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EFFECT OF THE $\alpha+t$ CLUSTER STRUCTURE OF ^{7}Li ON THE ^{6}Li$(n,t)^4$He REACTION CROSS SECTION

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Abstract. We investigate how the resonance energies and decay widths of ^{7}Li affect the calculated ^{6}Li$(n,t)^4$He cross section using an $\alpha+t$ two-cluster model. The resonance energies and decay widths of the low-lying odd-parity states of ^{7}Li are calculated with the complex scaling method (CSM) and the parity-dependent Nishioka α–t interaction, and are compared with evaluated values and with predictions of other phenomenological and microscopic models. The calculated $7/2^-_1$ resonance energy and decay width agree well with the evaluated values, whereas larger differences appear for the $5/2^-_1$ resonance energy and decay width. We then use the calculated resonance parameters in an $\alpha+t$ cluster-strength parametrization of the ^{6}Li$(n,t)^4$He cross section over the measured neutron-energy range $E_n = 3.3$–9.8 MeV, first with the present Nishioka+CSM resonance parameters and then with those obtained with the Morse potential, keeping all other parameters fixed. Both calculations reproduce the overall decrease of the measured cross section with increasing neutron energy. The Morse-potential calculation gives larger cross sections over the whole range above the lowest measured energy, by up to about 8 mb near $E_n \approx 5.3$ MeV and by about 30% at 9.8 MeV. Within the present two-resonance parametrization, this difference arises almost entirely from the $5/2^-_1$ resonance energy; the effect of its decay width and of the $7/2^-_1$ resonance is small. The cross section calculated in this parametrization is therefore most sensitive to the position of the $5/2^-_1$ resonance.

Keywords: ^{6}Li$(n,t)^4$He reaction; $\alpha+t$ cluster model; ^{7}Li resonances, neutron-induced reaction

INTRODUCTION

The ^{6}Li$(n,t)^4$He reaction has attracted considerable interest from both theoretical and experimental perspectives. Its large cross section and high Q-value ($Q = 4.783$ MeV) make it a standard reaction for neutron detection and flux measurements. The ^{6}Li nucleus is weakly bound with respect to the $\alpha+d$ breakup (separation energy 1.47 MeV) and exhibits a pronounced $\alpha+d$ cluster structure. Following neutron absorption, an intermediate ^{7}Li nucleus is formed, which subsequently decays into the $\alpha+t$ channel. Because the outgoing channel is an $\alpha+t$ cluster configuration of ^{7}Li, this reaction is particularly suitable for studying the role of ^{7}Li resonance parameters. In particular, the resonance energies and decay widths can affect how the calculated ^{6}Li$(n,t)^4$He cross section changes with incident neutron energy.

Recent measurements have extended the cross-section data for the ^{6}Li$(n,t)^4$He reaction in the fast-neutron region. Gledenov *et al.* measured the reaction using a gridded ionization chamber, detecting the emitted α particle and triton in coincidence, and obtained cross sections in the MeV neutron-energy region [1]. Kirsch *et al.* extended the measurements to neutron energies approaching 10 MeV using a ^{252}Cf fission chamber and ^{6}Li-containing scintillators [2]. Together, these measurements provide cross-section data over the neutron-energy range $E_n = 3.3$–9.8 MeV.

In the present work, we describe the intermediate ^{7}Li nucleus within an $\alpha+t$ two-cluster model. We calculate the resonance energies and decay widths of the low-lying odd-parity states using the CSM [3, 4, 5, 6, 7, 8] with the parity-dependent Nishioka α–t interaction [9]. The calculated resonance parameters are compared with evaluated

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data [10] and with results of phenomenological and microscopic $\alpha+t$ models [11, 12, 13, 14].

Next, we use the calculated resonance parameters in an $\alpha+t$ cluster-strength parametrization of the ^{6}Li$(n,t)^4$He cross section. We first calculate the cross section using the Nishioka+CSM resonance parameters and then using the Morse-potential values, while keeping the remaining cross-section parameters unchanged. By comparing the two calculations, we determine how the chosen resonance energies and decay widths affect the calculated cross section over the measured neutron-energy range.

