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One-nucleon-induced nonmesonic hypernuclear decay in laboratory coordinates

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Abstract. We present a formalism for the computation of one-nucleon-induced nonmesonic weak hypernuclear decay rates in laboratory coordinates, within an independent-particle shell model framework, with a view to its generalization to the case of two-nucleon-induced transitions.

Keywords: Nonmesonic weak decay, Shell model formalism, Laboratory coordinates
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Due to Pauli-blocking, the dominant channel for the weak decay of a lambda hyperon inside the nuclear medium is the one-nucleon-induced nonmesonic mode, $\Lambda N \to NN$. The main motivation to study this process is that it constitutes the only way available, at present, to probe the strangeness-changing weak interaction between baryons [1]. In a shell-model framework, the lowest order transition amplitude for this process can be decomposed into a summation over two-body matrix elements of the form $\langle[\ddot{v}_1\ddot{v}_2]JT|G|[\ddot{\lambda}\,\ddot{v}_F]JT\rangle$, where G is the correlated transition potential and the single-particle states $\ddot{v}_1$ and $\ddot{v}_2$ are in the continuum, while $\ddot{\lambda}$ and $\ddot{v}_F$ are in the discrete spectrum. Making a plane-wave Born approximation for the first two states and a harmonic oscillator approximation for the last two, these matrix elements can be conveniently computed by first implementing the transformation to relative ($\mathbf{r} = \mathbf{r}_1 - \mathbf{r}_2$) and center-of-mass ($\mathbf{R} = (\mathbf{r}_1 + \mathbf{r}_2)/2$) coordinates [2]. In a more sophisticated treatment, to partly include final-state interactions (FSI) through an optical potential [3], or if one wishes to extend this shell-model approach to two-nucleon-induced transitions [4], $\Lambda NN \to NNN$, other types of matrix elements come into play and this transformation cannot always be easily done. One must, then, resort to a calculation directly in terms of laboratory coordinates $(\mathbf{r}_1, \mathbf{r}_2)$. As a first step towards such an extension of the shell-model approach, we present here a formalism using laboratory coordinates applied to the treatment of one-nucleon-induced nonmesonic decay.

The transition potential, $\mathscr{V}$, can be obtained through one-meson-exchange models [5] and, in our work, short range correlations are approximately included by means of Jastrow-like correlation functions through the replacement $\mathscr{V} \mapsto \mathscr{G} = g_{\mathsf{NN}}(r)\,\mathscr{V}\,g_{\Lambda\mathsf{N}}(r)$ [2]. Adopting a formalism in which the lambda and the nucleon are treated as identical baryons occupying different states in strangeness-isospin space, we can write the

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correlated transition potential in second-quantized notation as[1]

$$\hat{V} = \frac{1}{4}\sum_{\alpha\beta\gamma\delta}\langle[\alpha\beta]|G|[\gamma\delta]\rangle\, a^{\dagger}_{\alpha}a^{\dagger}_{\beta}a_{\delta}a_{\gamma}. \tag{1}$$

To implement the isospurion stratagem [2], it is best to compute matrix elements of the transition potential in a basis coupled, not only in angular momentum, but also in isospin. Doing this, we can write[2]

$$\langle[\dot{\nu}_1\dot{\nu}_2]JT|G|[\ddot{\lambda}\,\dot{\nu}_F]JT\rangle \quad = \quad \langle[\dot{\nu}_1\dot{\nu}_2]JT|\mathscr{G}|(\ddot{\lambda}\,\dot{\nu}_F)JT\rangle \tag{2}$$

The several terms in the transition potential should be first arranged according to their spin-angle and isospin structure as follows $\mathscr{V} = \sum_{\alpha\tau} V_{\alpha\tau}(\sigma, r)I_{\tau} = \sum_{\alpha\tau} v_{\alpha\tau}(r)\Omega_{\alpha}I_{\tau}$, where the Ω_{α} characterize spin-independent, spin-spin, tensor and parity-violating terms and I_{τ} are isospin factors. To get the correlated matrix elements, it is sufficient to perform the replacements $v_{\alpha\tau}(r) \mapsto g_{\alpha\tau}(r) \equiv g_{\mathsf{NN}}(r)v_{\alpha\tau}(r)g_{\Lambda\mathsf{N}}(r)$. To make use of laboratory coordinates, we introduce the generalized multipole moments,

$$v^{kq}_{\alpha\tau}(r_1, r_2) = \frac{2k+1}{2}\int \frac{v_{\alpha\tau}(r)}{r^q} P_k(\cos\theta_{12})\, d\cos\theta_{12} \tag{3}$$

by means of which the matrix elements of any static term can be decomposed as

$$\langle(ab)J|V_{\alpha\tau}|(cd)J\rangle \quad = \quad \sum_{kq_1q_2}^{(q_1+q_2=q_\alpha)} f^{kq_1q_2}_{\alpha}(abcd;J)F^{kq_1q_2}_{\alpha\tau}(abcd) \tag{4}$$

The radial matrix elements have the form

$$F^{kq_1q_2}_{\alpha\tau}(abcd) = \int\int R_a(r_1)R_b(r_2)R_c(r_1)R_d(r_2)v^{kq_\alpha}_{\alpha\tau}(r_1, r_2)r_1^{q_1}r_2^{q_2}\, dr_1 dr_2 \tag{5}$$

and are numerically computed with the appropriate reduced radial wave-functions. The angular coefficients $f^{kq_1q_2}_{\alpha}(abcd;J)$ have different explicit expressions depending on the specific form of the angle-spin operator Ω_{α} and can be straightforwardly computed by means of angular momentum algebra. More details will be given elsewhere [6].

