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High-spin isomer in ^{211}Rn, and the shape of the yrast line

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High-spin yrast states in ^{211}Rn have been identified. A $\frac{61}{2}^-$, 380 ns isomer found at 8856 keV is characterized as a core-excited configuration. The average shape of the yrast line is smoother than that of its neighbor ^{212}Rn. This difference is attributed to the presence of the neutron hole.

[NUCLEAR REACTIONS ^{198}Pt(^{18}O, $5n$) ^{211}Rn, $E = 96$ MeV, measured $\sigma(E, E\gamma)$, γ-γ coincidences, deduced levels, measured n-γ coincidence, $\sigma(\theta)$, conversion electrons, deduced lifetimes, spins, parities. High-spin isomer, yrast line shape, core-excited configurations.]

There is considerable interest in the study of high-spin isomers or yrast traps,[1] and in the interplay between single-particle and collective effects near the yrast line. Bohr and Mottelson[2] have predicted that, for nuclei in which noninteracting particles align their angular momenta along the symmetry axis, the yrast energies plotted against $I(I+1)$ will on average follow a straight line whose slope corresponds to an effective moment of inertia close to the rigid body value.

Two regions where high-spin aligned valence particles and yrast isomers are likely to occur[3,4] are near $N = 82$ and $Z = 64$, and $N = 126$ and $Z = 82$, the closed (or suggested closed) shells. In the former region, states with spins up to about $36\hbar$ have been identified in ^{152}Dy and ^{151}Dy.[5,6] The effective moment of inertia deduced from the shape of the yrast line in those cases is greater than the rigid body value, and this has been interpreted as evidence for oblate deformation.[5,6]

An oblate deformation is favored because alignment of the individual particle angular momenta (to give states of high spin) leads to a concentration of valence nucleons in the equatorial plane of the nucleus. Polarization, or deformation, may then lower the energy of such configurations, leading in some cases to yrast isomers.

In the latter region, near the closed shells nucleus ^{208}Pb, only ^{212}Rn, which has four valence protons, has been studied to sufficiently high spin to allow a reliable measurement of the shape of the yrast line.[7,8] In that case two points emerge. Firstly, the highest state observed, a spin 30^+ isomer, has a configuration made up of aligned valence protons, and a neutron component formed by excitation of neutrons across the $N = 126$ shell. The implication of the relatively low energy of this and other core excited states is that the energy cost in exciting across the $N = 126$ gap is balanced by the gain in polarization of (oblate) deformation energy. The interplay and competition between particle residual interactions and deformation effects has been discussed by Andersson *et al.*[4] and Matsuyanagi *et al.*[9] Secondly, the average slope of the energy vs $I(I+1)$ plot corresponds to a moment of inertia of about 85 MeV^{-1} up to about spin 18, whereas for higher-spin states it changes abruptly to about 191 MeV^{-1}, approximately equal to the rigid body value.

In this Communication we present new results for ^{211}Rn, which has one neutron hole in the $N = 126$ shell. According to Matsuyanagi *et al.*[9] the presence of neutron holes will affect the preference for deformation in aligned configurations, and the identification of high-spin states in ^{211}Rn allows a direct comparison with ^{212}Rn to be made.

Recently we reported the ^{211}Rn level scheme up to spin $\frac{53}{2}^-$ from a study of γ decay following the ^{205}Tl(^{11}B, $5n$)^{211}Rn reaction.[10] The present measurements used the ^{198}Pt(^{18}O, $5n$)^{211}Rn reaction at 96 MeV to bring in more angular momentum than the earlier study. The improved high-spin population, together with extensive γ-γ-time coincidence measurements using two Ge-(Li) detectors, each in coincidence with a third Compton-suppressed Ge(Li) detector, allowed us to confirm and extend the previous scheme. Other measurements included singles γ-ray angular distributions, γ-ray excitation functions, pulsed beam γ-ray measurements, electron conversion coefficient measurements (both in singles, and with a time reference with respect to a pulsed beam), and neutron-γ coincidences measurements. To reduce the relaxation affecting the alignment of long lived states decaying in the platinum target, γ-ray anisotropies were also measured using a target thin enough to allow the excited nuclei to recoil and decay in a lead backing.

