INSTITUTE FOR NUCLEAR STUDY
UNIVERSITY OF TOKYO
Tanashi, Tokyo 188
Japan

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Long-Lived High-Spin Isomers in the Neutron-Deficient $1g_{9/2}$-shell Nuclei

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Institute for Nuclear Study, University of Tokyo

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Abstract

The neutron-deficient $1g_{9/2}$-shell nuclei are sutdied in the framework of the shell model with active nucleons occuping the $1g_{9/2}$ and $2p_{1/2}$ shells. The calculated result for ^{95}Pd shows good agreement with the recent experiment by Nolte and Hick. Many "spin-gap" Isomers are predicted in the region of A = 76∿84 and A = 95∿100.

It is well known that the effective interaction between a proton and a neutron is strongly attractive in their maximum spin state so as to yield a large "spin-gap" in multi-particle configuration [1, 2]. This feature of the effective p-n interaction is responsible for producing long-lived high-spin isomers near double-closed-shell nucleus. There are many examples of such "spin-gap" isomers in odd-A and odd-odd nuclei. On the other hand the $J = 16^+$ state at 2.39 MeV in ^{212}Po and the $J = 12^+$ at 6.8 MeV in ^{52}Fe are the only two examples in even-even nuclei [3, 4]. The existence of the spin-gap isomers can be expected in various mass regions including those which are far from the stability line. In this paper we report the results of the shell model calculations for the neutron-deficient $1g_{9/2}$-nuclei.

Two types of the spin-gaps arise in this mass region. One is a spin-gap due to the coexistence of the single-particle orbits of $1g_{9/2}$ and $2p_{1/2}$ and the other is due to the two-body effective p-n interaction within the $1g_{9/2}$-shell. It must be noted that the latter type of the spin-gap is expected only in the proton-particle and neutron-particle configuration (pn-configuration) or in the proton-hole and neutron-hole configuration ($\bar{p}\bar{n}$-configuration). Thus the most probable situation is obtained at the region near the N = Z line. In the following we mainly report the calculated results for the neutron-deficient $1g_{9/2}$-nuclei with A = 95∿100.

In the present calculations the nucleus ^{100}Sn is assumed to be an inert core and the model space employed consists of $1g_{9/2}$ and $2p_{1/2}$ orbitals for both $\bar{p}$ and $\bar{n}$.

The effective two-body interactions in the $1g_{9/2}$-$2p_{1/2}$ shells have been investigated intensively for the N = 50 and N = 49 nuclei near the stability line [5, 6, 7]. The $\bar{p}$-$\bar{p}$ and the $\bar{p}$-$\bar{n}$ interactions used in the present paper are those from ref. 7. The Coulomb effects are included in the $\bar{p}$-$\bar{p}$ interaction. The matrix elements of the $\bar{n}$-$\bar{n}$ interactions are assumed to be the same as the T = 1 component in the $\bar{p}$-$\bar{n}$ interaction. The single-hole energies of $\varepsilon_p(j)$ and $\varepsilon_n(j)$ relative to the ^{100}Sn core are derived from the single particle and hole energies of $\varepsilon_p(j)$ and $\varepsilon_n(j)$ with respect to ^{88}Sr core in conjunction with the two-body effective interaction mentioned above.

One of the most interesting nuclei in the neutron-deficient $1g_{9/2}$-region is ^{95}Pd. Recently it has been studied with the heavy-ion induced reaction by Nolte and Hick [8]. They found a new high-spin isomer ^{95}Pd^m which decayed through β^+ process with a half-like of 14±1 sec, and they also observed β-delayed proton emission.

The calculated energy spectrum of ^{95}Pd is shown in Fig. 1. The existence of two isomers are suggested; one is a $J = 1/2^-$ state laying at 0.85 MeV and the other is a $J = 21/2^+$ state at 1.90 MeV. The $J = 21/2^+$ state almost degenerates with a $J = 17/2^+$ state. The present model predicts the $J = 21/2^+$ state at 5 keV above the $J = 17/2^+$ state. This ordering, however, is very sensitive to the two-body interactions adopted. For example if one takes more attractive matrix element of $\langle 1g_{9/2}|V_{pn}|1g_{9/2}\rangle_{J=9}$ by 40 keV, the ordering is reversed. This variation of the matrix element is within the statistical errors in the original least-square fit in ref. 7. In other calculations the energy difference between these two levels, $E(21/2^+)-E(17/2^+)$, is predicted to be 20 keV with the effective interactions by Serduke et al. [6] and -40 keV by the $g^n_{9/2}$ model with the empirical interaction derived from the ^{90}Nb spectrum [8]. Thus it is highly expected that the lowest $J = 21/2^+$ state is lying below the lowest $J = 17/2^+$ state and a spin-gap exists between the $J = 13/2^+$ and the $21/2^+$ states which will be called a E4 spin-gap in this paper. Any other high-spin states cannot be obtained with a larger spin-gap. Therefore it is quite probable that the spin of the observed isomer $^{95}Pd^m$ is $J = 21/2^+$.

