One-neutron stripping processes to excited states of the ^{6}Li + ^{96}Zr reaction at near-barrier energies

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We report the measurement of one-neutron stripping to excited-state cross sections from the weakly bound projectile ^{6}Li to the ^{96}Zr target at near-barrier energies by the online γ-ray spectroscopy method. Transitions of the ^{97}Zr nucleus were clearly identified by γ-γ coincidences. This cross section was found to be much smaller than the previously reported complete-fusion cross section for this system at energies above the barrier, whereas it becomes of the same magnitude around the Coulomb-barrier energy. No evidence of two-neutron transfer was found. We also performed coupled reaction channel calculations for the one-neutron stripping process. The calculation results are discussed.

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I. INTRODUCTION

Over the past few years intense theoretical and experimental efforts have been made to investigate reactions and scattering induced by weakly bound nuclei, especially fusion, breakup, and elastic scattering [1–7]. Systematic results [8–13] have shown that the coupling effects of the breakup (BU) channel on the complete fusion (CF) of weakly bound nuclei suppress the CF at energies above the Coulomb barrier and produce some enhancements at sub-barrier energies. When the incomplete fusion (ICF) of part of the projectile's fragments is added to the CF, the total fusion (TF) does not show the suppression above the barrier, which means that part of the flux that would go to CF actually goes to ICF after the BU of the projectile. The elastic scattering of weakly bound nuclei shows a behavior of the energy dependence of the optical potential at near-barrier energies that is quite different from the usual threshold anomaly [14,15], which was named the "breakup threshold anomaly" [16]. This phenomenon is attributed to the repulsive polarization potential produced by the BU, which populates continuum states [17–23]. The same conclusions concerning this repulsive character of the BU polarization potential may be obtained by the analysis of fusion and quasi-elastic-barrier distributions [24–28]. Although most of the theoretical works consider the BU as a direct process, it has been shown experimentally that sequential BU consisting of transfer followed by BU may predominate over direct BU. Direct BU may be considered as a one- or two-step process; the latter corresponding to the situation when resonances are populated before the BU. The one-step process is called "prompt BU" [29–33], whereas the processes populating long-live resonances, with lifetimes much longer than the collision time, and the sequential BU of transfer followed by BU is called "delayed BU". Total reaction cross sections with weakly bound nuclei have been found to be systematically larger than similar ones with tightly bound systems [34–37].

Direct transfer of neutrons or clusters of nucleons involving stable and radioactive weakly bound projectiles have been investigated in the past years to contribute to the recent comprehensive investigation of reaction and scattering mechanisms involving weakly bound nuclei. It has been shown that, for neutron-halo nuclei such as ^{6}He, transfers of one or two neutrons have very large cross sections, mainly at sub-barrier energies [38–45]. For stable weakly bound nuclei like ^{6,7}Li, contrary to what happens for fusion and elastic-scattering data, there are only a few reported works on the neutron transfer [26,46–50]. For the ^{9}Be stable weakly bound projectile, one-neutron stripping has also been reported [51–54]. When the γ-spectroscopy method is used and characteristic γ lines of the target-like nuclei are detected, the transfer processes to excited states can be reliably identified. To contribute to recent investigations of reaction mechanisms involving weakly bound nuclei, in the present work we report the investigation of transfer cross sections for the ^{6}Li + ^{96}Zr system at near-barrier energies. In Sec. II we describe the experimental setup. In Sec. III we present the method to obtain the transfer cross sections by the online γ-ray method and the excitation functions obtained in the present work. In Sec. IV we present coupled reaction channel (CRC) calculations for transfer reactions for this system and compare them with the data. Finally, in Sec. V, a summary and some conclusions are presented.

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II. EXPERIMENTAL SETUP

The experiment was performed at the HI-13 Tandem Accelerator of the China Institute of Atomic Energy (CIAE) in Beijing. Beams of $^6Li^{3+}$ were produced in the energy range from 14 to 28 MeV in steps of 2 MeV. This range corresponds to energies from below to above the nominal Coulomb barrier of 17.4 MeV (16.36 MeV in the c.m. frame). A 99% enriched $^{96}ZrO_2$ foil with 550 $\mu g/cm^2$ thickness and a 1.92 mg/cm^2 gold backing was used. The cross sections were measured by using the online γ-ray-spectrometry method. Typical irradiation times were from 1 to 2 h. The beam flux was recorded by a Faraday cup placed behind the target. Two Si(Au) surface-barrier detectors were positioned at $\pm 30^\circ$ with respect to the beam direction for verification of the beam intensity, and normalization and centrality of the beam. An array consisting of nine Compton-suppressed bismuth-germanate high-purity Ge (BGO-HPGe) spectrometers and two planar HpGe detectors was used to detect online γ rays emitted by the reaction products. The absolute efficiency and energy calibration of the detectors were achieved by using a set of standard radioactive sources of ^{152}Eu and ^{133}Ba at the target position. The Versa Module Europa-based (VME-based) data acquisition system MIDAS was used to record the data. The average uncertainty (3.5%) of the efficiency and angular distributions of γ rays is mainly from the standard radioactive sources and the least squares fit method. The total uncertainty in this experiment for the values of the transfer cross sections comes from statistical errors associated with the yields of γ rays, and from systematic errors in the determination of the target thickness (1%), absolute efficiency, and intensity of beam. The overall error is in the range from 11% at higher energies to almost 17% at very low energies.

For the $^6Li + ^{96}Zr$ system, the $1n$ stripping channel has $Q_{g.s.} = -0.088$ MeV [55] (where "g.s." stands for "ground state"). The $1n$-pickup has $Q_{g.s.} = -0.603$ MeV [55]. The stripping and pickup of two neutrons have very negative $Q_{g.s.}$ values. Positive $Q_{g.s.}$ values exist for the stripping of deuteron (+9.747 MeV [55]), pickup of deuteron (+6.145 MeV [55]), stripping of one proton (+3.019 MeV [55]), and stripping of one α particle (+1.696 MeV [55]). However, among all of these possibilities, the Brink's matching conditions [56] are fulfilled only for the $1n$ stripping channel and deuteron stripping; the latter feeding mostly continuum states. So, the only transfer channel expected to be populated significantly and to decay by γ emission is the $1n$ stripping channel. Actually, this is, indeed, the only channel for which characteristic γ-ray lines were clearly identified.