THEORETICAL METHOD

Two-body $\alpha+t$ model

The ^{7}Li nucleus is described within a two-body $\alpha+t$ cluster model. The Hamiltonian of the relative motion is

$$H = T + V_N(r) + V_{\ell s}(r) + V_C(r) + \lambda \sum_f |\phi_f\rangle\langle\phi_f|, \tag{1}$$

where $T = -\frac{\hbar^2}{2\mu}\nabla^2$ is the kinetic energy of the relative motion with the $\alpha+t$ reduced mass μ ($\hbar^2/2\mu = 12.15$ MeV fm^2), V_N is the parity-dependent central nuclear interaction, $V_{\ell s}$ is the spin–orbit interaction, and V_C is the Coulomb interaction. The last term is the pseudopotential of the orthogonality condition model (OCM), which projects out the Pauli-forbidden states ϕ_f ($\lambda \to \infty$).

For the nuclear potential, we employ the parity-dependent α–t interaction proposed by Nishioka *et al.* within the OCM [9]. The potential was constructed to reproduce the low-lying states of the $\alpha+t$ system, including scattering and bound-state information, while the OCM treatment accounts for Pauli-forbidden states between the two clusters. For the $\alpha+t$ system the relative-motion states with $2n+\ell<3$ are Pauli forbidden; among the odd-parity states only the $0p$ state ($\ell=1$) is forbidden, so the $\ell=3$ states considered here are not affected by the projection. An important feature of this interaction is its explicit parity dependence, which originates from microscopic nucleon-exchange effects between the α and t clusters. The central interaction for the odd-parity states is

$$V_N^{(-)}(r) = -86.15\exp(-0.1644\,r^2)\ \text{MeV}, \tag{2}$$

with r in fm. The spin–orbit interaction has the Gaussian form

$$V_{\ell s}(r) = -V_0\exp(-0.25\,r^2)\,\ell\cdot\mathbf{s}. \tag{3}$$

For the $\ell=3$ doublet, $\langle\ell\cdot\mathbf{s}\rangle = +3/2$ for $J^\pi = 7/2^-$ and -2 for $J^\pi = 5/2^-$, so that a positive V_0 lowers the $7/2^-$ state relative to the $5/2^-$ state. We treat V_0 as the spin–orbit strength parameter and consider $V_0 = 2$, 4, and 6 MeV, examining the resulting spin–orbit splitting of the low-lying odd-parity states by comparison with the evaluated resonance energies of Ref. [10].

The Coulomb interaction between the α particle and the triton is

$$V_C^{\alpha t}(r) = \frac{Z_\alpha Z_t e^2}{r}\,\mathrm{erf}(\alpha_C r), \qquad \alpha_C = \sqrt{\frac{4}{3}\nu_\alpha}, \tag{4}$$

with $Z_\alpha = 2$, $Z_t = 1$, $e^2 = 1.44$ MeV fm, and $\nu_\alpha = \nu_t = 0.4555$ fm^{-2} ($\alpha_C = 0.779$ fm^{-1}).

Complex scaling method

In the CSM [3, 4, 5, 6, 7, 8], the relative coordinate is transformed as $r \to re^{i\theta}$, and the complex-scaled Schrödinger equation is

$$H^\theta \Psi^\pi_{J\nu}(\theta) = E^\theta_{J\nu}\Psi^\pi_{J\nu}(\theta), \tag{5}$$

where J^π is the spin and parity, ν is the state index, and θ is the scaling angle. Using an L^2 basis, the wave function is expanded as

$$\begin{aligned}\Psi^\pi_{J\nu}(\theta) &= \sum_{n=1}^{N} C^\pi_{n,J\nu}(\theta)\,\phi_n(r),\\ \phi_n(r) &\propto r^\ell\exp(-r^2/b_n^2),\end{aligned} \tag{6}$$

where the Gaussian range parameters b_n form a geometric progression. According to the ABC theorem [4, 5], the continuum states rotate in the complex energy plane by 2θ, whereas resonances appear as isolated eigenvalues independent of θ:

$$E = E_{\text{res}} - i\frac{\Gamma}{2}. \tag{7}$$

The resonance energies and widths reported below are stable against variation of the scaling angle in the range θ and against enlargement of the basis.

$\alpha+t$ cluster-strength parametrization of the measured cross section

We describe the $^6\mathrm{Li}(n,t)^4\mathrm{He}$ reaction through the formation and subsequent decay of the intermediate ^{7}Li nucleus,

$$^6\mathrm{Li}+n \to {}^7\mathrm{Li}^* \to \alpha+t. \tag{8}$$

Within the present model, we treat the intermediate ^{7}Li nucleus as an $\alpha+t$ two-cluster system and use its resonance parameters to construct the cluster-strength function entering the cross-section calculation.