Examples of the coincidence spectra are given in Fig. 1. The 1299 keV transition, the highest transition previously observed, is strongly populated by a 687, 769 keV cascade. The ordering of these (and other) transitions is unambiguously assigned by the coincidence relationships, by their time relationships (given the presence of isomers in the level scheme), their intensities, relative excitation functions, and from the magnitude of prompt and delayed components in their time spectra.

The level scheme for ^{211}Rn is given by Fig. 2. A new 380 $\pm$20 ns isomer is identified at 8856 + Δ keV. Its direct decay by the 687 keV transition is supported by the absence of a prompt component in the time spectrum of that transition, in contrast to the lower 769 keV transition. The long lifetime of this yrast trap is due to the $E3$ character of the 687 keV transition.

The 380 ns isomer is itself fed by a 1062 keV transition but no spin assignment was possible for the higher state. The stretched $E3$ and stretched $E1$ characters of the 687 and 769 keV transitions, assigned from their angular distributions, and K and L electron conversion coefficients, lead to spins of $\frac{61}{2}^-$ and $\frac{55}{2}^+$ for the 8856 + Δ and 8169 + Δ keV states, respectively. Other new information includes new states at 6715 + Δ and 5735 + Δ keV, established by low intensity cascades parallel to the main decays via the 1299 and 854 keV stretched $E3$ transitions, and a lifetime of 20 $\pm$3 ns for the 5247 + Δ keV state.

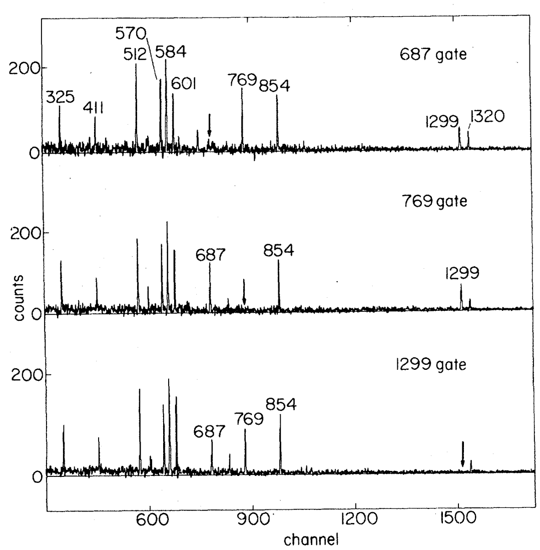

FIG. 1. Compton-suppressed γ-ray coincidence spectra in ^{211}Rn. The "prompt" time gate has a width of $\pm$150 ns; hence most of intensity following the 41 ns isomer, decaying initially by an 854 keV transition, is observed, but transitions below the low-lying 860 ns isomer are reduced in intensity. The arrows indicate the position of the γ-ray gates.