Additionally, one auxiliary ΔE-E telescope in the experimental setup was located at 65° with the beam direction, for the single identification of the light charged particles produced in the experiment. The distance between the target center and the telescope center was 55.0 mm. The telescope is composed of a silicon detector with diameter of 8 mm and a thickness 30.0 μm, and a stop silicon detector with a diameter of 12.0 mm and a thickness 1000 μm. A collimator with a diameter of 5.0 mm is put before the telescope. This telescope was regarded only as a reference to confirm the identification of the channels depending on the light charged particles produced.

TABLE I. Characteristic γ rays of ^{97}Zr [57].

Residual channels	Transition	E_γ (keV)	I_γ [57] (%)
^{97}Zr ($1n$ stripping)	$3/2^+ \longrightarrow 1/2^+$	1103.1	100
	$5/2^+ \longrightarrow 1/2^+$	1400.1	38

III. RESULTS AND DISCUSSION

The γ rays used to determine the one-neutron stripping cross sections are shown in Table I. They are the 1103.1 and 1400.1 keV characteristic lines of ^{97}Zr, feeding its ground state. The partial-level diagram of ^{97}Zr is shown in Fig. 1. From Fig. 1 we can clearly see the 1103.1 and 1400.1 keV energy levels, and the coincident relations among several γ rays. Figure 2(a) shows a typical online single-γ-ray spectrum, at $E_{lab} = 28$ MeV, where these two lines can be identified. Figures 2(b) and 2(c) are the coincident spectra of the 1103.1 and 1400.1 keV transitions, respectively, which are in agreement with the works of Refs. [57–59]. The strong γ-ray transitions observed in Fig. 2(a) come predominantly from residual nuclei from fusion evaporation processes. By measuring γ transitions to the ground state of ^{97}Zr, we are able to determine only the lower limit of the one-neutron stripping cross section, since we cannot observe the cross sections feeding directly the ^{97}Zr ground state.

Figure 3 shows a two-dimensional spectrum obtained at 28 MeV in our experiment, where alpha particles, deuterons, and protons are clearly identified. Protons may originate from several processes, such as the breakup of ^{5}Li after the one-neutron stripping of ^{6}Li, as observed in Refs. [30,31,49,50], or from the one-neutron stripping of the deuteron fragment after the ^{6}Li direct breakup into alpha + deuteron.

To obtain the cross section for a certain channel by using the online γ-ray method, one has to add all transitions which feed the ground state of the corresponding nucleus. Because the lifetimes of the excited states are much smaller than the irradiation time, the transitions may be considered as prompt. It is important to mention once more that, with this method, only cross sections to excited states can be determined because, if the ground state is directly populated, no γ ray is emitted. So,

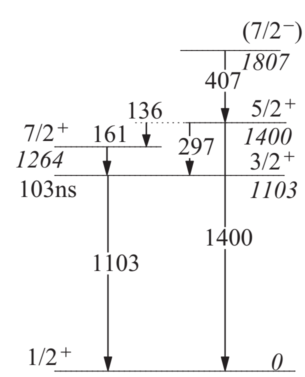

FIG. 1. The partial-level diagram of ^{97}Zr [57]. The energy is in units of keV.

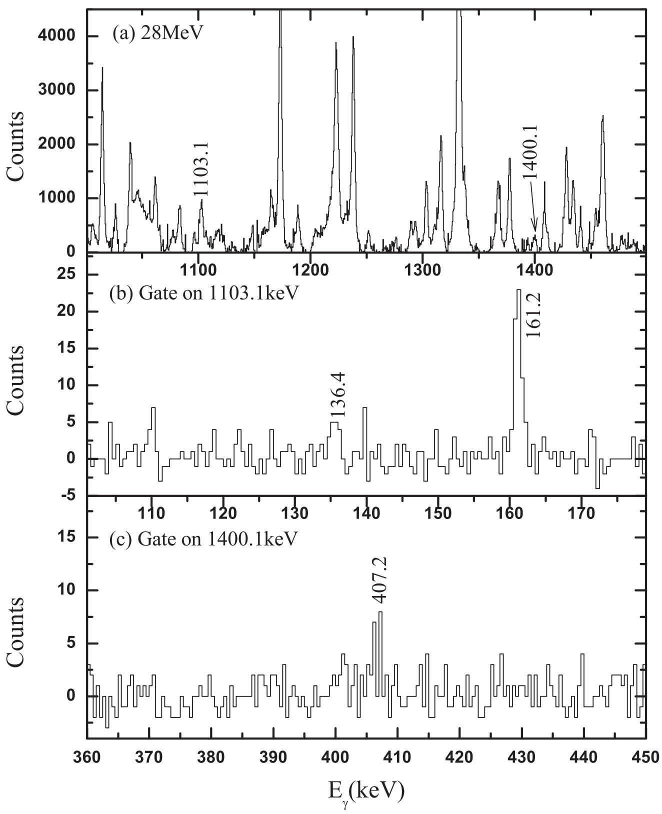

FIG. 2. (a) Typical online γ-ray spectrum depicting the γ lines of the $1n$ stripping residue nucleus ^{97}Zr in the ^{6}Li + ^{96}Zr system at the bombarding energy of 28 MeV. Panels (b)and (c) show the coincident spectra of the 1103.1 and 1400.1 keV transitions [57–59], respectively.

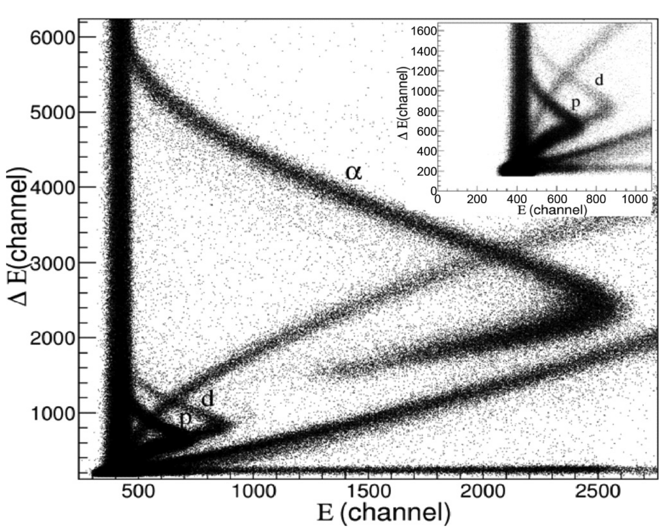

FIG. 3. Typical ΔE-E spectrum showing the light charged particles produced in the reaction ^{6}Li + ^{96}Zr at the bombarding energy of 28 MeV and at 65° with respect to the beam direction. Alpha particles, deuterons, and protons are clearly identified.

