Parity-violating $\alpha$-decay of the 3.56-MeV $J^\pi, T = 0^+, 1$ state of $^6$Li

Attila Csótó$^1$ and Karlheinz Langanke$^2$

$^1$National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

$^2$W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

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Abstract

We study the parity-violating $\alpha + d$ decay of the lowest $0^+$ state of $^6$Li in a microscopic three-cluster model. The initial bound and the final scattering states are described consistently within the same model. The parity-violating decay width is calculated in perturbation theory using the parity-nonconserving nucleon-nucleon interaction of Desplanques, Donoghue, and Holstein (DDH). We find that the decay width is sensitive to dynamical degrees of freedom which are beyond the $\alpha + p + n$ model, for example, $\alpha$ excitation and breakup. In our full model, which contains breathing excitations of the $\alpha$ particle and $^3$H+$^3$He rearrangement, the parity-nonconserving decay width is $\Gamma^{PNC}_{\alpha d} = 3.97 \cdot 10^{-9}$ eV, using the DDH coupling constants.
I. INTRODUCTION

Parity violation has played an important role in the understanding of the nature of the weak interaction. Today the weak interaction is well understood in the leptonic, semileptonic, and strange nonleptonic sectors. However, our picture of the nonstrange nonleptonic weak interaction, which appears in nuclear processes, e.g. in \( n + p \) scattering, is far from being complete [1,2]. The presence of the strong part of the nucleon-nucleon force makes the effect of the weak nucleon-nucleon interaction hardly observable. The size of the parity violating effect is, for example, typically in the order of \( 10^{-7} \) relative to the effect of the strong \( N-N \) force.

Despite the smallness of its effect, parity violation in a nuclear process was experimentally observed in 1967 by Lobashov et al. [3]. Since then, nuclear parity violation has been studied in \( p + p \) scattering and \( p + n \) capture, in few-nucleon systems (e.g. \( p + d \) and \( p + \alpha \) scattering), in parity-mixed doublets of light nuclei, and in polarized neutron scattering on heavy nuclei. For two excellent review articles on the nuclear parity violation experiments, see Refs. [1,2].

Complex nuclear structure and dynamics often leads to ambiguities in the theoretical description of nuclear parity violation involving light nuclei. However, impressive theoretical progress has been achieved recently in the description of the six-nucleon systems [4,5,6,7,8,9,10]. While realistic GFMC results for light nuclei, including for \( ^6 \text{Li} \), are very encouraging [4], these studies are basically restricted to bound states. However, effective many-body theories like the microscopic multicluster model yield a good and consistent description of the nuclear structure and dynamics (bound and scattering states) in the six-nucleon systems simultaneously [3,7]. This method appears thus to be well suited for the study of the parity-violating \( \alpha + d \) decay of the \( J^\pi, T = 0^+, 1 \) state of \(^6\text{Li} \) at 3.56 MeV excitation energy. As the spin-parity of the deuteron is \( 1^+ \), the decay of the \( 0^+ \) \(^6\text{Li} \) state into the \( \alpha + d \) channel is only possible if the continuum final state is \( J^\pi = 0^- \); thus this process violates parity. As the final state is \( T = 0 \), this process is sensitive to the isovector part of the parity-violating \( N-N \) potential. The best experimental upper limit for the parity-violating \( \alpha + d \) partial decay width is \( \Gamma \leq 6.5 \cdot 10^{-7} \) eV [11]. The two most comprehensive theoretical descriptions of this process are based on the shell model [12] and the harmonic oscillator cluster model [13], respectively. If one assumes the same parameters for the parity-violating \( N-N \) potential, these two studies find parity-violating decay widths which differ by orders of magnitude. Both of these models contain questionable approximations. In [13] the initial \( 0^+ \) wave function is rather schematically described by one \( \alpha(pn) \) configuration with total spin and angular momentum zero. Note that the initial state has a spatially extended halo-like neutron-proton tail [14]. The ability of the shell model [12] to reproduce such a loosely bound state with genuine three-body \( (\alpha + p + n) \) nature is questionable. A model which cannot reproduce this tail tends to compress the wave function inside, thus supposedly increasing the decay width. Moreover, both studies [12,13] use a potential model for the \( \alpha + d \) scattering, which is inconsistent with the description of the bound state.