Using the resultant wave functions we investigate the decay properties of the $J = 21/2^+$ state. Two decay modesare possible, i.e. the E4 γ-decay to the $J = 13/2^+$ 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 $e_p\langle 1g_{9/2}|r^2|1g_{9/2}\rangle \sim 500\ ef_m^4$ and of the β-ray energy being ΔE=0.6 MeV, though the calculated value depends much critically on the latter. For the β^+-decay we introduce the effective Gamov-Teller (GT) single-particle matrix element with the reduction factor α, namely

$$\langle (1g_{9/2})_n || t_+\sigma || (1g_{9/2})_p \rangle^{eff} = \sqrt{110/9}\,\alpha \ . \qquad (1)$$

Another matrix element $\langle (2p_{1/2})_n || t_+\sigma || (2p_{1/2})_p \rangle^{eff}$ is assumed to be the same as the single-particle estimate because the 2p-shell is closed in the ^{100}Sn core. We only consider the GT-transition to the low-lying $J = 19/2^+$ and $21/2^+$ in ^{95}Rh which are obtained by the present configuration of $(1g_{9/2}, 2p_{1/2})_p^{-5}$. The partial half-life of the GT-transitions above is estimated as about 30 sec for $\alpha = 0.5$. This value is in reasonable agreement with the measured value of 14 sec.

The predicted atomic mass-difference between ^{95}Pd and ^{95}Rh is 8.62 MeV or $Q_{\beta^+} = 7.60$ MeV by the present model (similar values are predicted by various mass formulae [10]). And the binding energy of proton B_p in ^{95}Rh is calculated to be 3.07 MeV which is in good agreement with the experimental value of $(Bp)_{exp} = 3.06 \pm 0.15$ [11]. Therefore it is possible that the $J = 21/2^+$ state decays to the excited states in ^{95}Rh high above the proton threshold which can decay through the one-proton emission. Thus we can understand the isomer ^{95}Pd^m as a β-delayed proton precursor.

The calculated energy spectra for the nuclei, ^{95}Ag, ^{96}Cd and ^{97}Cd are shown in Figs. 2, 3 and 4. The spectra show possible existence of long-lived isomers. Those isomers are $J = 1/2^-$ and $23/2^+$ states in ^{95}Ag, $J = 16^+$ state in ^{96}Cd and $J = 1/2^-$ and $25/2^+$ states in ^{97}Cd. The two $J = 1/2^-$ states mentioned above would be expected to have a similar decay mode to that of the $J = 1/2^-$ state in ^{95}Pd. The $J = 23/2^+$ state in ^{95}Ag appears with the M3 spin-gap. A simple estimation gives that the M3 γ-decay and the β^+-decay are comparable and that the half-life is predicted to be in an order of a second. From this $J = 23/2^+$ state a direct proton emission might be possible. The threshold energy for the proton emission Bp in ^{95}Ag is calculated to be 0.84 MeV by the present model and similar values (Bp = 0.88∿1.51 MeV) are predicted by mass formulae [10]. Therefore the $J = 23/2^+$ isomer can decay to the $J = 0^+$ ground state of ^{94}Pd by emitting a Ep∿1.7 MeV proton. Similar situation is also found for the

$J = 16^+$ state at 5.30 MeV in ^{96}Cd. The state appears with the E6 spin-gap and lies above the proton threshold of Bp = 2.96 MeV. The partial half-life of the GT-transition to the $J = 15^+$ state in ^{96}Ag is calculated to be 0.6 sec with the reduction factor of $\alpha = 0.5$ for the effective GT-operator. One needs more precise treatment on the penetrabilty through the Coulomb and centrifugal barriers in order to predict whether or not these two high-spin isomers can be detectable proton radioactivities. Up to know the only example of the proton radioactivity is the isomer ^{53m}Co [13] which suggests very hindered penetrability.