in the present work the one-neutron stripping cross section for the excited states of ^{97}Zr is given by

$$\sigma^*_{1n\ \mathrm{strip}}(E) = \frac{1}{N_B N_T}\left[\sum_{i=1}^{2} \frac{A_{E_{\gamma_i}}(E)}{\varepsilon_{E_{\gamma_i}}\varepsilon_d F^{\mathrm{CE}}_{E_{\gamma_i}}}\right], \tag{1}$$

where $i = 1$ corresponds to the 1103.1 keV transition and $i = 2$ corresponds to the 1400.1 keV transition. $A_{E_{\gamma_i}}$ is the yield of the γ peak with energy E_{γ_i} at the bombarding energy E. $\varepsilon_{E_{\gamma_i}}$ is the absolute efficiency of all the detectors for the γ ray with energy E_{γ_i}. ε_d is the correction factor for the dead time of the data-acquisition system. $\mathrm{F}^{\mathrm{CE}}_{E_{\gamma_i}}$ is the conversion electron correction for the $i \rightarrow$ g.s. transition. N_B and N_T are the total number of beam particles incident on the target and the target atoms per unit area, respectively.

For each transition, the accumulated number of counts during a run has to take into account the anisotropy of the emission and the detection efficiency such that one can write

$$A_{E_\gamma}(\theta) = N_{E_\gamma} F^{\mathrm{CE}}_{E_\gamma} \varepsilon_{E_\gamma} \varepsilon_d W_{E_\gamma}(\theta), \tag{2}$$

where N_{E_γ} is the number of γ rays from the excited state to the ground state with energy E_γ, and $W_{E_\gamma}(\theta)$ is the angular distribution of γ rays emitted at the detection angle θ. $W_{E_\gamma}(\theta)$ is given by

$$W_{E_\gamma}(\theta) = 1 + \sum_{j=2}^{\infty} A_j(E_\gamma) P_j(\cos\theta), \tag{3}$$

where P_j is the Legendre polynomials of order j, where j is an even number and $A_j(E_\gamma)$ depends on the specific transition. However, when a full angular distribution of γ rays is detected, as in the present work, the anisotropy of the γ emission does not need to be considered.

In Table II we show the cross sections corresponding to the 1103.1 and 1400.1 keV transitions, as well as the sum of these two cross sections, named "$1n$ stripping to excited states". To allow a comparison with the CF cross section measured by us and previously reported [60], we also show the CF cross sections in Table II. CF cross sections could not be measured at the lowest energy of 14 MeV. Figure 4 shows the $1n$ stripping to excited states and CF excitation functions for the ^{6}Li + ^{96}Zr system. One can observe that, in spite of the transfer Q value for the $1n$ stripping being around zero MeV, the lower limit of

TABLE II. The cross sections of CF [60] and $1n$ stripping to excited states, as well as the ones corresponding to the 1103.1 and 1400.1 keV energies for the ^{6}Li + ^{96}Zr system.

E_{lab} (MeV)	σ_{CF} (mb)	1103.1 keV (mb)	1400.1 keV (mb)	$1n$ stripping (mb)
28.0	787.57 ± 49.86	60.42 ± 7.40	21.42 ± 2.44	81.84 ± 7.79
26.0	773.10 ± 49.03	57.69 ± 6.81	19.72 ± 2.24	77.41 ± 7.17
24.0	572.59 ± 36.76	42.02 ± 5.59	11.96 ± 1.38	53.98 ± 5.76
22.0	330.43 ± 21.16	34.85 ± 4.34	9.26 ± 1.05	44.11 ± 4.46
20.0	239.53 ± 16.04	36.25 ± 4.49	8.20 ± 0.96	44.45 ± 4.59
18.0	74.12 ± 5.41	23.38 ± 3.24	3.70 ± 0.45	27.08 ± 3.27
16.0	10.74 ± 1.53	12.56 ± 1.70	0	12.56 ± 1.70
14.0		3.25 ± 0.55	0	3.25 ± 0.55

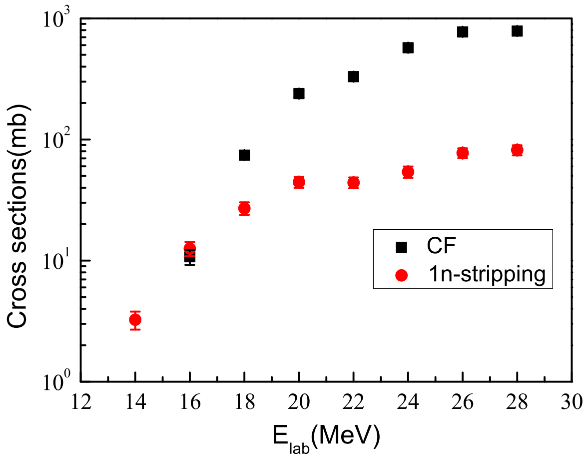

FIG. 4. Measured complete fusion and direct plus two-step $1n$ stripping to excited-state cross sections corresponding to 1103.1 and 1400.1 keV energies for the ^{6}Li + ^{96}Zr system at near- Coulomb-barrier energies.

the cross section for this channel, as determined in the present work, is similar to the fusion cross section at energies near that of the Coulomb barrier. Because its excitation function does not drop as fast as the CF excitation function, it is expected that transfer cross sections should be larger than the CF cross section at sub-barrier energies.

IV. COUPLED REACTION CHANNEL CALCULATIONS, COMPARISON WITH DATA, AND DISCUSSION

In this section we compare our experimental data with the results of calculations. We performed coupled reaction channel (CRC) calculations for the one-neutron stripping cross section for the ^{6}Li + ^{96}Zr system. To do so, there are various important ingredients to be taken into account, such as the optical potential, spectroscopic amplitudes, and form factors. For the real part of the optical potential, the double-folding São Paulo potential was used [61,62]. At near barrier energies this potential is equivalent to the usual double folding potential with the advantage that it has a comprehensive systematic for the matter densities. For this reason, this is a parameter-free potential. In our calculations we are not taking into account the breakup channel (the weakly bound ^{6}Li projectile can break into deuteron + alpha particle), so in the initial partition for the imaginary part of the optical potential we use the same radial dependence of the real part, with the strength coefficient $N_I = 0.6$. This procedure has been shown to account for the loss of flux to dissipative channels [63] as well as to breakup channels [64]. For the breakup channel, it has also been shown that its coupling to the elastic channel produces repulsive polarizations [65–67]. So the real part of the optical potential is also multiplied by a strength coefficient $N_R = 0.6$ [64,68].

