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Configuration of the two-neutron halo of ^{11}Li and Gamow-Teller transition

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Effects of the halo as well as meson exchange currents (MEC) are studied for the Gamow-Teller (GT) β transition $^{11}\mathrm{Li}(3/2^-)\rightarrow{}^{11}\mathrm{Be}(1/2^-,0.32\ \mathrm{MeV})$. They are found to be important to reduce transition matrix elements and remedy deviations from the observed $\log ft$ value of the GT transition. This GT transition is shown to play an indispensable role in identifying the structure of two-neutron halo of ^{11}Li. It is indicated that the two neutrons forming the halo consist of the $p_{1/2}^2$ configuration with 60–70 % probability.

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Neutron halo has been discovered in ^{11}Li and ^{11}Be owing to the recent developments of radioactive nuclear beams [1,2]. The first excited state of $^{11}\mathrm{Be}(1/2^-,0.32\ \mathrm{MeV})$ as well as the ground state $(1/2^+)$ have small neutron separation energies of $S_n=183$ and 503 keV, respectively, and hence are expected to have the neutron halo. In fact, this neutron halo has been discussed and confirmed for the ground state (g.s.) [3,4]. The ground state of $^{11}\mathrm{Li}(3/2^-)$ also has the neutron halo due to the small two-neutron separation energy of $S_{2n}=295$–340 keV [5,6].

In this paper, effects of the neutron halo on a Gamow-Teller (GT) β transition, $^{11}\mathrm{Li}(3/2^-\ \mathrm{g.s.})\rightarrow{}^{11}\mathrm{Be}(1/2^-,0.32\ \mathrm{MeV})$, will be investigated in terms of shell-model calculations with single-particle wave functions consistent with such small separation energies. Observed $\log ft$ value for the transition, $\log ft=5.58$ [7–9], is larger than the calculated values obtained by using the Cohen-Kurath interactions [10] with harmonic oscillator (HO) wave functions and by taking into account only one-body terms: $\log ft=4.59$–4.80 (see below and Fig. 2 also).

In this paper, effects of the halo of the neutron (ν) $p_{1/2}$ wave function in ^{11}Li and ^{11}Be are studied for one-body transition matrix elements as well as for two-body meson exchange currents. Diagrams considered in the present work are shown in Fig. 1. The neutron halo of ^{11}Li is expected to reduce $\nu p_{1/2}\rightarrow\pi p_{1/2},\pi p_{3/2}$ one-body transition matrix elements and hence enlarge the calculated $\log ft$ values. The halo also affects the two-body exchange current matrix elements when a halo neutron changes into a proton. The halo further affects the GT matrix elements when Δ_{33} resonances are excited from a halo orbit. One of the major open problems with respect to the two-neutron halo in ^{11}Li is to what extent the $(0p_{1/2})^2$ and $(1s_{1/2})^2$ configurations are included. We shall point out that the present GT matrix element presents precious information on the probability of the $(0p_{1/2})^2$ configuration, and thus determines a basic structure of the two-neutron halo. This probability varies drastically from one calculation to another as tabulated in Ref. [11], while no direct experimental information of this probability has been reported.

We start with a simple assumption that neutrons of ^{11}Li are not excited into the sd shell. The shell-model configuration amplitudes are obtained by using three sets of the Cohen-Kurath interactions, POT(8–16), TBE(8–16), and TBE(6–16) [10]. For the transition matrix element, we use the $\nu p_{1/2}$ single-particle wave function obtained in a Woods-Saxon well with a diffuseness parameter $a=0.57$ fm, so as to reproduce the observed single-neutron separation energy (S_n). This single-particle wave function is somewhat different from that assumed with the Cohen-Kurath interaction, primarily in its tail behavior. However, at the final stage of this paper, we will vary the shell-model configuration amplitudes by changing single-particle energies, and hence the present work is focused more directly upon the shell-model wave functions rather than the interaction. For this reason, the difference mentioned above is considered to be rather minor, while a more consistent treatment is desired to improve the accuracy of the arguments.