The $J = 25/2^+$ state at 2.41 MeV in ^{97}Cd is predicted as a pure β^+-decaying isomer because the state appears with the E6 spin-gap. The GT-transitions from this state are expected only to the $J = 23/2^+ \sim 27/2^+$ states in ^{97}Ag which include the excited $1g_{7/2}$-neutron components. Such states must lie high enough above the proton threshold in ^{97}Ag, because even the $J = 21/2^+$ state which is the highest spin state predicted by the $(1g_{9/2}, 2p_{1/2})_p^{-3}$ configuration lie above the proton threshold (Bp = 1.97 MeV). Therefore such daughter states would be proton emitters. Due to the large mass difference between ^{97}Cd and ^{97}Ag (Q_{β^+} = 9.80 MeV), the $J = 9/2^+_{gnd}$ state of ^{97}Cd is also expected to be a β-decay proton precursur. The evidence for the precursur has been already indicated by the experiment at CERN [12].

In summary, we showed that several isomers with half-lives of the order of a second could exist in the region of $A = 95 \sim 100$. The spin values of the predicted isomers change from nuclei to nuclei. Simple explanation for the most probable values can be given by considering the split of the $1g_{9/2}$ orbit into the msubstates, i.e. Nilsson orbits. Active holes occupy the substate in order of $|m| = 9/2, 7/2, \cdots$ and the maximum spin value for protons J_p (or J_n for neutron) is determined from the lowest active substate $|m|$ as $J_p = |m|$ or $2|m|-1$ depending on Z = odd or even. In the case of ^{95}Pd, for example, the four protons couple to $J_p = 6^+$ because the lowest active subshell is $|m| = 7/2$ and then align with the $|m| = 9/2$ neutron-hole so as to produce the $J = 21/2^+$ state. Such stretched states occationally appear with a large spin-gap. At the middle of the shell the most probable spin values predicted are small and the spin-gaps become obscure.

Similar isomers are predicted for the $1g_{9/2}$-nuclei at the beginning of the shell, i.e. the neutron-deficient nuclei with $A = 76 \sim 84$. Though the $2p_{3/2}$ nucleons become much more important in these nuclei, the present configuration assumed would be still adequate for the description of the high-spin states. Possible long-lived high-spin isomers suggested for the nuclei with $T_z \geq 0$ are a $J = 9^+$ state in ^{78}Y, $J = 19/2^-$ and $25/2^+$ in ^{79}Y, $J = 16^+$ in ^{80}Zr, $J = 16^-$ in ^{80}Y, $J = 25/2^+$ in ^{81}Zr, $J = 21/2^+$ in ^{81}Y, $J = 9^+$ and 17^+ in ^{82}Nb, $J = 19^-$ in ^{82}Zr, $J = 25/2^+$ in ^{93}Nb, and $J = 16^+$ and 19^- in ^{84}Mo. Among these states the $J = 16^+$ states in ^{80}Zr and ^{84}Mo and the $J = 25/2^+$ state in ^{81}Zr have been suggested as possible isomers by Peker et al. [14]

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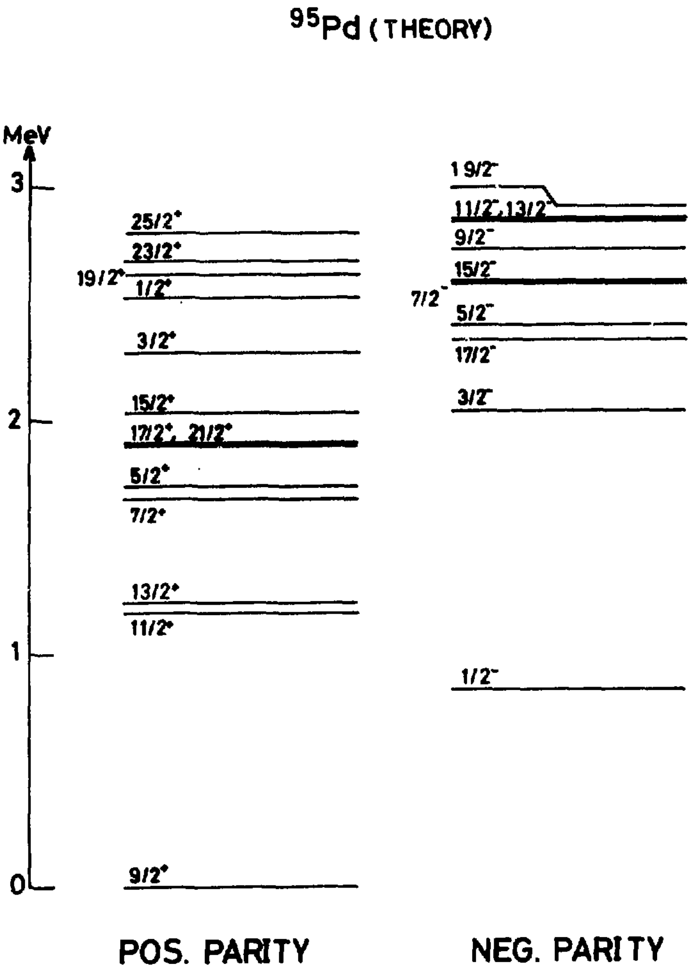
Figure captions