For the final partition (^{5}Li + ^{97}Zr,) the São Paulo potential was used for both the real and the imaginary parts with strength coefficients $N_R = 1.0$ and $N_I = 0.78$, respectively. This approach has been proven to be suitable for describing the elastic-scattering cross sections for several systems [69] over a wide energy interval. In the entrance partition, the

TABLE III. Comparison of experimental and NUSHELLX results for the ^{96,97}Zr spectra. The spin and parity of the states are shown in parentheses (for details, see the text).

Isotope	Expt. energies (I^π) (MeV)	NUSHELLX energies (I^π) (MeV)
^{96}**Zr**	0.0 (0^+)	0.0 (0^+)
	1.581 (0^+)	1.841 (0^+)
	1.750 (2^+)	1.563 (2^+)
	1.897 (3^-)	3.826 (3^-)
	2.225 (2^+)	2.386 (2^+)
	2.437 (3^+)	2.119 (3^+)
^{97}**Zr**	0.0 ($1/2^+$)	0.0 ($1/2^+$)
	1.103 ($3/2^+$)	0.875 ($3/2^+$)
	1.264 ($7/2^+$)	0.980 ($7/2^+$)
	1.400 ($5/2^+$)	0.942 ($5/2^+$)

collective states of the target were also considered. The details of the coupling of the first 2^+ (1.75 MeV) and 3^- (1.90 MeV) states were described recently in Ref. [60]. In addition to these one-step excitations, we added two-step quadrupole couplings to the states 0^+ (1.581 MeV), 2^+ (2.225), and 3^+ (2.437 MeV). The quadrupole-deformation parameter was considered the same as for the excitation of the first 2^+ state and taken from Ref. [70].

The spectroscopic amplitudes for target overlaps were determined by performing shell-model calculations, considering ^{90}Zr as a closed core, valence protons in the orbits $1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$, and $1g_{9/2}$, and neutrons in the orbits $1g_{7/2}$, $2d_{5/2}$, $2d_{3/2}$, and $3s_{1/2}$. This model space allowed us to construct both positive- and negative-parity states for both ^{96}Zr and ^{97}Zr. The shell-model calculations were performed with the NUSHELLX code [71], which makes it possible to compute the one-neutron-transfer amplitudes. As effective interaction, we used the **snt** interaction [72], which was set for this model space and is one of the standard interactions available in the NUSHELLX code. We also performed shell-model calculations using the space model **sne** with its respective interaction **snet** which allows us to include the $1h_{11/2}$ orbit, which has been shown to be relevant in transfer reaction involving zirconium isotopes [58]. Owing to our computational limitations, we did not calculate the spectroscopic amplitudes for the orbit $1h_{11/2}$. The spectroscopic amplitudes for the overlap of this orbit and the ground state (g.s.) of ^{96}Zr were taken from Ref. [58]. For the other overlaps involving the lower orbits, we used the values obtained with the **snt** interaction. In Table III the results of NUSHELLX calculations and the corresponding experimental spectra for both the ^{96}Zr and ^{97}Zr nuclei are shown. From this

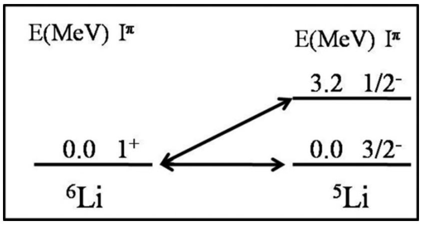

FIG. 5. Coupling scheme for the projectile overlaps.

TABLE IV. Spectroscopic amplitudes for the projectile $\langle ^{96}Zr|^{97}Zr\rangle$ overlap with ^{96}Zr as core, corresponding to the $1n$-transfer reaction.

Initial states	j	Final states	Espec. Amp.
$^{96}Zr_{g.s.}(0^+)$	$3s_{1/2}$	$^{97}Zr_{g.s.}(1/2^+)$	0.8792
	$2d_{3/2}$	$^{97}Zr_{1.103}(3/2^+)$	0.9163
	$1g_{7/2}$	$^{97}Zr_{1.264}(7/2^+)$	−0.9403
	$2d_{5/2}$	$^{97}Zr_{1.40}(5/2^+)$	−0.2920
$^{96}Zr_{1.581}(0^+)$	$3s_{1/2}$	$^{97}Zr_{g.s.}(1/2^+)$	0.2959
	$2d_{3/2}$	$^{97}Zr_{1.103}(3/2^+)$	0.0859
	$1g_{7/2}$	$^{97}Zr_{1.264}(7/2^+)$	−0.0922
	$2d_{5/2}$	$^{97}Zr_{1.40}(5/2^+)$	0.5147
$^{96}Zr_{1.750}(2^+)$	$2d_{3/2}$	$^{97}Zr_{g.s.}(1/2^+)$	0.1541
	$2d_{5/2}$	$^{97}Zr_{g.s.}(1/2^+)$	1.4718
	$3s_{1/2}$	$^{97}Zr_{1.103}(3/2^+)$	0.0516
	$2d_{3/2}$	$^{97}Zr_{1.103}(3/2^+)$	−0.0955
	$2d_{5/2}$	$^{97}Zr_{1.103}(3/2^+)$	0.0532
	$1g_{7/2}$	$^{97}Zr_{1.103}(3/2^+)$	−0.1500
	$2d_{3/2}$	$^{97}Zr_{1.264}(7/2^+)$	0.0745
	$2d_{5/2}$	$^{97}Zr_{1.264}(7/2^+)$	0.0033
	$1g_{7/2}$	$^{97}Zr_{1.264}(7/2^+)$	0.1070
	$3s_{1/2}$	$^{97}Zr_{1.40}(5/2^+)$	−0.6642
	$2d_{3/2}$	$^{97}Zr_{1.40}(5/2^+)$	−0.1531
	$2d_{5/2}$	$^{97}Zr_{1.40}(5/2^+)$	−0.3122
	$1g_{7/2}$	$^{97}Zr_{1.40}(5/2^+)$	−0.0983
$^{96}Zr_{2.225}(2^+)$	$2d_{3/2}$	$^{97}Zr_{g.s.}(1/2^+)$	0.0236
	$2d_{5/2}$	$^{97}Zr_{g.s.}(1/2^+)$	−0.2215
	$3s_{1/2}$	$^{97}Zr_{1.103}(3/2^+)$	0.1804
	$2d_{3/2}$	$^{97}Zr_{1.103}(3/2^+)$	0.0010
	$2d_{5/2}$	$^{97}Zr_{1.103}(3/2^+)$	0.7947
	$1g_{7/2}$	$^{97}Zr_{1.103}(3/2^+)$	−0.0700
	$2d_{3/2}$	$^{97}Zr_{1.264}(7/2^+)$	− 0.0709
	$2d_{5/2}$	$^{97}Zr_{1.264}(7/2^+)$	− 0.1457
	$1g_{7/2}$	$^{97}Zr_{1.264}(7/2^+)$	0.0084
	$3s_{1/2}$	$^{97}Zr_{1.40}(5/2^+)$	0.1654
	$2d_{3/2}$	$^{97}Zr_{1.40}(5/2^+)$	0.1447
	$2d_{5/2}$	$^{97}Zr_{1.40}(5/2^+)$	− 0.5266
	$1g_{7/2}$	$^{97}Zr_{1.40}(5/2^+)$	− 0.0361
$^{96}Zr_{2.438}(3^+)$	$2d_{5/2}$	$^{97}Zr_{g.s.}(1/2^+)$	1.7009
	$1g_{7/2}$	$^{97}Zr_{g.s.}(1/2^+)$	− 0.0118
	$2d_{3/2}$	$^{97}Zr_{1.103}(3/2^+)$	− 0.0543
	$2d_{5/2}$	$^{97}Zr_{1.103}(3/2^+)$	0.2763
	$1g_{7/2}$	$^{97}Zr_{1.103}(3/2^+)$	− 0.0343
	$3s_{1/2}$	$^{97}Zr_{1.264}(7/2^+)$	0.0251
	$2d_{3/2}$	$^{97}Zr_{1.264}(7/2^+)$	0.0783
	$2d_{5/2}$	$^{97}Zr_{1.264}(7/2^+)$	− 0.1128
	$1g_{7/2}$	$^{97}Zr_{1.264}(7/2^+)$	0.0618
	$3s_{1/2}$	$^{97}Zr_{1.40}(5/2^+)$	0.8267
	$2d_{3/2}$	$^{97}Zr_{1.40}(5/2^+)$	− 0.0809
	$2d_{5/2}$	$^{97}Zr_{1.40}(5/2^+)$	0.0163
	$1g_{7/2}$	$^{97}Zr_{1.40}(5/2^+)$	− 0.0154

