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Level structure and electromagnetic properties in ^{212}Ra

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We report the first study of ^{212}Ra by using a variety of in-beam techniques through the ^{204}Pb(^{12}C,4n)^{212}Ra reaction. The level scheme of ^{212}Ra up to a spin of 16 including 14 levels and 15 transitions has been established. Two isomeric states with half-lives of 10.9 and 0.85 μs were found, and their g factors were measured by the stroboscopic method. Configurations of the levels up to $I^\pi = 13^-$ have been assigned tentatively by the measured g factors, the systematics in the ^{210}Rn isotone, and the excitation energies estimated by the weak coupling of two-neutron hole states to the levels in ^{214}Ra.

In recent years many experimental and theoretical studies on nuclei near the $Z = 82$, $N = 126$ shell closure have been carried out. For Rn and Ra isotopes, however, the available experimental data via nuclear reactions are rather localized because of the available target and projectile combinations. Specifically, only the data of lighter isotopes ($N \leqslant 128$) (Refs. 1–5) are available for Rn, whereas only those of heavier isotopes ($N \geqslant 126$) (Refs. 4, 6–8) are available for Ra. These available data show the systematic variation of the nuclear structure from spherical to deformed or collective as the neutron number departs from 126. In $^{204}_{86}\mathrm{Rn}_{118}$ the level spacings and the reduced transition probability $B(E2;8^+\text{-}6^+)$[1] show more collectivity than those in $^{208-212}_{86}\mathrm{Rn}_{122-126}$ where long-lived ($T_{1/2} = 500$–900 ns) isomers were found. Excited states in $^{214}_{88}\mathrm{Ra}_{126}$ (Ref. 4) and $^{216}_{88}\mathrm{Ra}_{128}$ (Ref. 6) are explained in the framework of the spherical shell model, while in $^{218}_{88}\mathrm{Ra}_{130}$ (Ref. 7) no isomeric state was found and there are positive- and negative-parity bands which have regular level spacings, showing the collective nature of this heavier Ra isotope.

In this paper we present the first study of the level structure of $^{212}_{88}\mathrm{Ra}_{124}$ as a first step towards the investigation of the lighter Ra isotopes. Since there has been no published experimental work on ^{212}Ra previously, the comparison of the present data with the data on the neighboring isotopes ^{214,216}Ra (Refs. 4 and 6) or on the isotone ^{210}Rn (Ref. 3) would be a useful guide to investigate the level structure of ^{212}Ra. Furthermore, some isomers are expected to exist in ^{212}Ra from the systematics of the $N \leqslant 126$ Rn isotopes. The g-factor measurements will make it possible to assign the shell-model configurations of these isomers.

Self-supporting targets of enriched ^{204}Pb were bombarded with 70–90 MeV ^{12}C beams from the Institute for Nuclear Study, University of Tokyo SF cyclotron and the IPCR cyclotron. Levels in ^{212}Ra were populated with the (^{12}C, 4n) reaction and γ rays were detected with Ge(Li) detectors. The measurements performed in this work include γ-ray excitation function, γ-γ coincidence, pulsed-beam lifetime, delayed γ-γ coincidence, γ-ray angular distribution, γ-ray linear polarization, conversion coefficient, e^--γ coincidence, and g-factor measurements.

The identification of transitions arising from ^{212}Ra was made by comparing the excitation function of the ^{204}Pb (^{12}C, 4n) ^{212}Ra reaction ($Q = -56.2$ MeV) with that of the ^{206}Pb (^{12}C, 4n) ^{214}Ra reaction ($Q = -57.3$ MeV). Since the Q values of the above two reactions are almost the same, the excitation functions of γ rays from ^{212}Ra are expected to be quite similar to those of known γ rays from ^{214}Ra. In this way, three γ rays, 629.3, 825.0, and 440.8 keV, were assigned to be from ^{212}Ra and their ordering was determined from their intensities and the systematics in the Rn isotopes. The three lowest excited states [E_x (keV) $= 629.3(2^+)$, $1454.3(4^+)$, and $1895.1(6^+)$] were thus determined and their spins and parities were assigned from the measured angular distributions and linear polarizations[9] of γ rays.