Fig. 1 Calculated energy levels of ^{95}Pd.
Only the lowest levels with each spin-parity state are shown.

Fig. 2 Calculated energy levels of ^{95}Ag.
Only the lowest levels with each spin-parity state are shown.

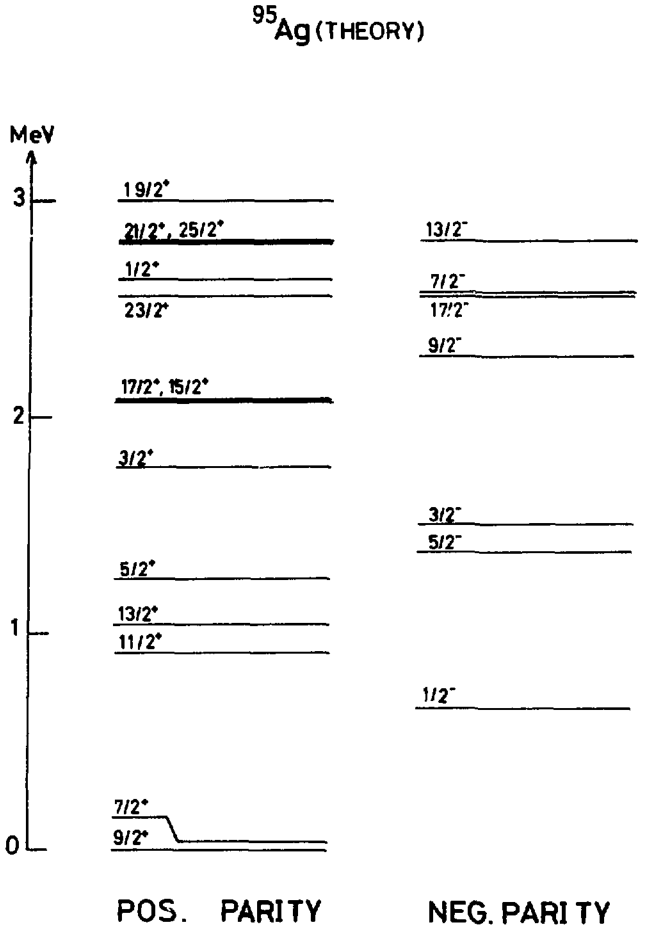
Fig. 3 Calculated energy levels of ^{96}Cd.
Only the lowest levels with each spin-parity state are shown.

Fig. 4 Calculated energy levels of ^{97}Cd.
Only the lowest levels with each spin-parity state are shown.