The neutron energy is related to the $\alpha+t$ relative energy and to the ^{7}Li excitation energy by

$$\begin{aligned} E_{\mathrm{rel}}^{(\alpha t)} &= \frac{M_{^6\mathrm{Li}}}{M_{^6\mathrm{Li}}+m_n}E_n+Q, \\ E_x(^7\mathrm{Li}) &= E_{\mathrm{rel}}^{(\alpha t)}+E_{\mathrm{th}}(\alpha+t), \end{aligned} \tag{9}$$

with $Q=4.783$ MeV and the $\alpha+t$ threshold energy $E_{\mathrm{th}}=2.467$ MeV. The measured neutron-energy range therefore corresponds to $E_{\mathrm{rel}}^{(\alpha t)}=7.61$–$13.18$ MeV and $E_x(^7\mathrm{Li})=10.08$–15.65 MeV. The low-lying $7/2_1^-$ and $5/2_1^-$ resonances included in the present parametrization lie below this energy range and are therefore not excited as resonances within the measured region, so they should not be interpreted as direct resonance states in this range. However, the corresponding Breit–Wigner functions remain finite above the resonance energies, so their off-resonance contributions may still affect the calculated cross section. The calculated resonance parameters are thus used to construct a phenomenological strength function that characterizes the possible contribution of the $\alpha+t$ cluster structure of the outgoing channel to the measured cross section.

For a given resonance state r, we describe the energy dependence by the Breit–Wigner strength function

$$B_r(E)=\frac{(\Gamma_r/2)^2}{(E-E_{R,r})^2+(\Gamma_r/2)^2}, \tag{10}$$

where $E_{R,r}$ and Γ_r denote the resonance energy and decay width, respectively. We use $B_r(E)$ only as a resonance-strength function and do not interpret it as a reaction cross section.

The contributions of the $7/2_1^-$ and $5/2_1^-$ states, denoted collectively by $\mathscr{R}=\{7/2_1^-,5/2_1^-\}$, are combined into the normalized $\alpha+t$ cluster-strength function

$$S_{\alpha t}(E_n)=\frac{\sum_{r\in\mathscr{R}}B_r\left(E_{\mathrm{rel}}^{(\alpha t)}\right)}{\max\limits_{E_n\in[3.3,9.8]\,\mathrm{MeV}}\left[\sum_{r\in\mathscr{R}}B_r\left(E_{\mathrm{rel}}^{(\alpha t)}\right)\right]}. \tag{11}$$

The cross section is parametrized as

$$\sigma_{n,t}^{\mathrm{fit}}(E_n)=a+b(E_n-E_{\mathrm{ref}})+cS_{\alpha t}(E_n), \tag{12}$$

where $a+b(E_n-E_{\mathrm{ref}})$ represents a smooth background contribution, $S_{\alpha t}(E_n)$ is the cluster-strength function, and $E_{\mathrm{ref}}=4.20$ MeV. The parameters of Eq. (12),

$$\begin{aligned} a &= 46.06\ \mathrm{mb}, \\ b &= -6.72\ \mathrm{mb\,MeV^{-1}}, \\ c &= 76.18\ \mathrm{mb}, \end{aligned} \tag{12a}$$

were determined by a least-squares fit to the combined data of Refs. [1, 2] using the Nishioka+CSM resonance parameters and are kept fixed in all calculations below. Because the background is linear and the strength function is normalized, Eq. (12) is a phenomenological parametrization valid only within the measured range.

Since both resonances lie well below the measured range, $|E_{\mathrm{rel}}^{(\alpha t)}-E_{R,r}|\gg\Gamma_r/2$, and

$$B_r(E)\simeq\frac{(\Gamma_r/2)^2}{(E-E_{R,r})^2}. \tag{13}$$

When one resonance dominates the sum, its width cancels in the normalization of Eq. (11), and $S_{\alpha t}\simeq(E_{\mathrm{min}}-E_{R,r})^2/(E-E_{R,r})^2$, where $E_{\mathrm{min}}=7.61$ MeV. The shape of $S_{\alpha t}$ is then determined mainly by the resonance energy, while the widths enter only through the relative weights of the two terms.