table one can observe a reasonable agreement between the theoretical and experimental spectra.

The spectroscopic amplitudes for the projectile overlaps were taken from Ref. [73], where the authors used the effective interaction for the $1p$ shell deduced in a previous paper [74]. The overlaps between the ^6Li g.s. and the ^5Li g.s., as well as the $1/2^-$ resonant state were included. Both the $1p_{3/2}$ and $1p_{1/2}$ components, of similar importance [74], were included in the calculations. The schematic picture of the projectile overlaps is shown in Fig. 5.

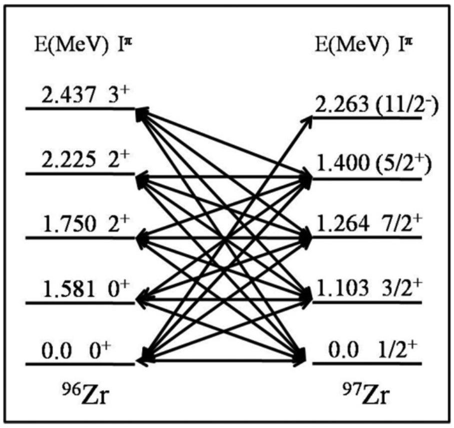

FIG. 6. Coupling scheme for the target overlaps.

The spectroscopic amplitudes for target overlaps, derived from the NUSHELLX code, used in the $1n$-transfer stripping calculations, are given in Table IV. The schematic picture of the target overlaps used in the calculations is shown in Fig. 6. Because we are including target excitations, the transfer to the final states of ^{97}Zr can occur in a direct way or through the excitation of the target (two-step process). The excitations in the final partition were not included. So, we consider having inelastic excitation followed by transfer, but not transfer followed by the excitation of the residual ^{97}Zr.

For both projectile and target, the Woods–Saxon form factors were used with reduced radii $r_0 = 1.2$ fm and diffuseness $a_0 = 0.65$ fm. The depths of the potential were varied to fit the experimental neutron binding energies. The spin-orbit interaction was also included with standard depth of 7 MeV.

For the CRC calculation, a prior exact finite-range approximation was used. Nonorthogonality corrections and full complex remnant term were used in the coupling scheme. All calculations were performed with the FRESCO code [75]. It is important to mention that, as usual for stripping reactions, the post form is used. Nevertheless, if all the relevant corrections (nonorthogonality terms, etc.) and correct optical potential are used, both forms of the matrix elements of the interaction are equivalent. This is an important crosscheck one should perform to access to the optical potential consistency. For this reason, we performed this crosscheck.

In Fig. 7 the experimental data are compared with the results of CRC calculations (full curve). One can observe that, although the energy dependencies of the experimental data and of the theoretical results have a similar shape, the theoretical curve is lower than the data. One should mention that, although in the calculations the direct feeding of the ^{97}Zr ground state was considered in the CRC calculations, it is not included in the curve of Fig. 7, because the experimental transfer cross sections are concerned only with transfer to excited states, owing to the experimental method used.

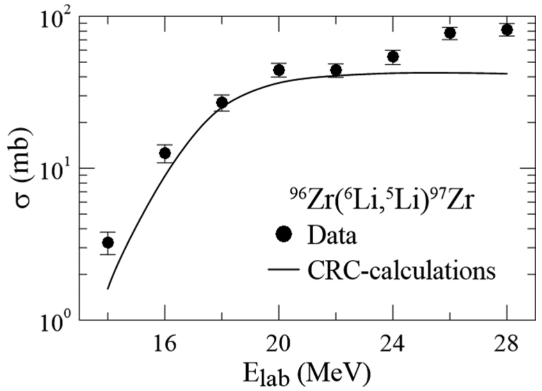

FIG. 7. Comparison of experimental data with CRC calculations for the $^6\mathrm{Li} + {}^{96}\mathrm{Zr} \rightarrow {}^{97}\mathrm{Zr}^* + p + \alpha$ reaction.

In the light of this comparison, we tried to understand this disagreement. First, we tried to enlarge our model space, although we expected that only a very large increment in the model space could account for this disagreement. Our computational limit for NUSHELL calculations did not allow us to calculate spectroscopic amplitudes for higher orbits. However, because we wanted to investigate whether the inclusion of these orbits would have a significant effect on the results, we included other higher orbits ($1h_{9/2}$, $2f_{7/2}$, $2f_{5/2}$, $3p_{3/2}$, and $3p_{1/2}$) assuming spectroscopic amplitudes equal to 1.0. We found negligible effect.