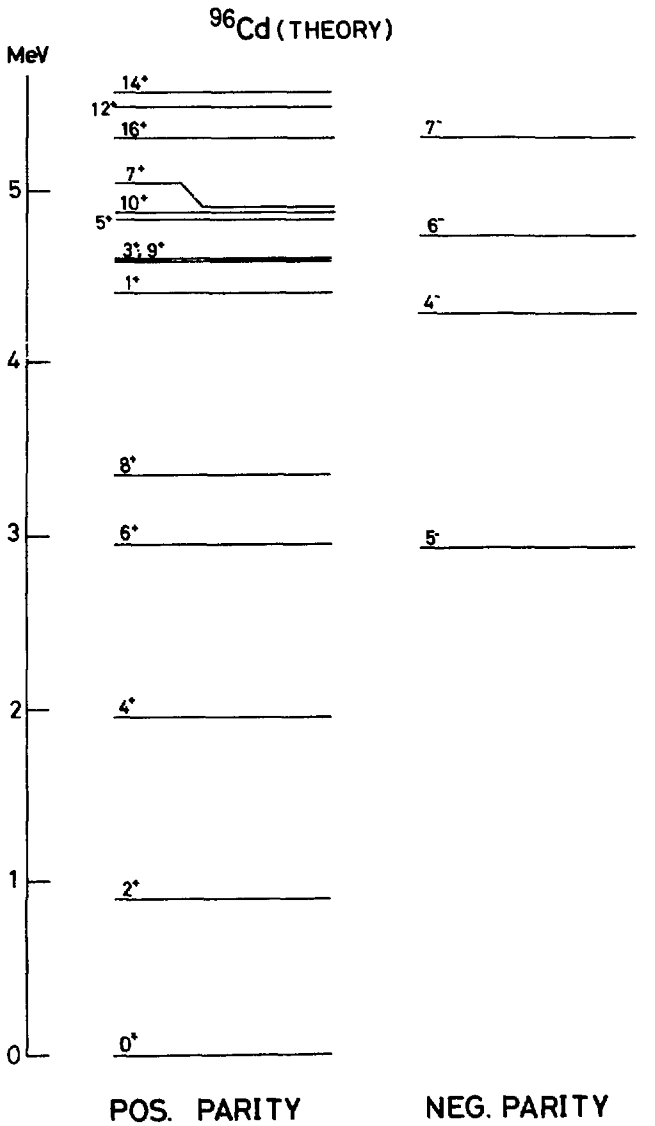
95Pd (THEORY)
MeV
3
2
1
0
25/2+
23/2+
19/2+
1/2+
3/2+
15/2+
17/2+, 21/2+
5/2+
7/2+
13/2+
11/2+
9/2+
19/2-
11/2-, 13/2-
9/2-
15/2-
7/2-
5/2-
17/2-
3/2-
1/2-
POS. PARITY
NEG. PARITY

Fig. 1



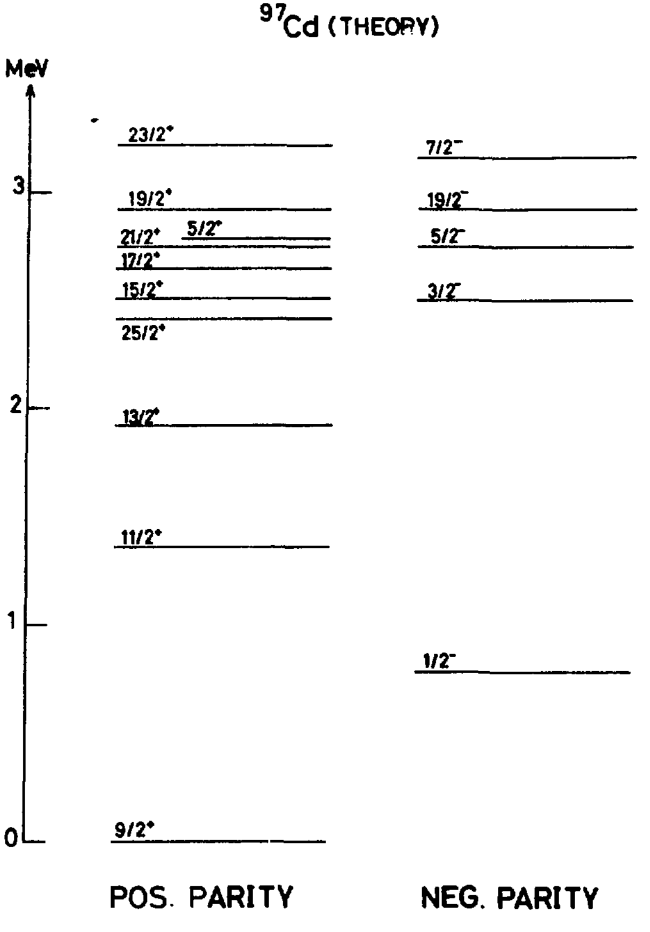
^{95}Ag (THEORY)
MeV
3
2
1
0
19/2+
21/2+, 25/2+
1/2+
23/2+
17/2+, 15/2+
3/2+
5/2+
13/2+
11/2+
7/2+
9/2+
13/2-
7/2-
17/2-
9/2-
3/2-
5/2-
1/2-
POS. PARITY
NEG. PARITY

Fig. 2



96Cd (THEORY)
MeV
14+
12+
16+
7+
10+
5+
3+, 9+
1+
8+
6+
4+
2+
0+
7-
6-
4-
5-
0
1
2
3
4
5
POS. PARITY
NEG. PARITY

Fig. 3



97Cd (THEORY)
MeV
3
2
1
0
23/2+
19/2+
21/2+
5/2+
17/2+
15/2+
25/2+
13/2+
11/2+
9/2+
7/2−
19/2−
5/2−
3/2−
1/2−
POS. PARITY
NEG. PARITY

Fig. 4