We make use of the weak coupling approximation for the ground state $|I\rangle$ of the decaying single-Λ hypernucleus, writing $|\dot{I}\rangle = \left(a^{\dagger}_{\dot{\lambda}} \times |\dot{C}\rangle\right)_{J_I}$ where $\dot{\lambda} = (1s_{1/2})_{\Lambda}$ and $|C\rangle$ is the hypernuclear core. For the mean field we use the extreme independent particle shell model, such that the final states of the residual nucleus have the form $|\dot{F}\rangle = |\dot{\nu}_F J_F\rangle = \frac{1}{Z_{\dot{\nu}_F J_F}}\left(\tilde{a}_{\dot{\nu}_F} \times |\dot{C}\rangle\right)_{J_F}$ where $Z_{\dot{\nu}_F J_F}$ is a normalization constant and $\tilde{a}_{\nu_F} = (-)^{j_F+m_F}a_{-\nu_F}$. All the nuclear structure information relevant for NMWD rates is then contained in the

[1] G is an extension of $\mathscr{G}$ to include the strangeness degree of freedom.
[2] The labels ν and λ are being used for N- and Λ-states, respectively.

inclusive spectroscopic factors $S(\dot{C}J_IJ\dot{\nu}_F) = \sum_{J_F} \left|\langle \dot{I}||(a^\dagger_{\dot{\lambda}} a^\dagger_{\dot{\nu}_F})_J||\dot{F}\rangle\right|^2$, for which explicit expressions can be obtained.

To calculate Γ_n and Γ_p, one must first compute the *nonnormalized* good-isospin rates[3]

$$\Gamma_N(T) = \frac{1}{2J_I+1}\left(\frac{2^5}{\pi}\right)\sum_{\ddot{\nu}_F}^{(N)}\sum_J S_N(\dot{C}J_IJ\ddot{\nu}_F)$$
$$\times \sum_{l_1j_1}\sum_{l_2j_2}\int p_1^2\,dp_1\int p_2^2\,dp_2\,\delta\left(\frac{p_1^2}{2\mathrm{M}}+\frac{p_2^2}{2\mathrm{M}}-\Delta_{\dot{\nu}_F}\right)\left|\langle[\ddot{\nu}_1\ddot{\nu}_2]JT|G|[\ddot{\lambda}\,\ddot{\nu}_F]JT\rangle\right|^2, \quad (6)$$

where $\mathrm{M} = (M_n+M_p)/2$ and $\Delta_{\dot{\nu}_F} = M_\Lambda - M_n + \varepsilon_{\dot{\lambda}} + \varepsilon_{\dot{\nu}_F}$ with the ε's being single-particle energies, and M_Λ, M_n and M_p, the baryon masses. We have used the notation $S_N(\dot{C}J_IJ\ddot{\nu}_F) = S(\dot{C}J_IJ\dot{\nu}_F)$ for $\dot{\nu}_F \equiv N\ddot{\nu}_F$ and $\sum_{\ddot{\nu}_F}^{(N)}$ indicates a summation over the single-particle levels for nucleons of kind N that are partialy or fully occupied in the hypernuclear core $|\dot{C}\rangle$. With the help of these quantities, one can obtain the single-nucleon-induced NMWD rates from the relations

$$\Gamma_n = \frac{1}{2}\Gamma_n(T=1) \quad \text{and} \quad \Gamma_p = \frac{1}{4}\Gamma_p(T=1)+\frac{1}{4}\Gamma_p(T=0) \qquad (7)$$

The expression in Eq. (6) was obtained by ignoring the recoil of the residual nucleus to allow the angular integration to be analytically performed. One may try to approximately include its effect through an angular-average approximation, which results in the replacement $\mathrm{M} \mapsto \frac{A-2}{A-1}\mathrm{M}$, where A is the baryon number of the decaying hypernucleus.

To summarize, we have developed a formalism to compute nonmesonic decay rates in laboratory coordinates. Our main objective is to apply it to the two-nucleon induced process where the matrix elements involved cannot be conveniently separated into relative and center-of-mass parts. For the moment we are testing the formalism in the simpler case of single-nucleon induced transitions. The numerical results have not yet been obtained.

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[3] By *nonnormalized* we mean that they do not take statistical factors into consideration.