In the present paper we study the problem in a six-body three-cluster model, which is practically complete in the \( \alpha + p + n \) space. We also investigate the effects of \( \alpha \) distortion and \( t^+ \)\(^3\text{He} \) rearrangement on the decay width. Our model correctly describes the spatially extended nature of the \( 0^+ \) bound state, and uses an \( \alpha + d \) scattering state which is consistent with the bound state. We try to use a model which is as parameter-free as possible by
requiring the good reproduction of the properties of the subsystems \((N + N \text{ and } \alpha + N)\) scattering states, channel thresholds, binding energies, etc.)

II. MODEL

We use the parity-nonconserving nucleon-nucleon potential of Desplanques, Donoghue, and Holstein [15], which was derived from a valence quark model. The isovector part of this potential reads

\begin{align}
V^{\text{PNC}}(r) &= \frac{f_\pi g_{\pi NN} i}{\sqrt{2}} \left( \frac{\tau_1 \times \tau_2}{2} \right) z (\sigma_1 + \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2M}, f_\pi(r) \right] \\
&\quad - g_\rho h_\rho^1 \left( \frac{\tau_1 + \tau_2}{2} \right) z (\sigma_1 - \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2M}, f_\rho(r) \right] \\
&\quad + i(1 + \chi_V)(\sigma_1 \times \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2M}, f_\rho(r) \right] \\
&\quad - g_\omega h_\omega^1 \left( \frac{\tau_1 - \tau_2}{2} \right) z (\sigma_1 + \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2M}, f_\omega(r) \right] \\
&\quad + i(1 + \chi_S)(\sigma_1 \times \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2M}, f_\omega(r) \right] \\
&\quad - g_\omega h_\omega^1 \left( \frac{\tau_1 - \tau_2}{2} \right) z (\sigma_1 + \sigma_2) \cdot \left[ \frac{p_1 - p_2}{2M}, f_\omega(r) \right], \tag{1}
\end{align}

where \(r = |\mathbf{r}_1 - \mathbf{r}_2|\), \(f_\alpha(r) = \exp(-m_\alpha r)/4\pi r\) with \(m_\alpha\) being the \(\pi^\pm, \rho\), and \(\omega\) meson masses, \(p_i\) are the nucleon momenta, \(M\) is the nucleon mass, and \(\sigma\) and \(\tau\) are the spin and isospin Pauli matrices, respectively. The scalar and vector magnetic moments are \(\chi_S = -0.12\), and \(\chi_V = 3.70\), and \([\ldots]\) and \(\{\ldots\}\) denote commutators and anticommutators, respectively. We use the redefined coupling constants of [1]

\[F_\pi = f_\pi g_{\pi NN}/\sqrt{32}, \quad F_1 = -g_\rho h_\rho^1/2, \quad G_1 = -g_\omega h_\omega^1/2.\]  

The best values and reasonable ranges of the coupling constants, based on the DDH theory, can be found in [1,15].

The parity-violating \(\alpha + d\) decay width is calculated perturbatively

\[\Gamma_{\alpha d}^{\text{PNC}} = \hbar W_{fi} = 2\pi \left| \langle \Psi^{\text{ad}} | \hat{V}^{\text{PNC}} | \Psi^{\text{6Li}} \rangle \right|^2 \varrho(E_f),\]  

where \(\varrho(E_F)\) is the density of the continuum states at the final state energy \(E_f = (3.563 - 1.475) = 2.088\) MeV.

Our initial \(^6\text{Li}\) state reads

\[\Psi^{\text{6Li}} = \Psi^{\text{ppm}} + \Psi^{\text{th}} = \sum_{(ij)k, S, L} A \left\{ \left[ \Phi^i(\Phi^j\Phi^k) \right]_{SL} \chi^{ij}_{(i,j)k,l} (\rho_{ij}, \rho_{i,j}) \right\}_{JM} + \sum_{S, L} A \left\{ \left[ \Phi^i\Phi^h \right]_{SL} \chi^{th}_{(i,j)} (\rho_{th}) \right\}_{JM}, \]  

\[3\]
where the indices $i, j, k$ denote any one of the labels $\alpha, p, n$. In (4) $A$ is the intercluster antisymmetrizer, the $\Phi$ cluster internal states are translationally invariant harmonic oscillator shell model states, the $\rho$ vectors are the different intercluster Jacobi coordinates, and [...] denotes angular momentum coupling. The sum over $S, l_1, l_2,$ and $L$ includes all angular momentum configurations of any significance. The last term in (4) is the $t + h = ^3\text{H} + ^3\text{He}$ rearrangement channel. The monopole breathing distortions of the $\alpha$ particle is considered by

$$
\Psi^{\alpha pm} = \Psi^{\alpha 1 pm} + \Psi^{\alpha 2 pm} + \ldots,
$$

where the antisymmetrized ground state ($i = 1$) and monopole excited states ($i > 1$) of the $\alpha$ particle are represented by the wave functions

$$
\Phi^{\alpha i} = \sum_{j=1}^{N_\alpha} A_{ij} \phi_{\beta j}^{\alpha}, \quad i = 1, 2, \ldots, N_\alpha.
$$