Then we tried to find other possible explanations for the disagreement. One possibility might be that the measured ^{97}Zr residual nucleus may originate from other reaction mechanisms that feed the same final states. So, we investigated the possibility that the breakup of the ^{6}Li into an alpha particle plus deuteron is followed by one neutron transferred from the deuteron to the target. The Q value for this ^{96}Zr(d,p) transfer reaction is $+3.35$ MeV. We performed calculations using the distorted wave Born approximation (DWBA) for the (d,p) reaction. The energy of the deuteron impinging on the ^{96}Zr target was taken to be the energy of the ^{6}Li minus the alpha-deuteron binding energy (1.47 MeV) multiplied by 2/6. The results showed large transfer-reaction cross sections. However, this is just a qualitative result, since we did not calculate the first step of the reaction; that is, the breakup probability. If the reaction proceeds through the 3^+ resonance state of ^{6}Li (as it probably occurs), the deuteron energy should be correct, too. This last option was not included in our tentative calculation.

Another possible reaction mechanism present might be the spectator model proposed in the 1980s by several groups [76–78]. In this case one considers the cluster structure of ^{6}Li. The alpha particle of ^{6}Li does not participate in the reaction, whereas the proton inside the deuteron remains as spectator and the neutron participates in a one-step (d,p) reaction with the target. The difference of this reaction mechanism with the one mentioned above is that the system does not loose energy breaking the ^{6}Li projectile (so, this is a one-step reaction mechanism). However, we are not able to perform this kind of calculation.

So, we suggest that the reaction mechanisms are more complex than the direct one, and two-step one-neutron stripping might solve the discrepancies between the theory and data. This has to be further investigated in the future.

V. SUMMARY AND CONCLUSIONS

We have measured the cross sections for the one-neutron stripping of ^{6}Li to the ^{96}Zr target, feeding excited states of ^{97}Zr, by the online γ- ray spectroscopy method, at energies close to the Coulomb barrier. This cross section is a lower limit for the one-neutron stripping cross section, since it is not possible to determine the cross section for the direct feeding of the ground state of ^{97}Zr by the online γ-spectroscopy method. The derived excitation function drops much less steeply than the complete-fusion excitation function at the lowest energy. At the barrier, this transfer cross section has the same magnitude as the CF cross section. An extrapolation of this trend leads to the conclusion that, at sub-barrier energies, it should predominate over the complete fusion cross section. This behavior may be explained by the peripheral (or surface) character of transfer and breakup reactions, which are direct processes. Particularly, neutron-transfer reactions do not require the tunneling of charged particles through the barrier, as does the fusion process. We believe that this is an important result to be reported, since it shows that, when one is dealing with reactions with weakly bound nuclei, even when the nuclei are not of neutron-halo type, the neutron-transfer reactions may contribute significantly to the total reaction cross section, especially at low energies close to and below the Coulomb barrier.

Our CRC calculations for the one-neutron stripping give results that are slightly lower than the data. We believe that more complex reaction mechanisms might be present, and that this is a very interesting subject to be investigated. Experimentally, one may perform γ-particle-coincidence experiments, as we plan to do in the near future. Theoretically, it is still a challenge for a computer code to take into account all possible reaction mechanisms that might be involved in such systems. As far as we know, this goal is still far from being achieved with present methods and computing facilities.

