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Shell-model calculations of high-spin isomers in neutron-deficient $1g_{9/2}$-shell nuclei

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The neutron-deficient $1g_{9/2}$-shell nuclei are studied in the framework of the shell model with the $(1g_{9/2}, 2p_{1/2})^{-n}$ configuration. Several "spin-gap" isomers with a half-life of an order of a second are predicted in ^{95}Pd, ^{95}Ag, ^{96}Cd, and ^{97}Cd. Among them, the $J=\frac{21}{2}^+$ state in ^{95}Pd is predicted to be an isomer which corresponds to ^{95}Pd^m recently observed by Nolte and Hick. It is also shown that the high-spin isomers above the proton threshold are rather stable against the proton emission.

[NUCLEAR STRUCTURE ^{95}Pd, ^{95}Ag, ^{96}Cd, ^{97}Cd; calculated levels, lifetime; $1g_{9/2}$-$2p_{1/2}$ shell model; predicted long-lived isomers with high spin.]

Recently Nolte and Hick found a new β-decaying isomer in ^{95}Pd with a half-life of 14 ± 1 sec.[1] From the spins of daughter states in ^{95}Rh, they have estimated a spin value of $J=\frac{21}{2}^+$ for this isomer. It is quite feasible that such a long-lived state is a "spin-gap" isomer[2,3] which is originated from the property of the effective interaction between protons and neutrons in the $1g_{9/2}$ shell. In the following, we report the results of the shell-model calculations on nuclei in the ^{95}Pd region focusing on the possible existence of high-spin isomers.

In the present calculations, the nucleus ^{100}Sn is assumed to be an inert core because $Z=N=50$ is magic[4] and the model space employed consists of $1g_{9/2}$ and $2p_{1/2}$ orbitals for active proton holes ($\bar{\text{p}}$) and neutron holes ($\bar{\text{n}}$).

The Hamiltonian

$$H=H_{\bar{\text{p}}}+H_{\bar{\text{n}}}+V_{\bar{\text{p}}\bar{\text{p}}}+V_{\bar{\text{n}}\bar{\text{n}}}+V_{\bar{\text{p}}\bar{\text{n}}} \tag{1}$$

is taken from the shell-model studies for the $N=50$ and $N=49$ nuclei around ^{90}Zr.[5-7] The $\bar{\text{p}}$-$\bar{\text{p}}$ and the $\bar{\text{p}}$-$\bar{\text{n}}$ interactions, $V_{\bar{\text{p}}\bar{\text{p}}}$ and $V_{\bar{\text{p}}\bar{\text{n}}}$, used in the present paper are derived from V_{pp} and $V_{\text{p}\bar{\text{n}}}$ of Ref. 7. The Coulomb effects are included in the $\bar{\text{p}}$-$\bar{\text{p}}$ interaction. The matrix elements of $V_{\bar{\text{n}}\bar{\text{n}}}$ are assumed to be the same as the $T=1$ component in the $\bar{\text{p}}$-$\bar{\text{n}}$ interaction. The single-hole energies of $\bar{\epsilon}_{\text{p}}(j)$ and $\bar{\epsilon}_{\text{n}}(j)$ relative to the ^{100}Sn core are derived from the single-particle and -hole energies of $\epsilon_{\text{p}}(j)$ and $\bar{\epsilon}_{\text{n}}(j)$ with respect to the ^{88}Sr core in conjunction with the two-body effective interactions mentioned above.