Since the time spectra of the above three lines not only showed a prompt peak but also a delayed component whose half-life was in the range of ~ 10 μs, the existence of a long-lived isomer(s) was expected at higher excitation energies. By using a newly designed gate and delay generator in conjunction with a pulsed ion source of the cyclotron, the half-life of the isomer was measured to be 10.9(4) μs from the energy spectra gated by the different time windows of the time spectrum in the off-beam period. This isomer was assigned to be 8^+ from the systematics of the neighboring nuclei, but we were unable to observe γ rays corresponding to the $8^+ \rightarrow 6^+$ transition because of its very low energy. The level scheme above the 8^+ isomer was constructed from the delayed γ-γ coincidences involving the three γ rays mentioned above. The multipolarities of the 504.8 and 655.0 keV transitions, however, could not be determined uniquely from the γ-ray measurements because of their weak intensities. The positive A_2 coefficients for the γ-ray angular distributions and the long lifetime of the initial state ($E_x = 2613.4$ keV) suggest an $E3$ character for both transitions.

In order to solve the above ambiguities, conversion electrons were measured with a Si(Li) detector in conjunction with a superconducting solenoid. The solenoid was set perpendicular to the beam direction and a thin target (~ 1 mg/cm^2) was located 2.2 cm upstream from the axis of the solenoid so that electrons emitted directly from the target could not reach the Si(Li) detector. The ^{212}Ra nuclei recoiled out of the target were caught by a Mylar catcher-foil set 3 cm downstream from the target and electrons emitted there were detected by the Si(Li) detector through the solenoid. Since we have also found another long-lived isomer with $T_{1/2} = 0.85(13)$ μs above the 8^+ isomer, we can observe the conversion electrons arising from transitions below this isomer. The conversion coefficients thus obtained showed the 619.0, 504.8, and 655.0 keV transitions to be of $E2$, $E3$, and $E3$ character, respectively, giving the spin and parity of the 2613.4 keV isomer to be 11^-. e^--γ coincidence measurements were also carried out with the same setting for electrons, and L- and M-conversion electron lines corresponding to the transition energy of 63.3 keV were clearly observed by gating with three γ rays below the 6^+ level. This 63.3 keV transition was identified as the missing $8^+ \rightarrow 6^+$ transition. The level scheme of ^{212}Ra thus obtained in this work is shown in Fig. 1.

The g factors of the 8^+ and 11^- isomers were measured by means of the stroboscopic method.[10] Varying the external magnetic field B, we measured the energy spectra gated on the time windows set in the delayed part of the time spectrum of the $\gamma - \tau_{\gamma\text{-}RF}$ coincidence. The stroboscopic resonance is observed when the Larmor frequency ω_L fulfills the condition $T_0 = \pi/\omega_L$ ($T_0 = 126$ ns: beam repetition time), giving the g factor as $g = \hbar\omega_L/(\mu_N B)$. The obtained results are $g = 0.888(9)$ for the 8^+ state and $g = 1.092(22)$ for the 11^- state.