The value of S_n is taken to be 160 keV in ^{11}Li, which is half of the average value of $S_{2n}=295$ keV [4] and $S_{2n}=340$ keV [7]. This wave function gives rms radius of 4.85 fm for the valence $\nu p_{1/2}$ orbit, that is close to the experimental values; 4.8 fm [1,2] to 4.9 fm [12]. Calculated results for $\log ft$ are found to be insensitive to the variation of S_n by ~ 30 keV. They are also insensitive to the values of the diffuseness parameter adopted ($a=0.44$–0.6 fm) so long as

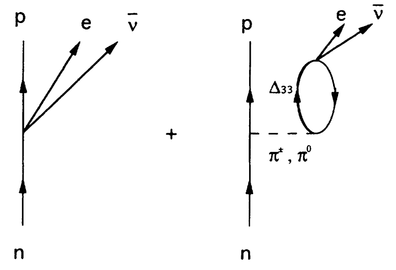

FIG. 1. One-body and two-body GT β-decay processes considered in the present work. The left figure denotes the one-body β^--decay processes, while the right one shows the one-pion exchange current processes due to Δ_{33}-isobar excitations.

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the rms radius of $\nu p_{1/2}$ is adjusted. The $\nu p_{1/2}$ wave function in ^{11}Be is taken to be the same as that in ^{11}Li. This is quite reasonable as the neutron separation energy of 183 keV in ^{11}Be is very close to the above S_n value of ^{11}Li.

Effects of the halo on the one-body terms ($O_1 = g_A \sigma \tau_+$, where $\tau_+ n = p$) are shown in Fig. 2. Upper two sets in Fig. 2 show the calculated logft values obtained with harmonic oscillator (HO) wave functions with $b = 1.64$ fm [13] and those obtained by using the Woods-Saxon wave function for $\nu p_{1/2}$. Note that the latter has the halo structure. Here, $ft = 6147/\{|\langle J_f || O_1 || J_i \rangle|^2/(2J_i+1)\}$ [14]. Only the dominant GT (1^+) transition is considered. The $E2$ (2^+) transition can affect logft only by <0.001 as $j_2(qR) \sim 0.016$ when $qR \sim 0.1 \times 4.9$ and can be safely neglected. The halo reduces the GT matrix elements by 35–43 % and is important to get close to the experimental logft value [7–9].

We now extend the shell-model configuration space so as to include the sd shell. Effects of the excitation of valence particles into the sd shell are investigated by using the Millener-Kurath interaction [15,16]. Three sets of interactions, PSDMK, PSDMK2, and PSKMK1 [16], whose p-shell part corresponds, respectively, to POT(8–16), TBE(8–16), and TBE(6–16), are used. The interactions in the sd shell are the one obtained by Preedom and Wildenthal [17] for PSDMK and PSDMK1, and the one obtained by Kuo [18] for PSDMK2. Excitations of up to 2 valence particles in the sd shell results in the increase of logft by 0.08–0.12 (see Fig. 2).

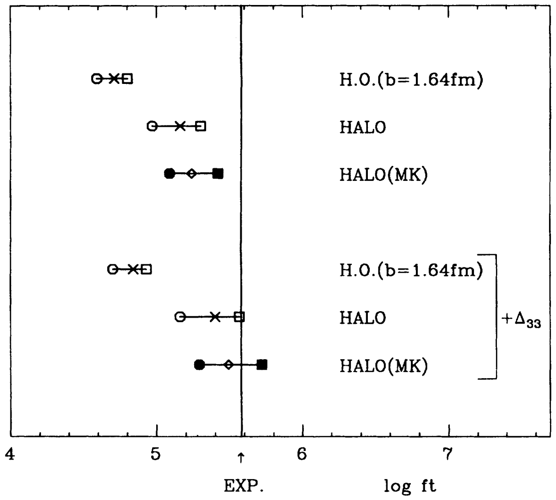

FIG. 2. Logft values of the GT transition. The observed value (log$ft = 5.58 \pm 0.01$ [8]) is indicated by a vertical line with "EXP." Symbols ○, ×, and □ denote three sets of the Cohen-Kurath wave functions: POT(8–16), TBE(8–16), and TBE(6–16), respectively. Results with $p^5(sd)^2$ configurations admixed by the Millener-Kurath interaction are shown by symbols ●, ◇, and ■, which correspond to ○, ×, and □, respectively. Lower three sets of the results in the figure include the contributions from the Δ_{33}-isobar exchange current, while upper three sets include only one-body terms.

