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Low-Lying Yrast States in ^{210}Rn and ^{211}Rn and the Competition between Neutron-Hole and Proton Excitations

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The γ-decay and nuclear structure of low-lying yrast and near yrast levels in ^{210}Rn and ^{211}Rn have been investigated. The cascade from the yrast 6^+ state in ^{210}Rn branches to two close-lying 4^+ states, deduced to be complete mixtures of the 4^+ states arising from the proton configuration, and from the neutron-hole intruder configuration. The influence of this proton—neutron-hole interaction on the yrast cascades in ^{211}Rn and ^{206}Rn, ^{208}Rn is discussed.

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Experiments which we have recently undertaken have elucidated the structure of the low-lying states of the neutron-hole isotopes ^{211}Rn and ^{210}Rn. These nuclei have four protons outside the ^{208}Pb core and, respectively, one and two neutron holes. In this Letter we wish to concentrate on the structure of the lower-lying yrast states which arise from the seniority-2, $h_{9/2}{}^4$ proton configuration coupled to one and two neutron holes, in the nuclei ^{211}Rn and ^{210}Rn, respectively, and to four and six neutron holes in ^{208}Rn and ^{206}Rn. Poletti *et al.*[1] have recently investigated the yrast states of ^{210}Rn, while for ^{211}Rn almost nothing of its structure has been established (Lederer and Shirley[2]). Information on the two lighter radon isotopes has been obtained by Ritchie[3] and by Horn, Baktash, and Lister.[4] We wish to report on a reinvestigation of the structure of the ^{210}Rn, on one aspect of the first extensive investigation of the ^{211}Rn structure and, in particular, to draw attention to the way in which the 4^+ states from the proton and neutron-hole configurations interact.

The Australian National University 14UD Pelletron accelerator was used to excite the nuclei using the reactions ^{205}Tl(^{11}B, $5n$)^{211}Rn and ^{205}Tl(^{10}B, $5n$)^{210}Rn, respectively, at bombarding energies near 70 MeV. As expected from nuclear structure systematics, both nuclei have a long-lived isomeric level at about 1600-keV excitation energy. In Fig. 1 we present the results of a delayed coincidence experiment for both nuclei. In the lower part of the figure we show the γ-ray spectrum delayed with respect to the 325-, 546-, 185-, and 712-keV γ-ray transitions which have already been shown (Poletti *et al.*[1]) to lie above the 8^+ isomeric state at $1665 + \Delta$ keV in ^{210}Rn. Of the five γ rays shown, further analysis revealed