Here $\phi_{\beta j}^{\alpha}$ is a translationally invariant shell–model wave function of the $\alpha$ particle with size parameter $\beta_j$ and the $A_{ij}$ parameters are to be determined by minimizing the energy of the $\alpha$ particle [6]. We choose the same parameters for the wave function as in Ref. [7]. We note, that the same model excellently reproduced the neutron halo structure of $^6\text{He}$ [7]. Thus the current approach is adequate to describe spatially extended systems, like the $0^+\text{ state}$ of $^6\text{Li}$, which is the analog of the $^6\text{He}$ ground state.

The wave function of the final continuum state reads (with $L = 1, S = 1, \text{and } J^{\pi} = 0^-$),

$$
\Psi^{\alpha d} = A \left\{ \left[ [\Phi^{\alpha 1} \Phi^{d 1}]_S g^{\alpha 1 d 1}_L (E, \rho_{ad}) \right]_{JM} \right\}
+ \sum_{i=2}^{N_\alpha} \sum_{j=2}^{N_d} A \left\{ \left[ [\Phi^{\alpha i} \Phi^{d j}]_S \chi^{\alpha i d j}_L (E, \rho_{ad}) \right]_{JM} \right\}
+ A \left\{ \left[ [\Phi^{d 1} \Phi^{h}]_S \chi^{th}_L (E, \rho_{th}) \right]_{JM} \right\}.
$$

Here $E$ is the $\alpha + d$ relative motion energy in the center-of-mass frame. To account for specific distortion effects in the deuteron, we expand its wave function by 5 basis states ($N_d = 5$). The ground state $\Phi^{d 1}$ reproduces the deuteron binding energy ($-2.20 \text{ MeV}$) and (point nucleon) rms-radius (1.95 fm) very well. In (4) the $\alpha + d$ final state is taken to be the time-reversed of a state with an incoming plane wave, $\exp(i k r)$, and scattered spherical waves. The plane wave is then projected to $L = 1$. The normalization of $g$ in (7) is chosen consistently with the form of the plane wave. Thus for $\rho_{ad} \to \infty$ one has

$$
g^{\alpha 1 d 1}_1 (E, \rho_{ad}) \to \frac{Y_{1m}(\hat{\rho}_{ad})(k \rho_{ad})^{-1}}{F_1(k \rho_{ad}) \cos \delta + G_1(k \rho_{ad}) \sin \delta},
$$

where $k$ is the wave number, $F_1$ and $G_1$ are Coulomb functions, and $\delta$ is the $^3P_0 \alpha + d$ phase shift at energy $E$.

Our model wave functions contain a large and physically most important part of the six-body Hilbert space. Although, our model is currently probably the closest approximation
to a consistent and dynamically correct full six-body description of the parity-violating decay process, it still has limitations. To estimate these limitations we perform a series of calculations in increasingly sophisticated model spaces by subsequently adding $t + h$ rearrangement and $\alpha$ distortions to our model.

Putting (4)-(5) into the six-nucleon Schrödinger equation which contains a parity-conserving two-nucleon strong and Coulomb interaction, we arrive at an equation for the intercluster relative motion functions $\chi$. These functions are expanded in terms of products of tempered Gaussian functions $\exp(-\gamma_i \rho^2)$ with different ranges $\gamma_i$ for each type of relative coordinate. The expansion coefficients are determined from a variational principle. The scattering states are calculated from a Kohn-Hulthén variational method for the $S$-matrix, which uses square integrable basis functions matched with the correct scattering asymptotics. Then, using the resulting six-nucleon wave functions, the decay width (3) is evaluated. All necessary matrix elements are calculated analytically by the aid of a symbolic computer language.