One-pion exchange currents due to Δ_{33}-isobar excitations are included next. The processes shown in Fig. 1 are all considered. The method of the calculation is the same as in Ref. [19]. For β^- decay, the contributions from the Δ_{33}-hole excitations are given by the following formula:

$$\begin{aligned}\langle j_2 || \delta O^\lambda || j_1 \rangle = & -(1/\Delta E) \sum_J (2J+1) W(\Delta h j_1 j_2; \lambda J) \sqrt{1+\delta_{j_2 h}} (-1)^{j_1+h-J} \\ & \times \{ \sqrt{2} \langle h_\pi || (O^\lambda_{N\Delta})^\dagger || \Delta \rangle \langle \Delta j_1 : J | V(1-P_\sigma P_M) | h_\pi j_2 : J \rangle \\ & + \sqrt{2}/3 \langle h_\nu || (O^\lambda_{N\Delta})^\dagger || \Delta \rangle \langle \Delta j_1 : J | V(1-P_\sigma P_M) | h_\nu j_2 : J \rangle \} + (-1)^{j_1-j_2} (j_1 \leftrightarrow j_2,\ h_\pi \leftrightarrow h_\nu), \end{aligned} \tag{1}$$

where λ is the rank of the transition operator ($\lambda = 1$ for the GT transition), $\Delta E = m_\Delta - m_N$, Δ (h) denotes the angular momentum of the Δ (hole) state, and π (ν) specifies that the hole is proton (neutron). In Eq. (1), $O_{N\Delta}^{\lambda=1} = g_A^* S T_\pm$, where S ($T_\pm$) is the spin (isospin) transition operator [20], is the $N-\Delta$ transition operator, and P_σ and P_M are spin- and space-exchange operators, respectively. The one-pion-exchange potential, $V = V_C(r) S_1 \sigma_2 + V_T(r) S_{12}$, where $S_{12} = \sqrt{30}[C^{(2)}(r) \times [S_1 \times \sigma_2]^{(2)}]^{(0)}$, has the central part $V_C(r) = \frac{1}{3} \times (1/4\pi) f_{\pi NN} f_{\pi N\Delta} e^{-\mu r}/r$ and the tensor part $V_T(r) = (1/4\pi) f_{\pi NN} f_{\pi N\Delta} [\frac{1}{3} + 1/\mu r + 1/(\mu r)^2] e^{-\mu r}/r$ with $(1/4\pi) f^2_{\pi NN} = 0.08$. A phenomenological Chew-Low value of $g_A^* = 2.1 g_A$ [21] with $g_A = 1.26$ is used here. The $\pi N \Delta$ coupling constant $f_{\pi N\Delta}$ is taken so as to satisfy $f_{\pi N\Delta}/f_{\pi NN} = g_A^*/g_A$ [21,22].

The contributions from the excitations of the Δ_{33} from the $0s_{1/2}$ core are evaluated exactly in the present calculation, while those from the excitations of the Δ_{33} from p shell are treated approximately. Although the Cohen-Kurath wave functions are of the intermediate coupling nature, in the case of $\nu p_{1/2} \rightarrow \pi p_{1/2}, \pi p_{3/2}$ transitions, the existence of the $\nu p_{3/2}$ core is assumed and the Δ_{33} resonances are allowed to be excited from the $s_{1/2}$ plus $\nu p_{3/2}$ closed core. In the case of $\nu p_{3/2} \rightarrow \pi p_{1/2}, \pi p_{3/2}$ transitions, the existence of the $\nu p_{1/2}$ core is assumed further and thus Δ_{33} resonances are allowed to be excited from the core consisting of $s_{1/2}$, $\nu p_{3/2}$, and $\nu p_{1/2}$. This approximation can be considered reasonable as the contribution of the Δ_{33} excitations from the $0s_{1/2}$ core is dominant in all the above cases. The halo in ^{11}Li and ^{11}Be reduces the two-body terms in the GT matrix elements by 7–8 %. In collecting various contributions, the halo effects on the one-body term reduce the GT matrix element from the original value to its ~60% (57–65 %). The meson exchange currents (MEC) further decrease this matrix element (see

Fig. 2); the matrix element becomes ~85% (85–87 %) even if the halo structure is neglected. If the halo and MEC are combined, the GT matrix element is reduced only to ~45% (41–52 %) of the original value. When the admixtures of the sd-shell configurations are taken into account, the matrix element becomes even to ~41% (34–45 %) of the original value.