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[1] L. F. Canto, P. R. S. Gomes, R. Donangelo, and M. S. Hussein, Phys. Rep. **424**, 1 (2006).
[2] N. Keeley, R. Raabe, N. Alamanos, and J. J. Sida, Prog. Part. Nucl. Phys. **59**, 579 (2007).
[3] N. Keeley, N. Alamanos, K. W. Kemper, and K. Rusek, Prog. Part. Nucl. Phys. **63**, 396 (2009).
[4] B. B. Back, H. Esbensen, C. L. Jiang, and K. E. Rehm, Rev. Mod. Phys. **86**, 317 (2014).
[5] J. F. Liang and C. Signorini, Int. J. Mod. Phys. E **14**, 1121 (2005).
[6] K. Hagino and N. Takigawa, Prog. Theor. Phys. **128**, 1061 (2012).
[7] L. F. Canto, P. R. S. Gomes, R. Donangelo, J. Lubian, and M. S. Hussein, Phys. Rep. **596**, 1 (2015).
[8] L. F. Canto, P. R. S. Gomes, J. Lubian, L. C. Chamon, and E. Crema, J. Phys. G **36**, 015109 (2009).
[9] L. F. Canto, P. R. S. Gomes, J. Lubian, L. C. Chamon, and E. Crema, Nucl. Phys. A **821**, 51 (2009).
[10] P. R. S. Gomes, J. Lubian, and L. F. Canto, Phys. Rev. C **79**, 027606 (2009).
[11] H. Kumawat, V. Jha, V. V. Parkar, B. J. Roy, S. K. Pandit, R. Palit, P. K. Rath, C. S. Palshetkar, S. K. Sharma, S. Thakur, A. K. Mohanty, A. Chatterjee, and S. Kailas, Phys. Rev. C **86**, 024607 (2012).
[12] M. K. Pradhan, A. Mukherjee, P. Basu, A. Goswami, R. Kshetri, R. Palit, V. V. Parkar, M. Ray, S. Roy, P. R. Chowdhury, M. S. Sarkar, and S. Santra, Phys. Rev. C **83**, 064606 (2011).
[13] B. Wang, W. J. Zhao, P. R. S. Gomes, E. G. Zhao, and S. G. Zhou, Phys. Rev. C **90**, 034612 (2014).
[14] G. R. Satchler, Phys. Rep. **199**, 147 (1991).
[15] M. A. Nagarajan, C. C. Mahaux, and G. R. Satchler, Phys. Rev. Lett. **54**, 1136 (1985).
[16] M. S. Hussein, P. R. S. Gomes, J. Lubian, and L. C. Chamon, Phys. Rev. C **73**, 044610 (2006).
[17] J. Lubian and F. M. Nunes, J. Phys. G **34**, 513 (2007).
[18] J. Lubian *et al.*, Nucl. Phys. A **791**, 24 (2007).
[19] V. N. Garcia, J. Lubian, P. R. S. Gomes, A. Gomez-Camacho, and L. F. Canto, Phys. Rev. C **80**, 037602 (2009).
[20] S. Santra, S. Kailas, K. Ramachandran, V. V. Parkar, V. Jha, B. J. Roy, and P. Shukla, Phys. Rev. C **83**, 034616 (2011).
[21] V. V. Parkar, V. Jha, S. K. Pandit, S. Santra, and S. Kailas, Phys. Rev. C **87**, 034602 (2013).
[22] J. Lubian, T. Correa, E. F. Aguilera, L. F. Canto, A. Gomez-Camacho, E. M. Quiroz, and P. R. S. Gomes, Phys. Rev. C **79**, 064605 (2009).
[23] N. Keeley, N. Alamanos, K. Rusek, and K. W. Kemper, Phys. Rev. C **71**, 014611 (2005).
[24] J. Lubian, T. Correa, P. R. S. Gomes, and L. F. Canto, Phys. Rev. C **78**, 064615 (2008).
[25] D. S. Monteiro, O. A. Capurro, A. Arazi, J. O. F. Niello, J. M. Figueira, G. V. Marti, D. M. Heimann, A. E. Negri, A. J. Pacheco, V. Guimarães, D. R. Otomar, J. Lubian, and P. R. S. Gomes, Phys. Rev. C **79**, 014601 (2009).
[26] C. S. Palshetkar, S. Thakur, V. Nanal, A. Shrivastava, N. Dokania, V. Singh, V. V. Parkar, P. C. Rout, R. Palit, R. G. Pillay, S. Bhattacharyya, A. Chatterjee, S. Santra, K. Ramachandran, and N. L. Singh, Phys. Rev. C **89**, 024607 (2014).
[27] H. M. Jia, C. J. Lin, H. Q. Zhang, Z. H. Liu, N. Yu, F. Yang, F. Jia, X. X. Xu, Z. D. Wu, S. T. Zhang, and C. L. Bai, Phys. Rev. C **82**, 027602 (2010).
[28] C. J. Lin *et al.*, Nucl. Phys. A **787**, 281c (2007).
[29] R. Rafiei, R. du Rietz, D. H. Luong, D. J. Hinde, M. Dasgupta, M. Evers, and A. Diaz-Torres, Phys. Rev. C **81**, 024601 (2010).
[30] D. H. Luong *et al.*, Phys. Lett. B **695**, 105 (2011).
[31] D. H. Luong, M. Dasgupta, D. J. Hinde, R. du Rietz, R. Rafiei, C. J. Lin, M. Evers, and A. Diaz-Torres, Phys. Rev. C **88**, 034609 (2013).
[32] A. Shrivastava *et al.*, Phys. Lett. B **633**, 463 (2006).
[33] S. Santra *et al.*, Phys. Lett. B **677**, 139 (2009).
[34] P. R. S. Gomes, J. Lubian, I. Padron, and R. M. Anjos, Phys. Rev. C **71**, 017601 (2005).
[35] J. M. B. Shorto *et al.*, Phys. Lett. B **678**, 77 (2009).
[36] P. N. de Faria, R. Lichtenthaler, K. C. C. Pires, A. M. Moro, A. Lépine-Szily, V. Guimarães, D. R. J. Mendes, Jr., A. Arazi, M. Rodríguez-Gallardo, A. Barioni, V. Morcelle, M. C. Morais, O. Camargo, Jr., J. A. Nuñez, and M. Assunção, Phys. Rev. C **81**, 044605 (2010).
[37] X. P. Yang, G. L. Zhang, and H. Q. Zhang, Phys. Rev. C **87**, 014603 (2013).
[38] R. Raabe *et al.*, Nature (London) **431**, 823 (2004).
[39] E. F. Aguilera, J. J. Kolata, F. M. Nunes, F. D. Becchetti, P. A. DeYoung, M. Goupell, V. Guimarães, B. Hughey, M. Y. Lee, D. Lizcano, E. Martinez-Quiroz, A. Nowlin, T. W. O'Donnell, G. F. Peaslee, D. Peterson, P. Santi, and R. White-Stevens, Phys. Rev. Lett. **84**, 5058 (2000); E. F. Aguilera, J. J. Kolata, F. M. Nunes, F. D. Becchetti, P. A. DeYoung, M. Goupell, V. Guimaraes, B. Hughey, M. Y. Lee, D. Lizcano, E. Martinez-Quiroz, A. Nowlin, T. W. O'Donnell, G. F. Peaslee, D. Peterson, P. Santi, and R. White-Stevens, Phys. Rev. C **63**, 061603(R) (2001).
[40] A. di Pietro *et al.*, Phys. Rev. C **69**, 044613 (2004).
[41] A. Navin, V. Tripathi, Y. Blumenfeld, V. Nanal, C. Simenel, J. M. Casandjian, G. de France, R. Raabe, D. Bazin, A. Chatterjee, M. Dasgupta, S. Kailas, R. C. Lemmon, K. Mahata, R. G. Pillay, E. C. Pollacco, K. Ramachandran, M. Rejmund, A. Shrivastava, J. L. Sida, and E. Tryggestad, Phys. Rev. C **70**, 044601 (2004).
[42] A. Chatterjee, A. Navin, A. Shrivastava, S. Bhattacharyya, M. Rejmund, N. Keeley, V. Nanal, J. Nyberg, R. G. Pillay, K. Ramachandran, I. Stefan, D. Bazin, D. Beaumel, Y. Blumenfeld, G. de France, D. Gupta, M. Labiche, A. Lemasson, R. Lemmon, R. Raabe, J. A. Scarpaci, C. Simenel, and C. Timis, Phys. Rev. Lett. **101**, 032701 (2008).
[43] A. Lemasson, A. Navin, N. Keeley, M. Rejmund, S. Bhattacharyya, A. Shrivastava, D. Bazin, D. Beaumel, Y. Blumenfeld, A. Chatterjee, D. Gupta, G. de France, B. Jacquot, M. Labiche, R. Lemmon, V. Nanal, J. Nyberg, R. G. Pillay, R. Raabe, K. Ramachandran, J. A. Scarpaci, C. Simenel, I. Stefan, and C. N. Timis, Phys. Rev. C **82**, 044617 (2010); A. Lemasson, A. Shrivastava, A. Navin, M. Rejmund, N. Keeley, V. Zelevinsky, S. Bhattacharyya, A. Chatterjee, G. de France, B. Jacquot, V. Nanal, R. G. Pillay, R. Raabe, and C. Schmitt, Phys. Rev. Lett. **103**, 232701 (2009).
[44] Y. E. Penionzhkevich *et al.*, Eur. Phys. J. A **31**, 185 (2007).
[45] L. Acosta, A. M. Sanchez-Benitez, M. E. Gomez, I. Martel, F. Perez-Bernal, F. Pizarro, J. Rodriguez-Quintero, K. Rusek, M. A. G. Alvarez, M. V. Andres, J. M. Espino, J. P. Fernandez-Garcia, J. Gomez-Camacho, A. M. Moro, C. Angulo, J. Cabrera, E. Casarejos, P. Demaret, M. J. G. Borge, D. Escrig, O. Tengblad, S. Cherubini, P. Figuera, M. Gulino, M. Freer, C. Metelko, V. Ziman, R. Raabe, I. Mukha, D. Smirnov, O. R. Kakuee, and J. Rahighi, Phys. Rev. C **84**, 044604 (2011).