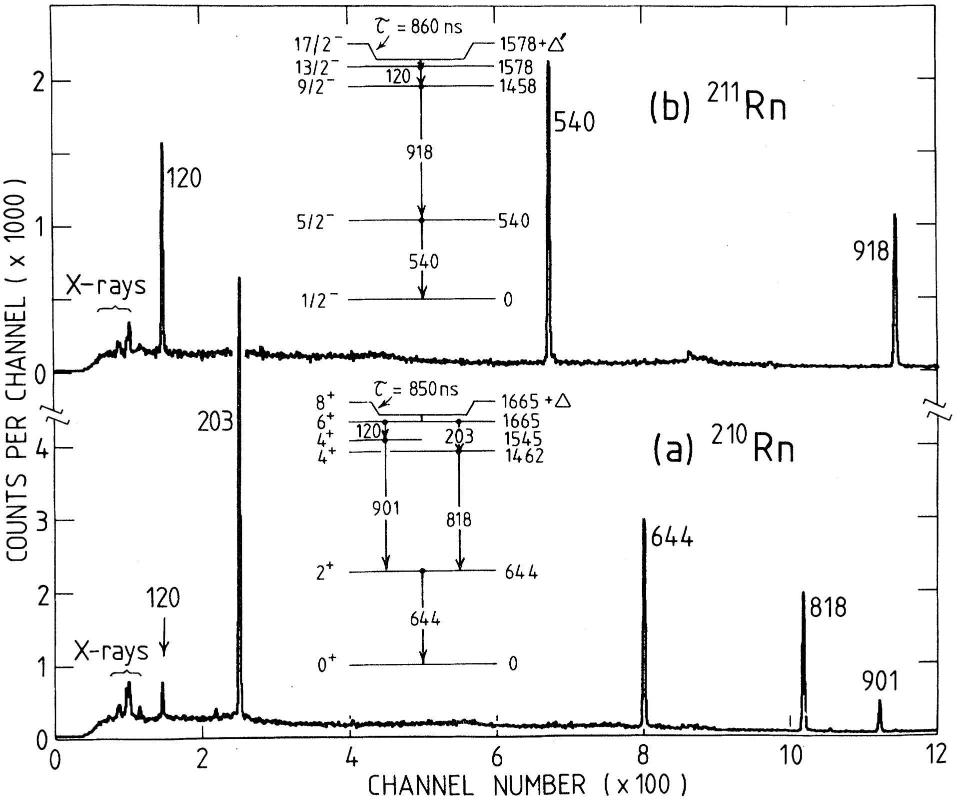

FIG. 1. "Delayed" γ-ray spectra in ^{210}Rn and ^{211}Rn. In the lower part of the figure, the γ rays in delayed coincidence with the known precursor γ rays above the 8^+ isomer in ^{210}Rn are shown. The 6^+ state γ decays $(6.6\pm 0.5)\%$ to the 4^+ state at 1545 keV and $(93.4\pm 0.5)\%$ to the lower state at 1462 keV. In the upper part of the figure the γ rays in delayed coincidence with the precursor γ rays above the $\frac{17}{2}^-$ isomer in ^{211}Rn are shown.

that four were in coincidence with the 644-keV γ ray and that they could be fitted into two parallel cascades. Direct and indirect measurements of conversion coefficients and γ-ray angular distribution measurements reveal that all transitions are $E2$ and stretched. We determined the mean life of this 8^+ state to be 850 ± 25 ns, while for the 6^+ state we establish a mean life of $\tau = 11\pm 1$ ns. This measurement together with the measured conversion coefficients of the 120- and 203-keV transitions imply, respectively, $B(E2) = 115 \pm 14\ e^2\cdot\mathrm{fm}^4$ and $114\pm 12\ e^2\cdot\mathrm{fm}^4$—rather stronger than those for similar transitions in ^{212}Rn (Horn *et al.*[5]). The deduced level scheme for these lower excited states of ^{210}Rn is given in the inset of Fig. 1. In other experiments we have determined that γ rays of 570, 584, and 601 keV lie above the isomer at $1578+\Delta'$ keV in ^{211}Rn and in the upper part of Fig. 1 we show the spectrum of γ rays delayed with respect to these transitions. Again we have established that the transitions are $E2$ and stretched. In this case we ascribe the isomerism to an unobserved low-energy $E2$ transition deexciting a $\frac{17}{2}^-$ level with a mean life of 860 ± 40 ns. The deduced level scheme for the lower-lying states of ^{211}Rn is given in the inset. In both cases we searched for the transition directly deexciting the isomer and for both nuclei we conclude that the transition energy is less than 50 keV.

By taking into account the systematics in this region of the periodic table it is easy to see that the isomeric levels arise mainly from the coupling of the $\pi(h_{9/2}{}^4)_{J=8}$ configuration to the $\nu(p_{1/2}{}^{-2})_{J=0}$ and $\nu(p_{1/2}{}^{-1})_{J=1/2}$ hole states to give states of spin-parity 8^+ and $\frac{17}{2}^-$ in ^{210}Rn and ^{211}Rn, respectively. In the case of ^{211}Rn this state deexcites by a cascade of $E2$ radiations through the $\pi h_{9/2}{}^4 \nu p_{1/2}{}^{-1}$ levels until it reaches the lowest quadrupole excitation at 540 keV. In ^{210}Rn the deexcitation splits following the 6^+ state and reveals the existence of another (nonyrast) 4^+ state.

In order to understand the intrusion of the second 4^+ state in ^{210}Rn and the absence of an equivalent state in ^{211}Rn, we examine the low-lying spectra of ^{206}Pb and ^{207}Pb (Lederer and Shirley[2]). While both have a low-lying quadrupole excitation (at 803 keV, $J^\pi = 2^+$ in ^{206}Pb and 570 keV, $J^\pi = \frac{5}{2}^-$ in ^{207}Pb), only in ^{206}Pb is there a state of sufficiently high spin ($J^\pi = 4^+$, $E_x = 1684$ keV) at a low enough energy to compete successfully with the $\pi h_{9/2}{}^4$ seniority-2, proton excitation. In Fig. 2 we trace this two-hole-state excitation, which is predominantly from the $\nu(f_{5/2}{}^{-2})_4$ and $\nu(f_{5/2}{}^{-1}p_{3/2}{}^{-1})_4$ neutron-hole configurations,[6] as, successively, two protons (^{208}Po) and then four protons are added (^{210}Rn). In ^{208}Po the increase in binding is insufficient to bring the 4^+ neutron-hole state below the 8^+ state belonging to the $\pi h_{9/2}{}^2$ configuration and it has been seen only in particle transfer reactions (Bhatia *et al.*[7]). However, in ^{210}Rn the extra binding brings it below the 6^+ state, essentially to the same energy as the lowest 4^+ state from the $\pi h_{9/2}{}^4$ configuration.