RESULTS AND DISCUSSION

Model dependence of the resonance states

The calculated and evaluated resonance parameters of the low-lying odd-parity states of ^{7}Li are summarized in Table 1. The resonance energies are given relative to the $\alpha + t$ threshold. The comparison includes phenomenological two-cluster descriptions, phase-shift-constrained interactions, and a microscopic many-body calculation, and therefore provides an indication of the theoretical model dependence of the $\alpha + t$ continuum spectrum.

For the $7/2^-_1$ state, the resonance energy is relatively stable among the phenomenological descriptions. The evaluated value is $E_R = 2.18$ MeV, while the present two-cluster CSM calculation gives 2.05 MeV. The Morse and Malfliet–Tjon potentials give 2.19 and 2.20 MeV, respectively. The NCSMC calculation predicts a higher value of 2.79 MeV. The calculated widths of this narrow state lie between 0.067 and 0.11 MeV in the phenomenological models, close to the evaluated width of 0.069 MeV; the present result, $\Gamma = 0.067$ MeV, is in good agreement with it. The NCSMC width (0.214 MeV) is larger, consistent with its higher resonance energy.

A stronger model dependence is found for the $5/2^-_1$ resonance. The evaluated resonance energy is 4.14 MeV, whereas the present two-cluster CSM calculation gives 4.93 MeV. The Morse potential places this state at 3.60 MeV, while the Malfliet–Tjon and NCSMC calculations give 4.18 and 4.04 MeV, respectively. The calculated decay widths range from 0.704 MeV for the Morse interaction to 1.41 MeV in the present calculation. The present calculation therefore overestimates the spin–orbit splitting of the $\ell = 3$ doublet (2.88 MeV, compared with the evaluated 1.96 MeV). Because the width of an $\ell = 3$ resonance increases rapidly with energy owing to the Coulomb–centrifugal barrier, the larger width of the present $5/2^-_1$ state is largely a consequence of its higher energy. These results show that the broader $5/2^-_1$ state is particularly sensitive to the theoretical description of the $\alpha + t$ subsystem.

The numerical values listed in Table 1 should not, however, be interpreted as predictions for identical theoretical problems. The f-wave Woods–Saxon interaction of Fortunato and Vitturi was adjusted to reproduce the experimental $7/2^-$ and $5/2^-$ resonance positions [11], whereas the Morse and Malfliet–Tjon interactions were constrained mainly by $\alpha + t$ elastic-scattering phase shifts [12, 13]. The NCSMC calculation provides a microscopic many-body description in which the $\alpha + t$ continuum is coupled to discrete many-body configurations [14].

The Morse potential

The present two-cluster calculation uses the Nishioka interaction described above; to assess the sensitivity of the calculated cross section to the $\alpha + t$ resonance parameters, an additional set of resonance parameters obtained with the Morse potential was also used in the cross-section calculation. The two sets of resonance parameters differ both in the form of the α–t interaction and in the method used to determine the resonance properties. In the present calculation, the parity-dependent Gaussian-type Nishioka potential is used in the two-cluster Hamiltonian, and the resonance energies and widths are obtained with the CSM. In contrast, the Morse potential is employed within a phase-function approach, in which the potential parameters are constrained by measured $\alpha + t$ scattering phase shifts and the resonance parameters are extracted from the resulting scattering behavior [12].

These different theoretical methods lead to noticeably different resonance parameters. For the $7/2^-_1$ state, the present calculation gives $E_R = 2.05$ MeV and $\Gamma = 0.067$ MeV, whereas the Morse calculation gives $E_R = 2.19$ MeV and $\Gamma = 0.090$ MeV. Thus, the resonance energies differ by about 0.14 MeV, while the decay widths differ by only about 0.02 MeV. A substantially larger difference is obtained for the $5/2^-_1$ state. The present calculation gives $E_R = 4.93$ MeV and $\Gamma = 1.41$ MeV, whereas the Morse potential gives $E_R = 3.60$ MeV and $\Gamma = 0.704$ MeV. The differ-

Table 1 – Comparison of the $7/2^-_1$ and $5/2^-_1$ resonance parameters of ^{7}Li obtained from different theoretical descriptions of the $\alpha+t$ system. Resonance energies are given relative to the $\alpha+t$ threshold.