Finally, we discuss the configurations of the two neutron halo in ^{11}Li. What is the probability of $\nu p_{1/2}^2$ and $\nu s_{1/2}^2$ configurations in the halo of ^{11}Li? We change the probability of $\nu p_{1/2}^2$ configuration by lowering the single-particle energies of $1s_{1/2}$, $0d_{5/2}$, and $0d_{3/2}$ orbits and study the variation of the calculated logft values. The change of these single-particle energies is assumed to be the same among them, for simplicity. We use the PSDMK2 interaction because this interaction is the original Millener-Kurath interaction [15] and has been most frequently used and tested by various authors [23]. The halo wave function is used for $\nu p_{1/2}$ in calculating β decay matrix elements, and the contributions from the MEC due to Δ_{33}-isobar current are included. The probability of the $\nu p_{1/2}^2$ configuration decreases as we lower the single-particle energies of the sd orbits. The mixing probability of $p^5(sd)^2$ configurations in ^{11}Be, on the other hand, is as small as 1.4% and changes only up to ~2%. The fraction of $sd \rightarrow sd$ transition in the GT matrix element, therefore, remains small (5–15 %), and halo effects in the sd shell are neglected here. Calculated results for logft are shown in Fig. 3. The calculated logft values increase almost linearly as the probability decreases down to ~60% and cross the observed value (log$ft = 5.58$) at ~65%. This value is a little smaller than the value obtained in Ref. [24]: probability=77%. Various theoretical values of the probability are compiled in Ref. [11].

In order to see the validity of the above change of the single-particle energies, the magnetic moment of ^{11}Li is calculated. The obtained value is 3.90 nm with the MEC (pair, pionic, and Δ_{33}-isobar currents) contribution (3.71 nm without the MEC contributions) for the PSDMK2 with the original single-particle energies for the sd orbits, which gives 89% probability of the $p_{1/2}^2$ configuration. When this probability is decreased to 63%, the calculated magnetic moment becomes 3.76 nm (3.57 nm) with (without) the MEC contributions and gets closer to the observed value: 3.67 nm [25]. This also supports the rather strong mixing of the sd-shell configuration in the two neutron halo in ^{11}Li.

We can conclude, within the present calculation, that both the effects of the halo and those of the exchange currents are important to reduce deviations from the observed logft value of the GT transition. The study of the effects due to the pair and ρ-π exchange currents, which are smaller than the effects of the Δ_{33}-exchange currents [21,22], are now under way. When the excitations of the valence particles into the sd shell are further taken into account, the experimental logft value is almost reproduced. The halo, the exchange currents, and the mixing of the sd-shell configuration contribute coherently to explain the observed logft value. We should emphasize that, among these effects, the halo produces the largest change of the β-decay matrix element, and that the anomalously large logft value can be used as another footprint of the halo in drip-line nuclei. We mention that the present study indicates rather strong mixing of the sd-shell configurations for the two halo neutrons. We would like to stress this new aspect of the GT decay as a tool for clarifying the configurations of the two-neutron halo. The problem of these configurations is related to the momentum correlation of the two halo neutrons [26]. A calculation with a two-body interaction and single-particle wave functions which are fully consistent with each other is desired, although achieving it will be difficult.

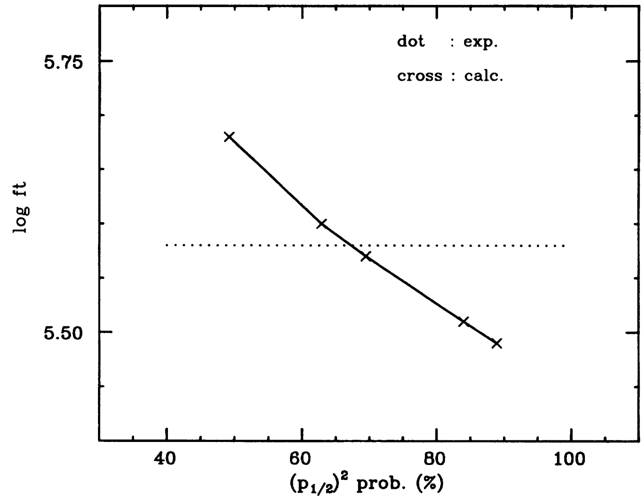

FIG. 3. Logft values of the GT transition vs probability of the $\nu p_{1/2}^2$ configuration. Dotted line shows the observed logft value: log $ft = 5.58$.

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