[46] A. Shrivastava, A. Navin, A. Lemasson, K. Ramachandran, V. Nanal, M. Rejmund, K. Hagino, T. Ichikawa, S. Bhattacharyya, A. Chatterjee, S. Kailas, K. Mahata, V. V. Parkar, R. G. Pillay, and P. C. Rout, Phys. Rev. Lett. **103**, 232702 (2009).
[47] A. Shrivastava *et al.*, Phys. Lett. B **718**, 931 (2013).
[48] A. di Pietro *et al.*, Phys. Rev. C **87**, 064614 (2013).
[49] R. Ost *et al.*, Eur. Phys. J. A **266**, 369 (1974).
[50] C. Signorini, A. Edifizi, M. Mazzocco, M. Lunardon, D. Fabris, A. Vitturi, P. Scopel, F. Soramel, L. Stroe, G. Prete, E. Fioretto, M. Cinausero, M. Trotta, A. Brondi, R. Moro, G. LaRana, E. Vardaci, A. Ordine, G. Inglima, M. LaCommara, D. Pierroutsakou, M. Romoli, M. Sandoli, A. Diaz-Torres, I. J. Thompson, and Z. H. Liu, Phys. Rev. C **67**, 044607 (2003).
[51] D. J. Hinde, M. Dasgupta, B. R. Fulton, C. R. Morton, R. J. Wooliscroft, A. C. Berriman, and K. Hagino, Phys. Rev. Lett. **89**, 272701 (2002).
[52] R. J. Woolliscroft, N. M. Clarke, B. R. Fulton, R. L. Cowin, M. Dasgupta, D. J. Hinde, C. R. Morton, and A. C. Berriman, Phys. Rev. C **68**, 014611 (2003).
[53] C. Signorini, Eur. Phys. J. A **13**, 129 (2002).
[54] Y. D. Fang, P. R. S. Gomes, J. Lubian, X. H. Zhou, Y. H. Zhang, J. L. Han, M. L. Liu, Y. Zheng, S. Guo, J. G. Wang, Y. H. Qiang, Z. G. Wang, X. G. Wu, C. Y. He, Y. Zheng, C. B. Li, S. P. Hu, and S. H. Yao, Phys. Rev. C **87**, 024604 (2013).
[55] Jagdish K. Tuli, *Nuclear Wallet Cards*, National Nuclear Data Center (www.nndc.bnl.gov) (2005).
[56] D. M. Brink, Phys. Lett. B **40**, 37 (1972).
[57] N. Nica, Nucl. Data Sheets **111**, 525 (2010).
[58] C. R. Binghan and G. T. Fabian, Phys. Rev. C **7**, 1509 (1973).
[59] M. Matejska–Mindas *et al.*, Phys. Rev. C **80**, 017302 (2009).
[60] S. P. Hu, G. L. Zhang, J. C. Yang, H. Q. Zhang, P. R. S. Gomes, J. Lubian, X. G. Wu, J. Zhong, C. Y. He, Y. Zheng, C. B. Li, G. S. Li, W. W. Qu, F. Wang, L. Zheng, L. Yu, Q. M. Chen, P. W. Luo, H. W. Li, Y. H. Wu, W. K. Zhou, B. J. Zhu, and H. B. Sun, Phys. Rev. C **91**, 044619 (2015).
[61] L. C. Chamon, D. Pereira, M. S. Hussein, M. A. Cândido Ribeiro, D. Galetti, Phys. Rev. Lett. **79**, 5218 (1997).
[62] L. C. Chamon, B. V. Carlson, L. R. Gasques, D. Pereira, C. DeConti, M. A. G. Alvarez, M. S. Hussein, M. A. CandidoRibeiro, E. S. Rossi, and C. P. Silva, Phys. Rev. C **66**, 014610 (2002).
[63] D. Pereira, J. Lubian, J. R. B. Oliveira, D. P. de Sousa, and L. C. Chamon, Phys. Lett. B **670**, 330 (2008).
[64] D. P. Sousa *et al.*, Nucl. Phys. A **836**, 1 (2010).
[65] T. Matsumoto, E. Hiyama, K. Ogata, Y. Iseri, M. Kamimura, S. Chiba, and M. Yahiro, Phys. Rev. C **70**, 061601(R) (2004).
[66] R. S. Mackintosh and N. Keeley, Phys. Rev. C **79**, 014611 (2009).
[67] K. Rusek, I. Martel, J. Gomez-Camacho, A. M. Moro, and R. Raabe, Phys. Rev. C **72**, 037603 (2005).
[68] Y. Sakuragi, M. Yahiro, and M. Kamimura, Prog. Theor. Phys. **70**, 1047 (1983).
[69] L. R. Gasques, L. C. Chamon, P. R. S. Gomes, and J. Lubian, Nucl. Phys. A **764**, 135 (2006).
[70] S. Raman, C. W. Nestor Jr., and P. Tikkanem, At. Data Nucl. Data Tables **78**, 1 (2001).
[71] W. D. M. Rae, www.garsington.eclipse.co.uk/
[72] T. Engeland, M. Hjorth-Jensen, and E. Osnes, Nucl. Phys. A **701**, 416C (2002).
[73] S. Cohen and D. Kurath, Nucl. Phys. A **101**, 1 (1967).
[74] S. Cohen and D. Kurath, Nucl. Phys. **73**, 1 (1965).
[75] I. J. Thompson, Comput. Phys. Rep. **7**, 167 (1988).
[76] M. S. Hussein and K. W. Mcvoy, Nucl. Phys. A **445**, 124 (1985).
[77] T. Udagawa and T. Tamura, Phys. Rev. C **24**, 1348 (1981).
[78] M. Ichimura, N. Austern, and C. M. Vincent, Phys. Rev. C **32**, 431 (1985).