Parity-violating α-decay of the 3.56 MeV 0^+ state of ^{6}Li in a microscopic α+p+n model[†]

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Model

Spin-parity of deuteron: $1^+ \Longrightarrow$ the decay of the 0^+ ^{6}Li state into the $\alpha + d$ channel is possible only if the continuum final state is $J^\pi = 0^-$. $\Longrightarrow$ This decay process violates parity in the nonstrange nonleptonic sector. $\Longrightarrow$ In principle the weak coupling constants can be extracted from the decay width.

Motivation: In ^{6}Li the few-body dynamics seems to be under much better control than in some heavier nuclei, where parity-violation was studied. Our main purpose is to study whether this is really the case, and thus whether theory can provide an estimate for the decay width with small uncertainty.

Parity-nonconserving (PNC) N-N force of Desplanques, Donoghue, and Holstein (DDH) (isovector part):

$$
\begin{aligned}
V^{PNC}(r) \;=\; & \frac{f_\pi g_{\pi NN} i}{\sqrt{2}} \left(\frac{\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2}{2}\right)_z (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\pi(r)\right] \\
- \; & g_\rho h_\rho^1 \left(\frac{\boldsymbol{\tau}_1 + \boldsymbol{\tau}_2}{2}\right)_z \Bigg((\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2) \cdot \left\{\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r)\right\} \\
& \qquad + i(1+\chi_V)(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2) \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r)\right] \Bigg) \\
- \; & g_\omega h_\omega^1 \left(\frac{\boldsymbol{\tau}_1 + \boldsymbol{\tau}_2}{2}\right)_z \Bigg((\boldsymbol{\sigma}_1 - \boldsymbol{\sigma}_2) \cdot \left\{\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\omega(r)\right\} \\
& \qquad + i(1+\chi_S)(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2) \cdot \left[\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\omega(r)\right] \Bigg) \\
+ \; & g_\rho h_\rho^1 \left(\frac{\boldsymbol{\tau}_1 - \boldsymbol{\tau}_2}{2}\right)_z (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \left\{\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\rho(r)\right\} \\
- \; & g_\omega h_\omega^1 \left(\frac{\boldsymbol{\tau}_1 - \boldsymbol{\tau}_2}{2}\right)_z (\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2) \cdot \left\{\frac{\mathbf{p}_1 - \mathbf{p}_2}{2M}, f_\omega(r)\right\}
\end{aligned}
$$

$r = |\mathbf{r}_1 - \mathbf{r}_2|$, $f_\alpha(r) = \exp(-m_\alpha r)/4\pi r$ (m_α are the $\pi^\pm$, ρ, and ω meson masses), $\mathbf{p}_i$ are the nucleon momenta, M is the nucleon mass, $\boldsymbol{\sigma}$ and $\boldsymbol{\tau}$ 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 [...] and {...} denote commutators and anticommutators, respectively.

The PNC $\alpha + d$ **decay width** is calculated perturbatively:

$$\Gamma^{PNC}_{\alpha d} = \hbar W_{fi} = 2\pi \left| \langle \Psi^{\alpha d} | \widehat{V}^{PNC} | \Psi^{^6\mathrm{Li}} \rangle \right|^2 \varrho(E_f),$$

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.

Wave functions:

Initial state:

$$\begin{aligned}\Psi^{^6\mathrm{Li}} = \Psi^{\alpha pn} + \Psi^{th} &= \sum_{(ij)k,S,l_1,l_2,L} \mathcal{A}\left\{ \left[\left[\Phi^i (\Phi^j \Phi^k) \right]_S \chi^{i(jk)}_{[l_1 l_2]L} (\boldsymbol{\rho}_{jk}, \boldsymbol{\rho}_{i(jk)}) \right]_{JM} \right\} \\ &+ \sum_{S,L} \mathcal{A}\left\{ \left[[\Phi^t \Phi^h]_S \chi^{th}_L (\boldsymbol{\rho}_{th}) \right]_{JM} \right\},\end{aligned}$$

where i, j, and k denote any one of the labels α, p, and n, $\mathcal{A}$ is the intercluster antisymmetrizer, the Φ cluster internal states are translationally invariant harmonic oscillator shell model states, the $\boldsymbol{\rho}$ vectors are the different intercluster Jacobi coordinates, $t + h$=^{3}H+^{3}He, and [...] denotes angular momentum coupling. Monopole breathing distortions of the α particle can be considered by $\Psi^{\alpha pn} = \Psi^{\alpha_1 pn} + \Psi^{\alpha_2 pn} + \ldots$.

Final state (with $L = 1$, $S = 1$, and $J^\pi = 0^-$):

$$
\begin{aligned}
\Psi^{\alpha d} \;&=\; \mathcal{A}\left\{\left[[\Phi^{\alpha_1}\Phi^{d_1}]_S \; g_L^{\alpha_1 d_1}(E, \boldsymbol{\rho}_{\alpha d})\right]_{JM}\right\} \\
&+\; \sum_{\substack{i=1 \\ i+j>2}}^{N_\alpha} \sum_{j=1}^{N_d} \mathcal{A}\left\{\left[[\Phi^{\alpha_i}\Phi^{d_j}]_S \; \chi_L^{\alpha_i d_j}(E, \boldsymbol{\rho}_{\alpha d})\right]_{JM}\right\} \\
&+\; \mathcal{A}\left\{\left[[\Phi^{t}\Phi^{h}]_S \; \chi_L^{th}(E, \boldsymbol{\rho}_{th})\right]_{JM}\right\}
\end{aligned}
$$

where g is the scattering wave function in the $\alpha + d$ relative motion.