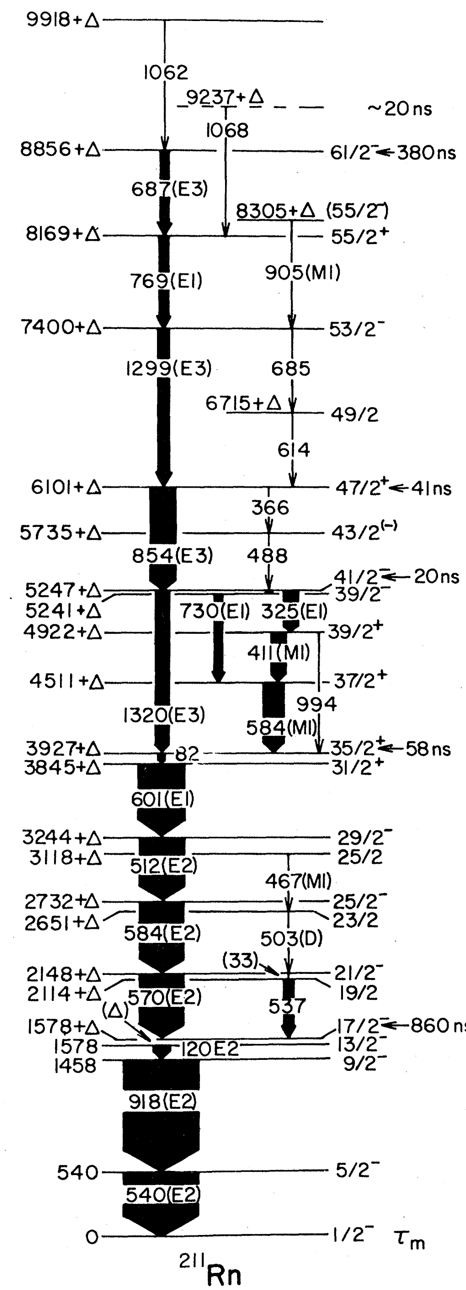

FIG. 2. Level scheme of ^{211}Rn. The widths of the transitions shown are proportional to their γ-ray intensity in the ^{198}Pt(^{16}O, $5n$)^{211}Rn reaction at 96 MeV.

The configurations we suggest for the $\frac{55}{2}^+$ and $\frac{61}{2}^-$ states in ^{211}Rn are given in Table I. They are essentially those of the $\frac{41}{2}^-$ (20 ns) 5247 + Δ keV state in ^{211}Rn coupled to neutron excitations with spin 7^- and 10^+, formed by exciting an $f_{5/2}$ core neutron to the $g_{9/2}$ or $j_{15/2}$ orbitals, across the $N = 126$ gap. The ex-

TABLE I. Configurations in ^{211}Rn.

Excitation energy (keV)	I^{π}	Proposed configuration	Estimated energy	Energy difference
$8856+\Delta$	$\frac{61}{2}^{-}$	$\pi[h_{9/2}{}^{2}i_{13/2}{}^{2}]_{20+}\nu p_{1/2}{}^{-1}[f_{5/2}{}^{-1}j_{15/2}]^{10+}$	10682	−1800
$8169+\Delta$	$\frac{55}{2}^{+}$	$\pi[h_{9/2}{}^{2}i_{13/2}{}^{2}]_{20+}\nu p_{1/2}{}^{-1}[f_{5/2}{}^{-1}g_{9/2}]_{7-}$	9282	−1100

pected excitation energies estimated from the energy of the $\frac{41}{2}^{-}$ state, and the particle-hole energies of the $[\nu(f_{5/2})^{-1}g_{9/2}]_{7-}$ and $[\nu(f_{5/2})^{-1}j_{15/2}]_{10+}$ configurations,[11,12] are also given in the table. The experimental states are depressed by 1.1 and 1.8 MeV compared to these estimates, a depression which is similar to that seen in core-excited isomers in this region[13] and which is comparable to the energy gain of several MeV available from deformation.[9]

Direct support for the proposed configurations also comes from the $B(E3)$ value for the 687 keV transition. It is $(6.2\pm0.3)\times10^{4}\ e^{2}\mathrm{fm}^{6}$, (equivalent to about 24 single particle units), which is close to the $B(E3)$ of the $j_{15/2}$ to $g_{9/2}$ transition in ^{209}Pb of $(6.8\pm1.4)\times10^{4}\ e^{2}\mathrm{fm}^{6}$.[14]