### III. RESULTS

We consider four different model spaces with increasing level of sophistication: (i) no $\alpha$ breathing modes ($N_\alpha = 1$) and no $t + h$ rearrangement channel: $\{\alpha_1 + p + n\}$; (ii) $N_\alpha = 1$ and the $t + h$ channel is included: $\{\alpha_1 + p + n; t + h\}$; (iii) $N_\alpha = 3$ and no $t + h$ channel: $\{\alpha_3 + p + n\}$; (iv) $N_\alpha = 3$ and the $t + h$ channel is included: $\{\alpha_3 + p + n; t + h\}$. We use the Minnesota effective interaction as the parity-conserving strong nucleon-nucleon force. It has been shown, that this interaction provides excellent $N + N$ and $\alpha + N$ phase shifts in the $\{\alpha_3 + N, T + d\}$ and $\{\alpha_1 + N\}$ models by using $u = 0.92$ and $u = 0.98$ exchange mixture parameters of the central interaction and slightly different spin-orbit forces, respectively. Here we refit the $u$ parameter in order to reproduce the experimental binding energy of the $0^+\text{ state}$ ($0.137\text{ MeV}$ relative to the $\alpha + p + n$ threshold) in all four models. These adjustments are rather small. For example, in our full model we have to change $u$ by only 0.7%. The weights of the $(L, S) = (0, 0)$ and $(1, 1)$ components of the wave functions are between 86.5–89.5% and 13.5–10.5%, respectively in the four different models in accordance with the results of several different model calculations (e.g., [3,11]).

In Fig. 1 we show the $0^-\text{ phase shifts}$ of our four models, together with the experimental data and the phase shift generated by the McIntyre-Haeberli optical potential. Note that the two lowest-energy experimental data points are not tabulated in [19], we read them off the figure of Ref. [19]. All our theoretical models slightly underestimate the absolute value of the phase shift at $E = 2.09\text{ MeV}$, which is the final energy of the decay process. The full model (iv) is closest to experiment. Below we investigate the sensitivity of the decay width on the phase shift at 2.09 MeV.

The low-lying $\alpha + d$ spectrum of $^6\text{Li}$ is reproduced well by all four models. For example, in the $\{\alpha_1 + p + n, t + h\}$ model, the $J^\pi = 1^+, 0^+ (\text{ground state}), 3^+, 0$, and $2^+, 0$ $^6\text{Li}$ states are at –1.421 MeV, 0.637 MeV ($\Gamma = 0.012\text{ MeV}$), and 4.254 MeV ($\Gamma = 2.78\text{ MeV}$), respectively, while the experimental values are –1.475 MeV, 0.71 MeV ($\Gamma = 0.024\text{ MeV}$), and 2.83 MeV ($\Gamma = 1.7\text{ MeV}$). All energies are relative to the $\alpha + d$ threshold. As in all models the deuteron has the correct binding energy, the position of the $\alpha + d$ threshold relative to the $\alpha + p + n$ is
always reproduced. Moreover, the $^5\text{He}+p$ and $^5\text{Li}+n$ thresholds are at the correct position, while our $t+h$ threshold is 4-5 MeV higher than experimentally.

In Table I we show the parity-violating $\alpha+d$ partial decay widths given by our four different model spaces, taking into account only the pion term of (1) and using the DDH best value for $F_\pi$. The spread among the results is almost an order of magnitude. To understand the origin of these big differences we performed some test calculations. We found that the width depends moderately on the $\alpha+d$ phase shift at 2.09 MeV. If we used a scattering wave function which reproduced the phase shift of the McIntyre-Haeberli potential at 2.09 MeV, then $\Gamma_{ad}^{\text{PNC}}$ was increased by roughly 50%. We checked the sensitivity of $\Gamma$ on the binding energy of the $0^+$ state by using the original $u = 0.98$ exchange mixture parameter in our simplest model. The binding energy decreases by 350 keV (resulting in a positive energy pseudo-bound state) which leads to a 15% decrease in $\Gamma$. Obviously, a larger probability of finding nucleons farther from each other decreases somewhat the magnitude of the internal wave function and reduces $\Gamma$.

We checked the role of the orthogonal $(L,S) = (0,0)$ and $(1,1)$ components in the bound state wave function of our four models by performing calculations for the two components separately. In each case the exchange mixture parameter $u$ has been refitted to reproduce the correct $0^+$ binding energy. For the $\{\alpha_1+p+n\}$ model space, the individual $(0,0)$ and $(1,1)$ components yield widths of $2.13 \cdot 10^{-10}$ eV and $2.23 \cdot 10^{-8}$ eV, respectively. This is to be compared with the result $\Gamma = 1.06 \cdot 10^{-9}$ eV, obtained if both components are considered. Although we observe a strong sensitivity of $\Gamma$ on the weight of the $(L,S) = (1,1)$ component, this cannot explain the big differences in Table I alone, as the weight of this component is roughly the same in all model spaces.