			$7/2^-_1$		$5/2^-_1$	
Model	Approach	Interaction	E_R (MeV)	Γ (MeV)	E_R (MeV)	Γ (MeV)
Evaluated [10]	Evaluated data	–	2.18	0.069	4.14	0.918
Present work	Two-cluster CSM	Nishioka (OCM) + Gaussian ℓs	2.05	0.067	4.93	1.41
Fortunato–Vitturi [11]	Dicluster model	Woods–Saxon + derivative ℓs	2.18[a]	0.110	4.14[a]	0.930
Morse potential [12]	Phase-function method	Morse + finite-size Coulomb	2.19	0.090	3.60	0.704
Malfliet–Tjon [13]	Phase-function method	Malfliet–Tjon + Hulthén Coulomb	2.20	0.099	4.18	1.100
NCSMC [14]	Microscopic many-body	SRG-evolved chiral N^{3}LO NN	2.79	0.214	4.04	0.785

[a] The f-wave Woods–Saxon parameters were adjusted to reproduce the $7/2^-$ and $5/2^-$ resonances at the experimental energies.

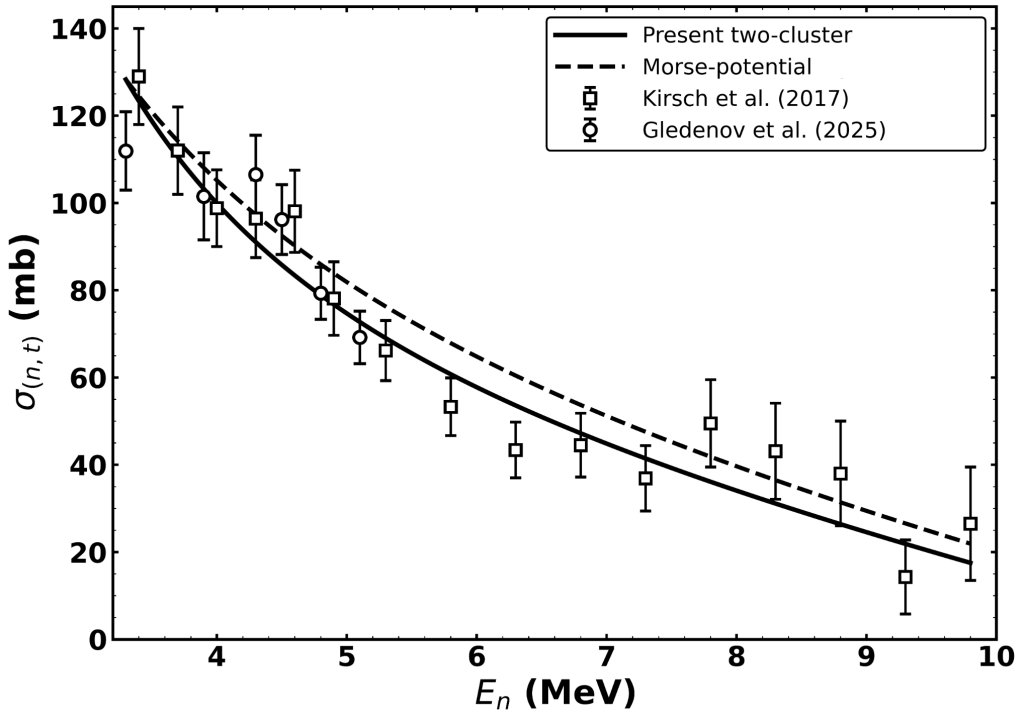


Figure 1 - Measured and calculated cross sections for the ^{6}Li$(n,t)^4$He reaction as a function of neutron energy. Open circles represent the data of Gledenov *et al.* [1], while open squares denote the measurements of Kirsch *et al.* [2], which extend the experimental comparison to approximately 10 MeV. The solid curve is obtained using the resonance energies and widths from the present $\alpha+t$ two-cluster calculation, whereas the dashed curve corresponds to the resonance parameters of the Morse potential; the parameters a, b, and c of Eq.(12) are the same for both curves.

ences are 1.33 MeV in resonance energy and 0.71 MeV in decay width.

The Morse interaction was selected because its resonance energies and decay widths were obtained independently from $\alpha + t$ scattering phase shifts and differ appreciably from those of the present Nishioka+CSM calculation. By contrast, the Fortunato–Vitturi resonance energies were adjusted to reproduce the experimental values, and the Malfliet–Tjon resonance energies lie close to the evaluated values. The NCSMC calculation differs not only in the effective interaction but also in the microscopic many-body framework. The Morse potential therefore provides the most informative alternative parameter set for the cross-section comparison.