The calculated energy spectrum of ^{95}Pd is shown in Fig. 1. The existence of two isomers is suggested; one is a $J=\frac{1}{2}^-$ state laying at 0.85 MeV and the other is a $J=\frac{21}{2}^+$ state at 1.90 MeV. The present model predicts the $J=\frac{21}{2}^+$ state at 5 keV above the $J=\frac{17}{2}^+$ state. This ordering, however, is very sensitive to the details of the two-body interactions adopted. For example, if one takes the more attractive value for the matrix element of $\langle 1g_{9/2}^2 | V_{\text{pn}} | 1g_{9/2}^2 \rangle_{J=9}$ by 40 keV, the ordering is inversed. This ambiguity in the value of the matrix element is possible since the statistical error in the original least-square fit was 70 keV for this element.[7] The energy difference between these two levels, $E(\frac{21}{2}^+)-E(\frac{17}{2}^+)$, is predicted to be 20 keV with the effective interactions by Serduke, Lawson, and Gloeckner[6] and -40 keV by the $g_{9/2}^n$ model with the empirical interaction derived from the ^{90}Nb spectrum.[8] Thus, it is highly expected that the lowest $J=\frac{21}{2}^+$ state is lying below the lowest $J=\frac{17}{2}^+$ state and a spin gap exists between the $J=\frac{13}{2}^+$ and the $\frac{21}{2}^+$ states which will be called an $E4$ spin gap in this paper.

Using the resultant wave functions we investigate the decay properties of the $J=\frac{21}{2}^+$ state, i.e., the $E4$ transition to the $J=\frac{13}{2}^+$ state at 1.32 MeV and the β^+ decay to ^{95}Ru. The partial half-life for the $E4$ transition is calculated to be 80 sec under the assumption of

$$e_{\text{p}} \langle 1g_{9/2} | r^4 | 1g_{9/2} \rangle = 500\ e\ \text{fm}^4$$

and of the energy difference $\Delta E=0.6$ MeV, though the calculated result depends much more critically on the latter. For the β^+ decay we introduce the effective Gamow-Teller (GT) single-particle matrix element with the reduction factor α, namely,

$$\langle (1g_{9/2})_{\text{n}} \| t_+\sigma \| (1g_{9/2})_{\text{p}} \rangle^{\text{eff}} = (\tfrac{110}{9})^{1/2}\alpha \ . \tag{2}$$

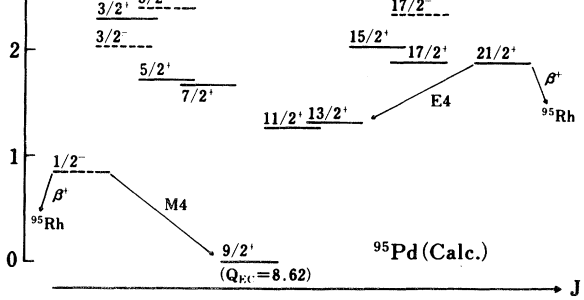

FIG. 1. Calculated energy levels of ^{95}Pd. The lowest levels with each spin-parity state below 3 MeV are shown by solid lines for positive-parity states and by dashed lines for negative-parity states. The transitions from the isomeric states are indicated by arrows.

Another matrix element

$$\langle (2p_{1/2})_{\text{n}} \| t_{+}\sigma \| (2p_{1/2})_{\text{p}} \rangle^{\text{eff}}$$

is assumed to be the same as the single-particle estimate. By using a value of $\alpha = 0.5$ which reproduces the measured log*ft* value for β^+ transition of

$$^{93}\text{Ru}(\tfrac{9}{2}^+\ \text{g.s.}) \to {}^{93}\text{Tc}(\tfrac{9}{2}^+\ \text{g.s.})\ ,$$

we calculate the log*ft* values of GT transitions to several low-lying $\frac{19}{2}^+$ and $\frac{21}{2}^+$ states in ^{95}Rh. A log*ft* value of 5.66 is obtained for the main transition to the ^{95}Rh $(\frac{19}{2}^+$ at 3.4 MeV). The partial half-life of the GT transitions above is estimated as about 80 sec. Therefore, the calculated value of the half-life is 40 sec, though a larger value of α provides better agreement with the measured half-life of 14 sec. Since any other high-spin states in ^{95}Pd are not accompanied by a larger spin gap than $E4$, we conclude that the spin of the observed isomer $^{95}\text{Pd}^m$ must be $J = \frac{21}{2}^+$. Furthermore, because of a large Q_{EC} value, the β-delayed proton emission from this state which has been observed by Nolte and Hick[1] is expected in the present shell model.