The level structures of a pair of isotones, ^{210}Rn (Ref. 3) and ^{212}Ra, are compared in Fig. 2. The high-j proton orbitals above the $Z = 82$ shell closure, $h_{9/2}$, $f_{7/2}$, and $i_{13/2}$, give the configurations of $\pi(h_{9/2}^6)$, $\pi(h_{9/2}^5 f_{7/2})$, and $\pi(h_{9/2}^5 i_{13/2})$ for the low-lying levels in ^{214}Ra$_{126}$ (Ref. 4). In ^{212}Ra, levels with these proton configurations coupled with two-neutron-hole configurations are expected to occur. The level structure from the $\pi^6\nu^{-2}$ configuration in ^{212}Ra would be analogous to that from the $\pi^4\nu^{-2}$ configuration in ^{210}Rn because the seniority of the proton configuration is $v \leqq 4$ (Ref. 4) up to spin $I \sim 20$. In ^{210}Rn$_{124}$, the 2^+ level is formed by the two-neutron-hole states such as $\nu(p_{1/2}^{-1} p_{3/2}^{-1})$, $\nu(p_{1/2}^{-1} f_{5/2}^{-1})$, etc., and the 4^+ level is considered as $\pi(h_{9/2}^4)_{4^+}$ strongly mixed with $\nu_{4^+}^{-2}$ in contrast to the $N = 126$ isotones where all the levels up to 8^+ are formed predominantly by the $\pi(h_{9/2}^n)$ configurations. The excitation energies of the 2^+ and 4^+ levels in ^{212}Ra are almost equal to those in ^{210} Rn, suggesting the same configurations for the corresponding levels in both isotopes.

The 6^+ and 8^+ levels in ^{212}Ra are expected to have fairly pure $\pi(h_{9/2}^6)$ configuration, since their excitation energies are quite similar to those in ^{214}Ra$_{126}$ and the small 8^+-6^+ energy spacing and the existence of the 8^+ state as a long-lived isomer are common characteristic features of nuclei in this region. In fact, the measured g factor $g(8^+) = 0.888(9)$ supports the $\pi(h_{9/2}^6)_{8^+}$ configuration. The excitation energy of the 11^- level in ^{212}Ra is very close to those in ^{210}Rn and ^{214}Ra, suggesting the same configuration $\pi(h_{9/2}^{5}\,{}^{1} i_{13/2})_{11^-}$ for these 11^- states. The measured g factor $g(11^-) = 1.092(22)$ supports this configuration for ^{212}Ra.

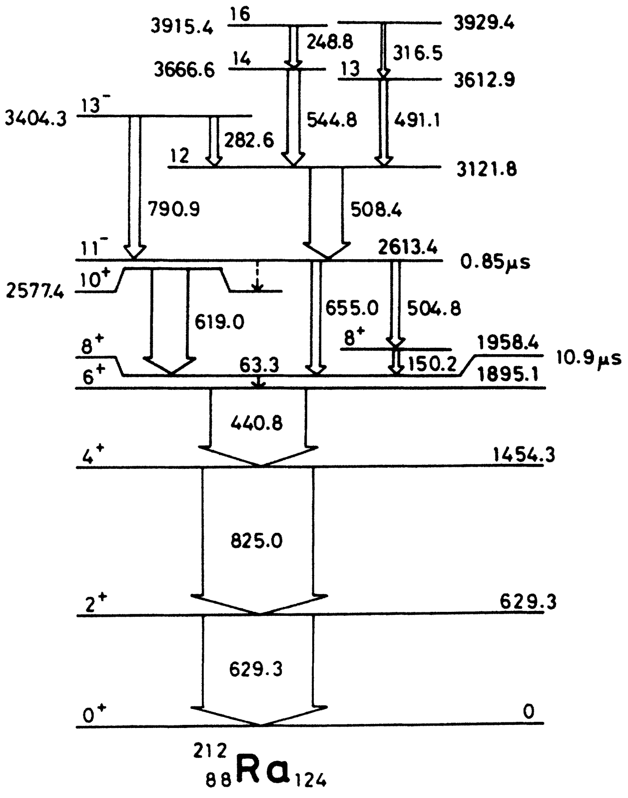

FIG. 1. The level scheme of ^{212}Ra from this work. Errors in excitation energies are typically ±0.5 keV.

