Brief Reports

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Yrast states of ^{216}Rn and the extent of a region of possible static intrinsic reflection asymmetry

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We report the results of a study of the yrast excitation spectrum for ^{216}Rn via the ^{208}Pb(^{14}C,α2n)^{216}Rn reaction. Measurements of γ-γ coincidences, γ-ray angular distributions, and γ-x-ray coincidences were made. We propose a level spectrum up to $J^{\pi}=(10^{+})$ which does not exhibit the alternating parity structure observed in several isotopes of radium and thorium. From an examination of information on ^{216}Rn and the neighboring nuclei, we can tentatively determine that the radon isotopes of masses 216 to 222 and the $N=128$ isotones ^{216}Ra and ^{218}Th define a lower mass boundary of a region beyond which static intrinsic reflection asymmetric shapes may exist in the nuclear ground states.

It has been conjectured[1,2] that static intrinsic reflection asymmetric shapes exist in the ground states of a number of isotopes of radium and thorium. Such a shape can arise from an alpha particle clustering configuration[1] or a static octupole shape component.[2] Although these two nuclear configurations differ in detail, their excitation spectra are predicted to be nearly identical. Each reflection asymmetric configuration would lead to alternating parity yrast sequences such as those which are indeed observed in ^{218,220}Ra (Refs. 3–7) and $^{220-226}$Th (Refs. 8–11). The nuclei ^{216}Ra (Ref. 12) and ^{218}Th,[10] however, do not display the alternating parity structure and consequently define lower mass limits on the region in which these shapes may exist for their respective isotopic chains. Clearly, it is of interest to establish how far this region extends along the proton number axis. In this paper, we report on a search for yrast states of ^{216}Rn produced via the ^{208}Pb(^{14}C,α2n)^{216}Rn reaction; with this study, ^{216}Rn becomes the lightest $N=130$ isotone studied with a heavy-ion-induced reaction.

Our experimental measurements included γ-γ coincidences, γ-ray angular distributions, and γ-x-ray coincidences; all were performed using ^{14}C beams of 67–68 MeV from the Brookhaven National Laboratory MP7 Tandem Van de Graaff accelerator and a thick (50 mg/cm^2) target of enriched ^{208}Pb. For the γ-γ experiment, one HPGe n-type detector of 20% efficiency and two Ge(Li) detectors of 22% and 19% efficiency were used; each had a resolution of 2.0–2.1 keV FWHM at 1.33 MeV. A total of 1.7×10^{8} coincidence events were collected on magnetic tape for off-line analysis. The γ-ray angular distributions were studied with both a planar Ge detector (resolution 700 eV at 122 keV) and a Compton-suppressed spectrometer. The latter consisted of a HPGe n-type detector (33% efficiency and 2.5 keV resolution FWHM at 1.33 MeV) placed in the central cavity of a 24.5 cm$\times$20.3 cm NaI(Tl) crystal, which was operated in anticoincidence with the Ge detector. The Compton-suppressed system was used to measure γ rays of energies greater than 400 keV for which the efficiency of the planar Ge detector was small. Data were taken at six angles between 0° and 90°. Both the planar Ge detector and a HPGe n-type detector (20% efficiency and 2.1 keV resolution FWHM at 1.33 MeV) were utilized for the γ-x-ray experiment. Results from these experiments on the excitation spectra of ^{219}Ra (produced by the 3n reaction channel) and ^{220}Ra (the 2n channel) have been published previously.[6,13]

An excited state of ^{216}Rn at 465±4 keV was reported from an earlier study of the alpha particle decay of ^{220}Ra and was tentatively assigned[14] $J^{\pi}=2^{+}$. Our γ-ray spectrum exhibits a peak at 461.9 keV, an energy consistent with the alpha particle decay measurement, which had not been assigned to a particular one of the 2n, 3n, or 4n evaporation channels. A positive identification of this γ ray with $Z=86$ was based on the x-ray spectrum, shown in Fig. 1, measured in coincidence with the 461.9 keV peak. The energy scale of Fig. 1 has been compressed, corresponding to an effective dispersion of 2 keV per channel. This dispersion is nevertheless sufficient to distinguish the $K\alpha$ x-ray doublet of Rn from the $K\alpha$ x-ray doublets of Fr and Ra, respectively, and is also adequate to eliminate the possibility that the peak we observed results from accidental coincidences with $K\beta$ x rays from the Pb target.

The γ-ray spectrum gated on the 461.9 keV transition is shown in Fig. 2. Three strong transitions at 378.9, 385.4, and 419.4 keV and a weaker one at 465.9 keV all appear to occur in cascade with the 461.9 keV γ ray. The 205.1, 234.3, 294.8, and 414.0 keV γ rays from ^{219}Ra appear weakly in this spectrum because of contamination of the 461.9 keV peak by adjacent strong ^{219}Ra peaks in the gating spectrum.