In Fig. 2 we show the calculated energy spectrum of ^{95}Ag. The $J = \frac{23}{2}^+$ state obtained at 2.56 MeV is associated with an $M3$ spin gap and expected to be an isomer as well as the $J = \frac{1}{2}^-$ state at 0.66 MeV. To estimate the lifetime of the $J = \frac{23}{2}^+$ state one has to pay attention to the direct proton emission from this state. The threshold for the proton emission B_p in ^{95}Ag is calculated to be 0.84 MeV by the present model. Similar values ($B_p = 0.88 \sim 1.51$ MeV) are obtained by various mass formulas.[9,10] Based on the R-matrix theory we have calculated the probability of the proton emission from this state to the $J = 0^+$ and 2^+ states in ^{94}Pd and found that the predicted partial lifetime will be larger than a year. This hindrance is due to high angular momentum ($l = 12$ or 10) carried by the emitted proton.

According to the discussion above, the lifetime of the $J = \frac{23}{2}^+$ state is actually determined by the $M3$ transition and by the β^+ decay. By the use of the effective values of the matrix element of

$$\langle 1g_{9/2} \| M3 \| 1g_{9/2} \rangle = 410\ \mu_{\text{N}}\text{fm}^2$$

for protons and $-180\ \mu_{\text{N}}\text{fm}^2$ for neutrons, the partial half-life of the $M3$ transition is calculated to be 0.4 sec. A comparable value, 1.0 sec, is obtained for the β^+ decay to the low-lying states in ^{95}Pd. Then we get a value of 0.3 sec for the half-life of the $J = \frac{23}{2}^+$ isomeric state in ^{95}Ag. Since the threshold energy for $^{94}\text{Rh}(10^+) + \text{p}$ is about 4.6 MeV in ^{95}Pd, it is expected that the β-delayed proton emission occurs through the highly excited $J = \frac{21}{2}^+$ states in ^{95}Pd.

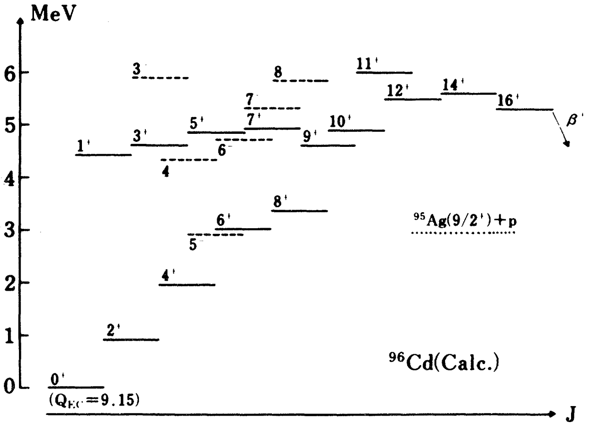

FIG. 3. Calculated energy levels of ^{96}Cd. The lowest levels with each spin-parity state below 6 MeV are shown.

The result for the even-even nucleus ^{96}Cd is shown in Fig. 3. The $J = 16^+$ state predicted at 5.30 MeV appears with a $E6$ spin gap. Though the state lies above the proton threshold ($B_{\text{p}} = 2.96$ MeV) and has been suggested as a possible proton emitter by Peker *et al.*,[11] it is shown, similarly to ^{95}Ag, that the state is almost stable against the proton emission. A value of 0.5 sec is calculated as the half-life with a reduction factor $\alpha = 0.5$ for the GT operator [Eq. (2)]. It is also suggested that this isomeric state is a precursor for the β-delayed proton emission, since the $^{95}\text{Pd}(\frac{29}{2}^+) + \text{p}$ channel opens at the excitation energy of about 6.1 MeV in ^{96}Ag.