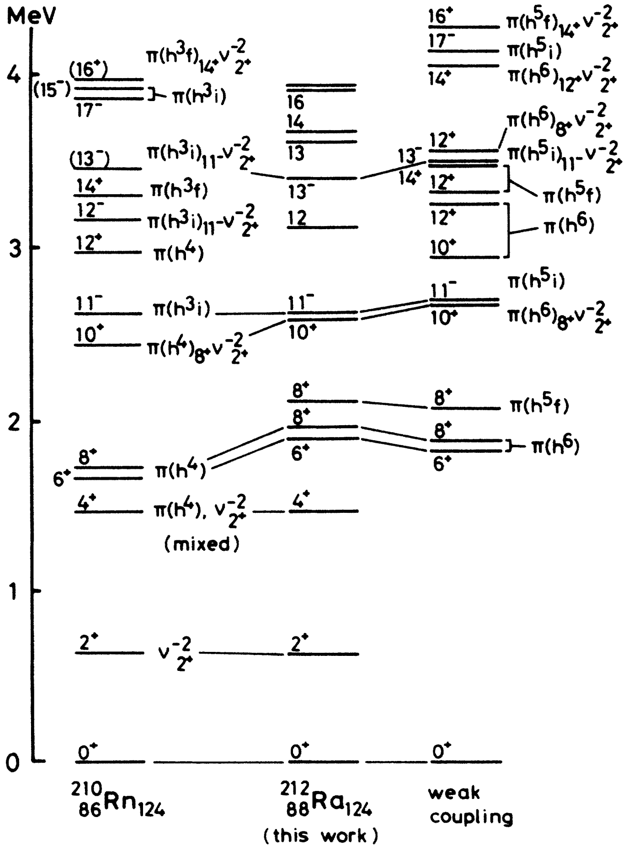

FIG. 2. A comparison of the level structures of ^{210}Rn (Ref. 3) and ^{212}Ra. Levels from the weak coupling calculation are also shown with their configurations. Here, h, f, and i mean the shell-model orbitals $h_{9/2}$, $f_{7/2}$, and $i_{13/2}$ for protons, respectively. ν_J^{-2} means two-neutron-hole state coupled to an angular momentum J.

TABLE I. Systematics of the reduced transition probabilities $B(E2;8^+ \rightarrow 6^+)$ in Weisskopf units (W.u.) for the Po, Rn, and Ra isotopes.

	N				
	120	122	124	126	128
Po			1.5	1.07	4.6
Ref.			14	15	16
Rn	1.76	0.18	0.16	0.12	2.4
Ref.	1	2	3	17	5
Ra			0.0087	0.0013	9.6
Ref.			Present	4	18

The excitation energies for levels above the 8^+ isomer were estimated by the zero-order weak coupling calculation in which the energies from the data on ^{214}Ra were used for the proton configurations and the energies of the lowest 2^+ and 4^+ levels of $^{206}_{82}\mathrm{Pb}_{124}$ (Ref. 11) are used for the two-neutron-hole configurations. These levels are also shown in Fig. 2. From this figure we may assign the configurations of the 10^+ and 13^- levels to be $[\pi(h^6_{9/2})_{8^+} \otimes \nu^{-2}_{2^+}]_{10^+}$ and $[\pi(h^5_{9/2}i_{13/2})_{11^-} \otimes \nu^{-2}_{2^+}]_{13^-}$, respectively. The decay property of a parity-undetermined $I=12$ level at 3121.8 keV, that decays to the 11^- level but not to the 10^+ level, is quite similar to that in ^{210}Rn, suggesting its configuration to be $\pi(h^5_{9/2}i_{13/2})_{12^-}$.