The assigned ordering of transitions in the cascade (see Fig. 3) is based on their intensities in the spectrum coincident with the 461.9 keV γ ray. The angular distribution data (see Table I) are consistent with the 385.4 and 461.9 keV transitions being of stretched quadrupole character; the other three members of the cascade are obscured in the γ-ray singles spectrum by doublets from stronger channels. Consequently, the tentative spin assignments given for energy levels above the 461.9 keV state are based on the systematic behavior of neighboring nuclei. The yrast spectra of these neighbors suggest that the level at 840.8 keV has $J^{\pi}=3^{-}$ or 4^{+}. The 4^{+} state is populated more strongly than the 3^{-} state in heavy-ion studies of the radium and thorium isotopes, so we make the tentative assignment $J^{\pi}=(4^{+})$. Similar arguments lead us to favor the assignments of 6^{+} (instead of 5^{-}) for the 1226.2 keV level and 8^{+} (instead of 7^{-}) for the 1645.6 keV level.

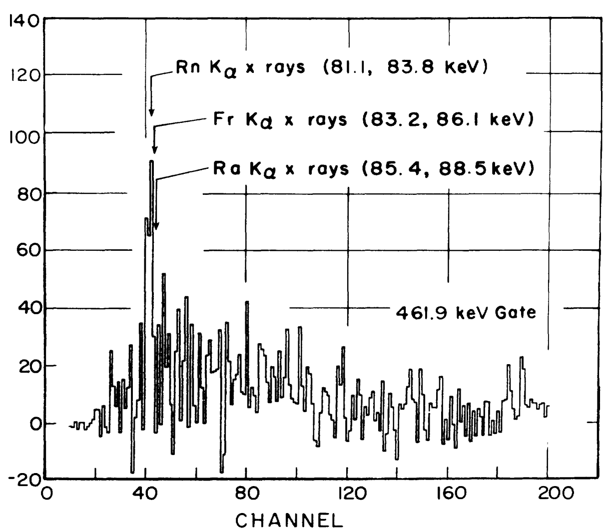

FIG. 1. The x-ray spectrum (after background subtraction) in coincidence with the 461.9 keV γ ray assigned to ^{216}Rn. The energy scale has been compressed, corresponding to a dispersion of 2 keV per channel. The expected centroids of the unresolved $K\alpha_1+K\alpha_2$ x rays are indicated for $_{86}$Rn, $_{87}$Fr, and $_{88}$Ra. The $K\alpha_1$ and $K\alpha_2$ energies are indicated in parentheses.

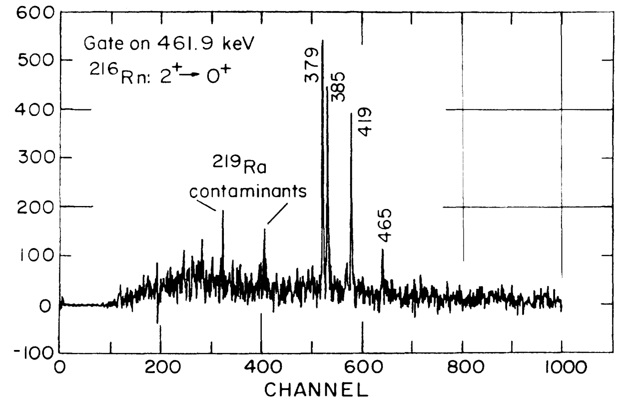

FIG. 2. The γ-ray spectrum (after background subtraction) in coincidence with the 461.9 keV γ ray. The peaks labeled by their energies (given in keV) correspond to cascade transitions through the 461.9 keV level of ^{216}Rn.

Further support for these assignments can be inferred from the observation that the low-lying $J^{\pi}=3^{-}$ states in ^{218}Rn and ^{220}Rn are 300 keV higher in excitation energy than the corresponding states in ^{220}Ra and ^{222}Ra. If the lowest energy negative parity states in ^{216}Rn are displaced a similar amount with respect to those in ^{218}Ra, then these states would be nonyrast in ^{216}Rn. In such a case, we would expect to observe the negative parity states in ^{216}Rn only weakly in the heavy-ion fusion-evaporation reaction used for this study.