Comparing the ^{211}Rn and ^{212}Rn level schemes, an obvious association between the $\frac{61}{2}^{-}$ and $\frac{55}{2}^{+}$ states in ^{211}Rn, and the 30^{+} (isomeric) and 27^{-} states at $8850+\Delta'$ and $7849+\Delta'$ keV in ^{212}Rn, through the addition of a $p_{1/2}$ neutron hole, suggests itself. The configuration of the 30^{+} isomer in ^{212}Rn originally suggested by Horn *et al.*[7,8] agrees with that implied by our ^{211}Rn assignment. However, Matsuyangi *et al.*[9] argue against that configuration in ^{212}Rn on the grounds that the alignment of the neutron particle-hole would be unfavored by the residual interaction. Nevertheless, the configurations suggested by Matsuyanagi *et al.*[9] and Andersson *et al.*[4] would not explain the enhanced (32 single particle units) $E3$ transition connecting the 30^{+} and 27^{-} states in ^{211}Rn, as pointed out earlier.[10]

Further, their configurations already include a pair of $p_{1/2}$ neutron holes coupled to $J=0$, and in that case there would not be equivalent states, related simply by the addition of a $p_{1/2}$ neutron hole, in ^{211}Rn, as is apparently the case. This, however, is an oversimplification since the ^{206}Pb ground state, which would be the core in the case of a 0^{+}, 2 neutron hole excitation in ^{212}Rn, is only about 60% the $\nu(p_{1/2})^{-2}$ configuration.[15] Similarly, the high-spin isomers in ^{211}Rn and ^{212}Rn may not be pure configurations, and detailed calculations would be required to elucidate the structure of these apparently related states.

The yrast lines for ^{211}Rn and ^{212}Rn are compared in Fig. 3. As was mentioned earlier, the slope of the ^{212}Rn yrast line has two components, in contrast to ^{211}Rn. The change in ^{212}Rn occurs where core-excited configurations intrude into the yrast sequence near spin 19, but, except for the two highest states discussed above, related states between spin 20 and 26 are not observed in ^{211}Rn (see Ref. 10).

Two curves are shown for ^{211}Rn in Fig. 3. The first represents a linear fit to the states between spin $\frac{9}{2}$ and $\frac{61}{2}$, with a resulting effective moment of inertia of 119 MeV^{-1}. This is considerably less than the rigid body value, but is higher than in the low-spin region of ^{212}Rn. The difference at low spin between ^{211}Rn and ^{212}Rn can be attributed to the availability of the $p_{1/2}$ and $f_{5/2}$ neutron holes for alignment in ^{211}Rn. The second curve, a fit with a quadratic term in $I(I+1)$, gives a considerably improved representation of the experimental data. In both linear and quadratic fits the yrast traps in ^{211}Rn fall below the average line, as is expected for favored configurations.

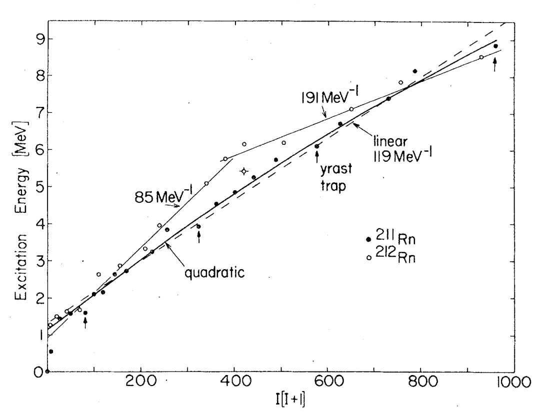

FIG. 3. Plot of excitation energy vs $I(I+1)$ for yrast states in ^{211}Rn and ^{212}Rn (from Refs. 7 and 8). The solid and dashed lines represent fits to the experimental data. The effective moments of inertia for the linear fits are indicated. The quadratic fit to the ^{211}Rn data has the parametrization $E(\mathrm{MeV})=1.088+0.10102\times10^{-1}\ I(I+1)-0.1945\times10^{-5}[I(I+1)]^{2}$. The vertical arrows indicate yrast traps in ^{211}Rn.

The progression towards a higher apparent moment of inertia, represented by the quadratic fit, may be, in general terms, in agreement with the calculations of Ref. 9 which suggest that the presence of the aligned neutron holes will inhibit oblate deformation. An *abrupt* change may be absent because core-excited states, which are favored by deformation, intrude into the yrast line at higher spins than in ^{212}Rn.

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