In the first calculation, the resonance energies and widths obtained with the present Nishioka+CSM calculation are used in the $\alpha + t$ strength function. In the second calculation, these quantities are replaced by the Morse-potential results, while the form and remaining parameters of the cross-section parametrization are kept unchanged. Accordingly, the difference between the two calculated cross sections arises only from the different resonance energies and decay widths.

Calculation of the ^{6}*Li*$(n,t)^4$*He cross section*

The experimental cross sections used in this calculation are taken from the measurements of Gledenov *et al.* [1] and Kirsch *et al.* [2] in the range $E_n = 3.3$–9.8 MeV.

As shown in Fig. 1, the measured ^{6}Li$(n,t)^4$He cross sections are compared with calculations performed using the two sets of ^{7}Li resonance parameters. In both cases, Eq. (12) is used without modifying the cross-section parametrization. The solid curve corresponds to the resonance energies and decay widths obtained in the present Nishioka+CSM calculation, whereas the dashed curve is obtained by replacing these values with the corresponding Morse-potential results.

Both calculations reproduce the overall experimental trend, namely the gradual decrease of the ^{6}Li$(n,t)^4$He cross section with increasing neutron energy. Because of the normalization in Eq.(11), the two curves coincide at the lowest energy, $E_n = 3.3$ MeV. Above this energy the calculation based on the Morse-potential resonance parameters gives systematically larger cross sections than the present Nishioka+CSM result. The absolute difference reaches about 8 mb near $E_n \approx 5.3$ MeV and decreases to about 5 mb at 9.8 MeV, where it corresponds to about 30% of the calculated cross section.

Within the present two-resonance parametrization, this difference is governed mainly by the $5/2^-_1$ resonance. Because the $5/2^-_1$ term is closer to the measured range and much broader, it accounts for more than 99% of the summed strength in Eq. (11), whereas the contribution of the narrow $7/2^-_1$ term is negligible. To separate the two parameters, we repeated the calculation by changing only one quantity at a time. Replacing only the $5/2^-_1$ resonance energy by the Morse value (4.93→3.60 MeV) changes the cross section by up to 8.4 mb, whereas replacing only its width (1.41→0.704 MeV) changes it by less than 1 mb, and replacing the $7/2^-_1$ parameters has no visible effect. This is consistent with Eq. (13): the shape of the normalized strength function is determined mainly by the $5/2^-_1$ resonance energy. A lower $5/2^-_1$ resonance energy, i.e., a larger distance from the measured range, gives a normalized strength function that decreases more slowly with energy, and hence a larger calculated cross section at higher neutron energies.

The remaining local deviations from the data, e.g., near $E_n \approx 6$–7 MeV and 7.8–8.8 MeV, cannot be described by the off-resonance tails of the two low-lying states. These energies correspond to $E_x(^7\text{Li}) \approx 10$–$15.6$ MeV, where higher-lying ^{7}Li states are known [10], and their explicit inclusion would be required for a more complete description.

CONCLUSION

The resonance energies and decay widths of the low-lying odd-parity states of ^{7}Li were calculated within an $\alpha + t$ two-cluster model using the complex scaling method with the parity-dependent Nishioka α–t interaction. Comparison with eval-

uated values and other calculations shows that the $7/2^-_1$ resonance energy and width are well reproduced, whereas larger differences occur for the $5/2^-_1$ resonance, particularly in its energy and decay width.

These resonance parameters were employed in an $\alpha+t$ cluster-strength parametrization of the ^{6}Li$(n,t)^4$He cross section over $E_n = 3.3$–9.8 MeV. Calculations using the present Nishioka+CSM and Morse-potential resonance parameters both reproduce the overall decrease of the measured cross section with increasing neutron energy. The Morse-potential calculation gives larger cross sections above the lowest measured energy, and within the present two-resonance parametrization this difference is governed mainly by the energy of the $5/2^-_1$ resonance, while the influence of its width is small.

The $7/2^-_1$ and $5/2^-_1$ states lie below the $\alpha+t$ relative-energy range corresponding to the measurements and are therefore not directly excited as resonances in this region. Their off-resonance contributions, however, may affect the calculated cross section. The remaining local deviations from the experimental data indicate that additional ^{7}Li states and reaction effects may be required for a more complete description. The present results therefore show that the adopted resonance parameters, especially the energy of the $5/2^-_1$ state, have an important effect on the calculated ^{6}Li$(n,t)^4$He cross section within the present parametrization.

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