Results

- Good reproduction of the ${}^3P_0$ $\alpha + d$ phase shift.
- Strong, unanticipated dependence of Γ^{PNC} on the model space:

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

(Here α_3 denotes model spaces with breathing distortions.)

This strong model dependence is caused by cancellations in the decay width matrix element:

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

$M_{LS} = -i\sqrt{2\pi\varrho(E_f)}\langle\Psi_{LS}^{^6\mathrm{Li}}|\widehat{V}_\pi^{PNC}|\Psi^{\alpha d}\rangle/F_\pi$, where $\Psi^{^6\mathrm{Li}} = \Psi_{00}^{^6\mathrm{Li}} + \Psi_{11}^{^6\mathrm{Li}}$ is the total wave function in the various model spaces.

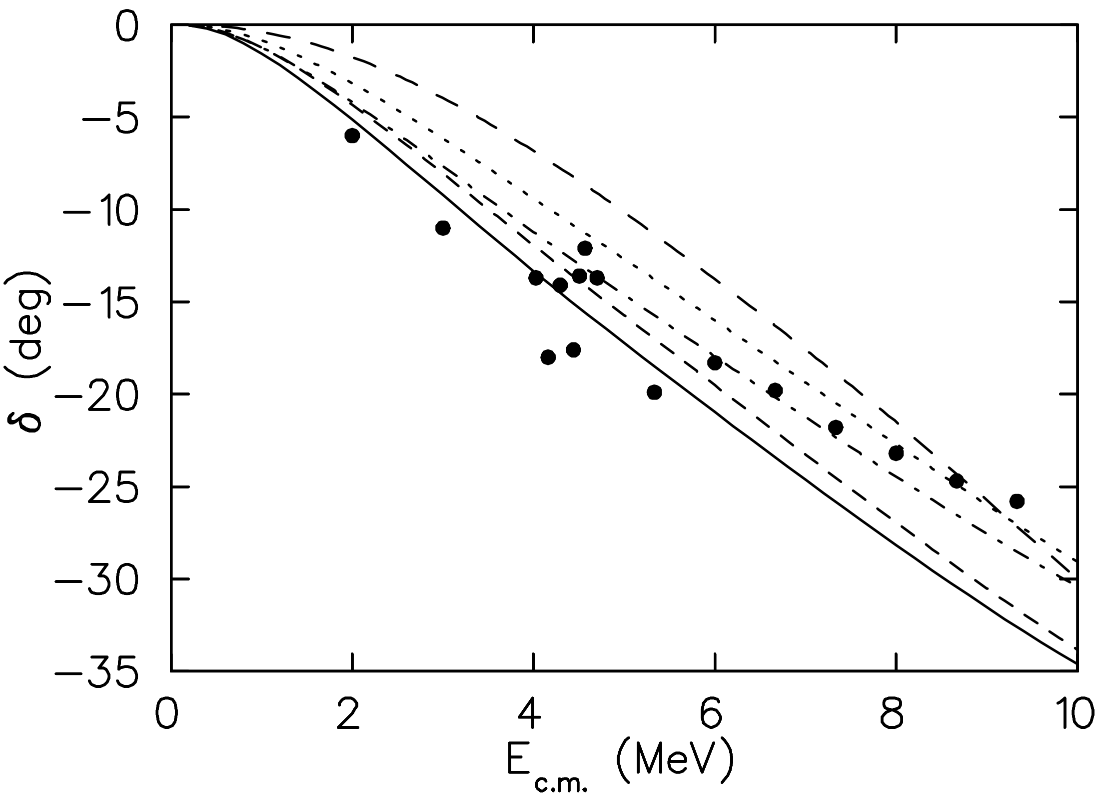

Figure 1: $^3P_0$ $\alpha + d$ phase shift as calculated in our various model spaces. The long-dashed line shows the phase shift as calculated from the McIntyre-Haeberli optical potential. The dots are experimental data.

In our full model:

$$\Gamma_{\alpha d}^{PNC} = (55.2F_\pi + 9.26F_1 + 6.59G_1)^2 \ \text{eV}$$

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

Coupling constants	$\Gamma_{\alpha d}^{PNC}$ (eV)	$\Gamma_{\alpha d}^{PNC,\pi}$ (eV)
DDH	3.97×10^{-9}	3.55×10^{-9}
DZ	4.28×10^{-10}	2.22×10^{-10}
FCDH	1.73×10^{-9}	1.21×10^{-9}

Summary

- The parity-violating α-decay of the ^{6}Li $J^\pi, T = 0^-, 1$ state is described in a microscopic $\alpha + p + n$ RGM model

- The parity-violating decay width is calculated perturbatively

- The decay width is very sensitive to dynamical degrees of freedom beyond $\alpha + p + n$

- The current theoretical prediction $\Gamma_{\alpha d}^{PNC} \approx 4 \times 10^{-9}$ eV is much smaller than the experimental upper limit $\Gamma_{\alpha d}^{PNC} \leq 6.5 \times 10^{-7}$ eV