Our surprising experimental result is that the two 4^+ states in ^{210}Rn are completely mixed. The basis for this conclusion is the analysis of the $B(E2)$ strengths of the transitions from the 6^+ state to the two 4^+ states which are, as stated earlier, nearly equal.

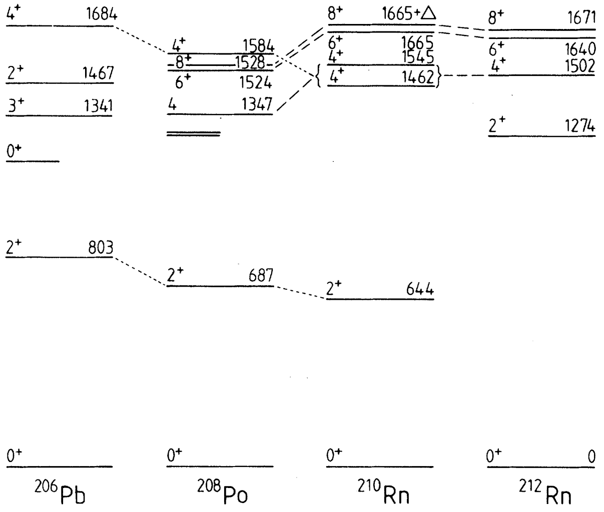

FIG. 2. Level schemes showing the systematics of the energy of the lowest 4^+ state arising from the $h_{9/2}{}^4$ or the $h_{9/2}{}^2$ configuration and the 4^+ states arising from the neutron-hole excitation in ^{206}Pb, ^{208}Po, and ^{210}Rn. The ^{212}Rn and ^{210}Rn schemes illustrate the relative lack of sensitivity of the excitation energies of the 6^+ and 8^+, $h_{9/2}{}^4$ states to the two neutron holes in ^{210}Rn.

In zeroth order the $E2$ transition from the 6^+ proton state to the unperturbed 4^+ neutron-hole state is forbidden[8] and we therefore attribute the strong transition observed to mixing with the 4^+ proton configuration. From the $B(E2)$ ratio and observed separation of the 4^+ states of 83 keV, we estimate the effective mixing matrix element as 41.49 ± 0.03 keV [the error quoted here only reflects the error in the $B(E2)$ ratio], which in turn implies a separation of the unperturbed 4^+ states of $0.4^{+3.1}_{-3.5}$ keV. The wave functions of the final states are, therefore,

$$|1462, 4^+\rangle = (0.709 \pm 0.015) |\pi(h_{9/2}{}^4)_4 \nu(p_{1/2}{}^{-2}, f_{5/2}{}^{-2}, p_{3/2}{}^{-2})_0\rangle$$
$$- (0.705 \mp 0.015) |\pi(h_{9/2}{}^4)_0 \nu(f_{5/2}{}^{-2}, f_{5/2}{}^{-1}p_{3/2}{}^{-1})_4\rangle$$

with the complementary wave function for the 1545-keV, 4^+ state. Here we have explicitly shown the main neutron-hole configurations found in the ground state, and 4^+ excited state of the core nucleus ^{206}Pb. These neutron-hole admixtures are crucial since mixing between the dominant configurations, $|\pi(h_{9/2}{}^4)_4 \nu(p_{1/2}{}^{-2})_0\rangle$ and $|\pi(h_{9/2}{}^4)_0 \nu(f_{5/2}{}^{-2})_4\rangle$, through the two-body proton-neutron interaction is identically zero.