In Table II we list the partial contributions of the $(L,S) = (0,0)$ and $(1,1)$ components of the bound state to the parity-violating matrix element for our four model spaces. One can see that the contribution of the $(0,0)$ component changes its sign when going from the model with only one $\alpha$-particle basis state to the one which contains $\alpha$ breathing modes. This is obviously the consequence of some kind of cancellations taking place in the matrix element. These strong cancellations appear to be a warning that it is dangerous to generate bound and scattering states inconsistently from different models, as has been done in [12] and [13]. A similar sensitivity is found in the modelling of the beta-delayed deuteron emission process in $^6\text{He}$ [21].

As $\Gamma$ only moderately depends on the scattering state, the main origin of these cancellations must be in the bound state wave function. As the matrix element of the parity-violating interaction cannot be rewritten in a form which contains only relative motions, we cannot directly determine which property of the bound state wave function causes the sign change in the $(0,0)$ component. By investigating the contribution of the individual $\alpha$-particle basis states, we find that the contributions of the excited $\alpha$ pseudo-states are substantial, but they do not cause the sign change. As in Ref. [21], their effect might be to shift the nodal positions in the bound state wave function.

From Table II we observe that our model has a non-anticipated sensitivity to the model space, showing that the parity-violating decay is determined by components in the model space which are not well constrained by the other low-energy properties of the 6-nucleon systems which our models describe quite well. Nevertheless we will complete our study by calculating the decay width $\Gamma$ within our most elaborate model space (iv) and using the full
parity-violating interaction as defined in Eqs. (1)-(2). Then

$$\Gamma_{ad}^{PNC} = (55.2 \cdot F_\pi + 9.26 \cdot F_1 + 6.59 \cdot G_1)^2 \text{ eV.} \quad (9)$$

In Table II we give \(\Gamma\) for the coupling constants of [15], [22], and [23], respectively. One observes about an order of magnitude spread among the decay widths calculated for these different sets of coupling constants. For comparison, Table II also gives \(\Gamma\) using only the pion contribution in the parity-violating potential. As the \(\rho\) and \(\omega\) contributions are small, the decay width shows about an order of magnitude variation among the various model spaces.

Finally, we compare our results with the predictions of [12] and [13]. In these models the pionic term alone gives \(1.3 \times 10^{-8}\) eV and \(1.1 \times 10^{-11}\) eV, respectively, using the DDH best value for the coupling constant. In [13] only the \((L, S) = (0, 0)\) component is included in the bound state wave function which might partly explain the smallness of their reported decay width. In [12] the \((L, S)\) weights are similar to ours, being 89.4% and 10.4% for \((0, 0)\) and \((1, 1)\), respectively. Compared to [12], we do not take into account the D state of the deuteron (our parity-conserving \(N\)-\(N\) interaction is designed for a pure \(S\)-state deuteron). According to [12], inclusion of the deuteron D-state increases \(\Gamma\) by 50%. Thus our decay width appears to be about a factor of two smaller than the estimate given in Ref. [12] which is partly due to the use of a too attractive scattering potential in [12]. In contrast to the present results, Ref. [13] finds a substantial contribution of the \(\omega\) term in the parity-violating interaction to the decay width.

**IV. CONCLUSION**

In summary, we have studied the parity-violating \(\alpha + d\) decay of the lowest \(0^+\) state of \(^6\)Li within a microscopic multicluster model. We have performed a series of studies based on a three-cluster \(\alpha + p + n\) model space (including all possible arrangement of the clusters and within each arrangement all relevant angular momenta) and its extension to additionally include monopole breathing modes of the \(\alpha\) particle and the \(^3\)H\(^+\)\(^3\)He rearrangement channel. For the parity-conserving interaction we used the Minnesota force which reproduces all relevant subsystem properties reasonably well. We have calculated the decay width in perturbation theory, using a consistent description of the \(0^+\) bound state and the final \(0^-\) scattering state.