The $B(E2)$ values for the $8^+ \rightarrow 6^+$ transitions in nuclei near ^{212}Ra are listed in Table I. In each of the isotopes, the $B(E2)$ value becomes minimum at $N=126$ and the value for $^{206}\mathrm{Rn}_{120}$ is a factor of 10 greater than that for $^{208}\mathrm{Rn}_{122}$. Such an increase of the $B(E2)$ value probably means the collective property of ^{206}Rn induced by the admixture of components other than $\pi(h^4_{9/2})$, which is the main configuration in isotopes near $N=126$. Small $B(E2)$ values in the Rn and Ra isotopes which lie in the middle of the $h_{9/2}$ proton shell are explained, at least qualitatively, by the expression $B(E2) \propto (U_j^2 - V_j^2)^2$ (Ref. 12). It should be noted that the $B(E2)$ values for the Ra isotopes are two orders of magnitude smaller than those for the Rn isotopes, indicating the $h_{9/2}$ proton shell is nearly half-full at $Z=88$ rather than at $Z=86$.

The g factors of the $\pi(h^n_{9/2})$ configuration for the $N=124$ and 126 isotones are shown in Fig. 3, including the present result for the 8^+ isomer in ^{212}Ra. The solid lines in the figure show the calculated values including the blocking effect by Towner *et al.*,[13] which are normalized so as to reproduce the experimental values at ^{207}Bi and ^{209}Bi, respectively. The calculation for the $N=126$ isotones is in good agreement with the experimental values and the same calculation should also be applicable to reproduce the systematic behavior of the g factors for the $N=124$ isotones, since the effect of two-neutron-hole seems to be negligible as mentioned before. In fact, the g factor of the 8^+ state in ^{212}Ra is almost equal to that in ^{214}Ra: $g(^{212}\mathrm{Ra};8^+)=0.888(9)$ and $g(^{214}\mathrm{Ra};8^+)=0.890(4)$. Since the present value of $g(8^+)$ for ^{212}Ra agrees quite well with the calculated line for $N=124$ isotones, rather scattered experimental values for $^{209}_{85}\mathrm{At}_{124}$ and $^{210}_{86}\mathrm{Rn}_{124}$ around the calculated values are probably due to experimental uncertainties.

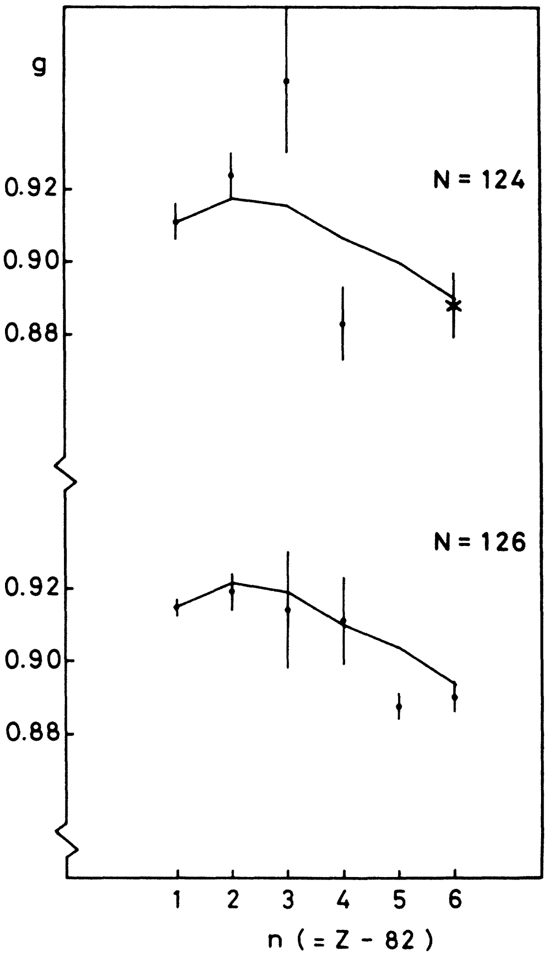

FIG. 3. Systematics of g factors for the states of the $\pi(h^n_{9/2})$ configurations in the $N=124$ and 126 isotones, where n means the number of protons on the $Z=82$ core. The experimental g factors are taken from Refs. 11, 13, 15, 19, 20, and references therein.

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