Assuming similar neutron admixtures in ^{210}Rn as are known in ^{206}Pb, we can make an estimate of the expected mixing between the 4^+ states. Taking the known $\nu(f_{5/2}{}^{-2})_0$ admixture in the ^{206}Pb ground state,[9] the amplitude of the $\nu(f_{5/2}{}^{-2})_4$ component for the ^{206}Pb 4^+ excited state given by True[6] and the experimental two-body proton-neutron interaction deduced from the $\pi h_{9/2} \nu f_{5/2}{}^{-1}$ multiplet in ^{208}Bi,[10] we calculate the expected matrix element between the 4^+ states in ^{210}Rn as 26^{+6}_{-5} keV. We have not included the $\nu(f_{5/2}{}^{-1}p_{3/2}{}^{-1})_4$ component since it involves off-diagonal matrix elements which are not directly available from experiment. This estimate is consistent with the results of a large shell-model calculation for ^{210}Rn.[11]

The proton-neutron interaction, acting through neutron-hole admixtures, therefore provides a plausible explanation for the 40-keV interaction between the 4^+ states. The bifurcation of the yrast cascade in ^{210}Rn is a direct result of the competition between the 4^+ proton and 4^+ neutron-hole excitations. An equivalent effect does not occur in ^{211}Rn because the ^{207}Pb core lacks a low-lying $\frac{9}{2}^-$ neutron-hole state and there is, therefore, no associated low-lying $\frac{9}{2}^-$ level in ^{211}Rn to compete with the $|\pi(h_{9/2}{}^4)_4\nu(p_{1/2}{}^{-1}),\frac{9}{2}\rangle$ yrast state.

Finally it is of some interest to trace the competition between the proton excitations and the neutron-hole excitations through the even radon isotopes. The decay schemes are summarized in Fig. 3. We note that whereas in ^{210}Rn both of the 4^+ states are populated by the decay of the 6^+ level, in ^{208}Rn only the upper of the two 4^+ states is populated, while in ^{206}Rn it is the lower one to which the 6^+ state decays.

This unexpected difference in branching can be understood as follows. In the absence of mixing, the $\pi h_{9/2}{}^4$, 6^+ state will decay to the 4^+ state of the same configuration. In ^{210}Rn, mixing of the 4^+ proton and neutron-hole states results in a splitting of the decay from the 6^+ state. In ^{208}Rn the 4^+ neutron-hole state is well below the 4^+ proton state but, since the mixing is small, it is effectively by-passed in the cascade despite its lower energy.[12] In ^{206}Rn the 4^+ proton state is yrast and well separated from the neutron-hole state, therefore, again, the yrast cascade from the 6^+ state is not split. The low energy of the 4^+ neutron-hole state in ^{208}Rn compared with its even neighbors is in agreement with the excitation energy of the related 4^+ state in ^{204}Pb (the isotone of ^{208}Rn) where it is lower in energy than in its even Pb neighbors.

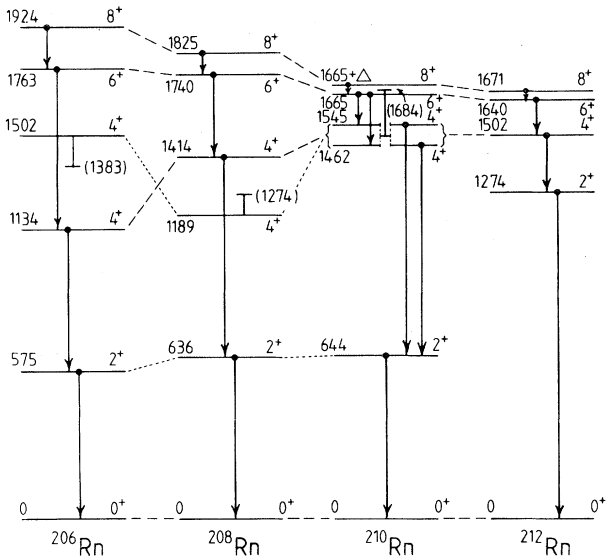

FIG. 3. Competition between the 4^+ states arising from the $\pi h_{9/2}{}^4$ configuration and the neutron-hole 4^+ excitation in the ^{206}Rn, ^{208}Rn, and ^{210}Rn isotopes. Related levels arising from the $\pi h_{9/2}{}^4$ excitations are connected by dashed lines, while similar levels resulting from neutron-hole excitations are connected by dotted lines. The short horizontal bars labeled by bracketed energies show the position of the 4^+ neutron-hole excitation in the related Pb isotopes. They are joined by the short vertical lines to the levels identified as 4^+ neutron-hole excitations in each Rn isotope.

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