The spin-gap isomers observed in even-even nuclei are very rare. Up to now we have only three examples, i.e., the $J = 12^+$ state in ^{52}Fe,[12] the $J = 16^+$ state in ^{178}Hf,[13] and the $J = (16^+)$ state in ^{212}Po.[14] The isomer predicted by the present shell model will be a new example in the even-even nucleus.

In ^{97}Cd (Fig. 4), two states, the $J = \frac{1}{2}^-$ state at 0.78 MeV

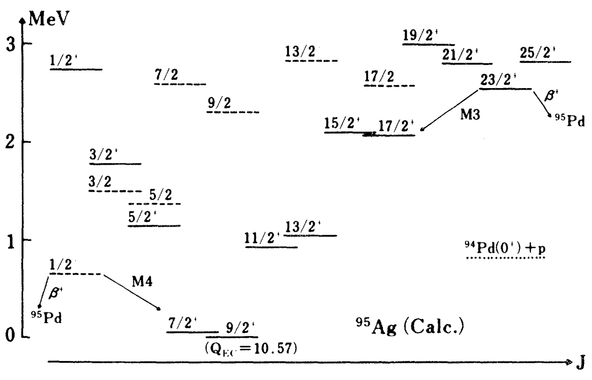

FIG. 2. Calculated energy levels of ^{95}Ag. The lowest levels with each spin-parity state below 3 MeV are shown. The proton threshold is indicated by the dotted line.

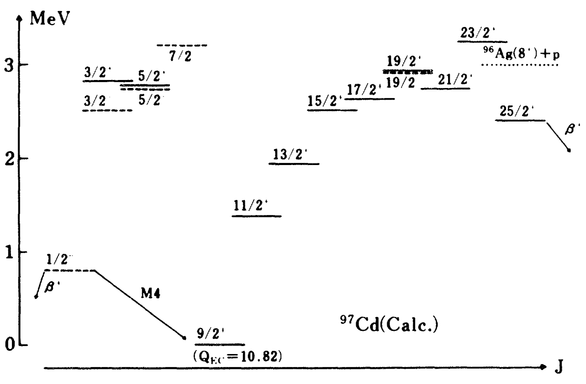

FIG. 4. Calculated energy levels of ^{97}Cd. The lowest levels with each spin-parity state below 3.5 MeV are shown.

and the $J=\frac{25}{2}^+$ state at 2.41 MeV, are predicted as isomeric states. The $J=\frac{25}{2}^+$ state is obtained with the $E6$ spin gap and expected to be a pure β^+-decaying isomer. Since the $J=\frac{21}{2}^+$ state is the highest spin state in the present model for ^{97}Ag, the daughter states to which the isomeric state can decay by the GT transition are produced by excitation of the neutron core, i.e., $|(1g_{9/2})^{-1}(1g_{7/2})\rangle$ neutron component. Since such core excited states exist at relatively high excitation energy region in ^{97}Ag , it is expected that the lifetime will be longer than a second and the branching ratio of the β-delayed proton emission, e.g.,

$$^{97}\mathrm{Cd}(\tfrac{25}{2}^+)\to 97\mathrm{Ag}^*(\tfrac{23}{2}^+)\to {}^{96}\mathrm{Pd}(10^+)+\mathrm{p}$$

will be large. The precursor character of ^{97}Cd has been indicated by the experiment at the ISOLDE on-line isotope separator.[15]

In summary, possible existence of long-lived state with high spins are suggested in ^{95}Pd, ^{95}Ag, and ^{96,97}Cd. This is because the effective p-n interaction favors an aligned p-n pair which can be directly shown by the $M9$ spin gap predicted in ^{98}In. The high-spin isomers above the proton threshold are predicted to be mostly stable against the direct proton emission in the present cases, but will be precursors of the β-delayed proton emission. The numerical calculations were carried out with FACOM M-180 II AD at the Institute for Nuclear Study, University of Tokyo.

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