeva *et al.*, Nucl. Data Sheets **120**, 272 (2014).

[46] A. J. Koning and M. C. Duijvestijn, Nucl. Phys. A **744**, 15 (2004).