We have found that the parity-nonconserving \(\alpha + d\) decay width \(\Gamma_{ad}^{PNC}\) is moderately sensitive to the correct reproduction of the experimental \(\alpha + d\) phase shift and the \(0^+\) binding energy. On the other hand, we have demonstrated that \(\Gamma_{ad}^{PNC}\) is very sensitive to the presence of the 10–15% \((L, S) = (1, 1)\) component in the bound state wave function. As the inclusion of \(\alpha\) breathing modes and the \(^3\)H\(^+\)\(^3\)He rearrangement channel changes \(\Gamma\) considerably, we find that dynamical degrees of freedom beyond the \(\alpha + p + n\) three-cluster space are quite important. The decay width in our most complete model, using the DDH best values for the weak coupling constants, is \(\Gamma_{ad}^{PNC} = 3.97 \times 10^{-9}\) eV compared to the experimental upper limit \(\Gamma_{ad}^{PNC} \leq 6.5 \times 10^{-7}\) eV.

Our most important result, however, is that the state-of-the-art microscopic multicluster model does not constrain the parity-violating decay width of the \(T = 1\) state at \(E =\)
3.56 MeV in \(^6\)Li sufficiently well; despite the fact that this model is very successful in simultaneously describing other low-energy properties of the six-nucleon system. We note that a similar sensitivity has already been observed in cluster model studies of the beta-delayed deuteron emission process in \(^6\)He [21]. Improved dynamical calculations in larger six-body model spaces would be welcome to clarify the role of other degrees of freedom beyond our model, for example, by including the D-state components in the deuteron and \(\alpha\)-particle. Such calculations are, however, very challenging, as they have to consistently reproduce the spatially extended halo-like nature of the \(^6\)Li \(0^+\) state and the \(\alpha+d\) scattering state.

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FIGURES

FIG. 1. $^3P_0 \alpha + d$ phase shift as calculated in our different model spaces (dotted line: (i), dot-dashed: (ii), short-dashed: (iii), and solid: (iv)). The long-dashed line shows the phase shift as calculated from the McIntyre-Haeberli optical potential [20]). The dots are experimental data taken from Ref. [19].
TABLE I. Parity-nonconserving $\alpha + d$ decay widths, calculated in the various model spaces for the $0^+$ bound state of $^6$Li. Only the pion term is included in the parity-violating potential.

| Model       | $\Gamma_{\alpha d}^{PNC,\pi}$ (eV) |
|-------------|-----------------------------------|
| $\{\alpha_1 + p + n\}$ | $1.06 \cdot 10^{-9}$ |
| $\{\alpha_1 + p + n; t + h\}$ | $4.92 \cdot 10^{-10}$ |
| $\{\alpha_3 + p + n\}$ | $2.15 \cdot 10^{-9}$ |
| $\{\alpha_3 + p + n; t + h\}$ | $3.55 \cdot 10^{-9}$ |

TABLE II. Contribution of the $(L, S) = (0, 0)$ and $(1, 1)$ components to the pion term of the parity-violating matrix element. The contribution is defined by $M_{LS} = -i\sqrt{2}\varpi(E_f)\langle\Psi_{LS}^{^6Li}|\hat{V}_{\pi}^{PNC}|\Psi^{\alpha d}\rangle/F_{\pi}$, where $\Psi^{^6Li} = \Psi_{00}^{^6Li} + \Psi_{11}^{^6Li}$ is the total wave function in the various model spaces.

| Model       | $M_{00}$ ($\sqrt{eV}$) | $M_{11}$ ($\sqrt{eV}$) |
|-------------|------------------------|------------------------|
| $\{\alpha_1 + p + n\}$ | $-14.5$                | $44.6$                 |
| $\{\alpha_1 + p + n; t + h\}$ | $-12.8$                | $33.4$                 |
| $\{\alpha_3 + p + n\}$ | $16.0$                 | $27.0$                 |
| $\{\alpha_3 + p + n; t + h\}$ | $32.1$                 | $23.1$                 |

TABLE III. Parity-nonconserving $\alpha + d$ decay widths in our full model (iv), calculated using the full parity-violating potential (first column) and its pionic term only (second column). The calculations have been performed for various sets of weak coupling constants.

| Coupling constants | $\Gamma_{\alpha d}^{PNC}$ (eV) | $\Gamma_{\alpha d}^{PNC,\pi}$ (eV) |
|--------------------|----------------------------------|-----------------------------------|
| DDH [15]           | $3.97 \cdot 10^{-9}$            | $3.55 \cdot 10^{-9}$             |
| DZ [22]            | $4.28 \cdot 10^{-10}$           | $2.22 \cdot 10^{-10}$            |
| FCDH [23]          | $1.73 \cdot 10^{-9}$            | $1.21 \cdot 10^{-9}$             |