Our final level spectrum is shown in Fig. 3; the indicated transition intensities are corrected for the internal electron conversion.[15,16] The intensity of the 461.9 keV γ ray is deduced directly from γ-ray singles spectra and, there-

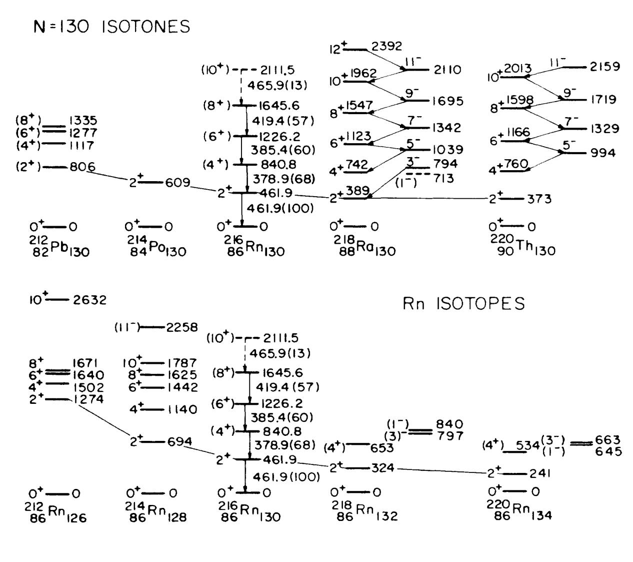

FIG. 3. Systematic behavior of excitation spectra in the $N=130$ isotones and Rn isotopes (Refs. 4, 8, and 17–23).

TABLE I. Properties of γ rays observed in ^{216}Rn.

E_γ (keV)[a]	A_2	A_4	I_γ[b]	I_{Tr}[c]	$J_f \to J_i$
378.9[d]			67(4)	68(6)	$(4^+)\to 2^+$
385.4	0.27(6)	−0.11(14)	59(3)	60(3)	$(6^+)\to(4^+)$
419.4[e]			56(3)	57(5)	$(8^+)\to(6^+)$
461.9	0.10(4)	−0.08(9)	100(5)	100(5)	$2^+\to 0^+$
465.9[d]			13(2)		$(10^+)\to(8^+)$

[a]Energies are accurate to ±0.2 keV.
[b]Bare γ-ray intensity relative to 461.9 keV gamma ray.
[c]Intensity (including internal conversion) relative to 461.9 keV transition.
[d]Doublet in ^{219}Ra.
[e]Doublet in ^{218}Ra.

fore, includes the expected yield from the alpha-particle decay of ^{220}Ra. From measurements of the relative yields of ^{216}Rn and ^{220}Ra and the previously reported rates of alpha-particle decay from ^{220}Ra to states of ^{216}Rn,[14] we estimate that 8% of the intensity quoted for the 461.9 keV γ ray results from the alpha-particle decay.

In conclusion, we find no evidence for alternating parity structure in ^{216}Rn up to $J=8$. This observation is consistent with the hypothesis that ^{216}Rn defines, for the $N=130$ isotones, a lower mass limit on the region in which static intrinsic reflection asymmetric shapes may exist in the ground state. Although no high-spin information is available for the heavier Rn isotopes, some spectroscopic information is known for ^{218,220,222}Rn from studies of alpha-particle decay.[17–19] In Ref. 20 it was noted that the relative positions of the 1_1^- and 3_1^- states strongly favor an octupole vibrational interpretation over the hypothesis of static reflection asymmetric shapes for these three isotopes. Therefore, the chain of Rn isotopes of mass 216—222 quite likely forms, together with the $N=128$ isotones ^{216}Ra and ^{218}Th, a lower mass boundary on a region of possible static intrinsic reflection asymmetric ground state shapes.

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[1]F. Iachello and A. D. Jackson, Phys. Lett. **108B**, 151 (1982).
[2]G. A. Leander, R. K. Sheline, P. Möller, P. Olanders, I. Ragnarsson, and A. J. Sierk, Nucl. Phys. **A388**, 452 (1982).
[3]J. Fernandez-Niello, H. Puchta, F. Riess, and W. Trautmann, Nucl. Phys. **A391**, 221 (1982).
[4]M. Gai, J. F. Ennis, M. Ruscev, E. C. Schloemer, B. Shivakumar, S. M. Sterbenz, N. Tsoupas, and D. A. Bromley, Phys. Rev. Lett. **51**, 646 (1983).
[5]J. D. Burrows, P. A. Butler, K. A. Connell, A. N. James, G. D. Jones, A. M. Y. El-Lawindy, T. P. Morrison, J. Simpson, and R. Wadsworth, J. Phys. G **10**, 1449 (1984).
[6]P. D. Cottle, J. F. Shriner, Jr., F. Dellagiacoma, J. F. Ennis, M. Gai, D. A. Bromley, J. W. Olness, E. K. Warburton, L. Hildingsson, M. A. Quader, and D. B. Fossan, Phys. Rev. C **30**, 1768 (1984); J. F. Shriner, Jr., P. D. Cottle, J. F. Ennis, M. Gai, D. A. Bromley, J. W. Olness, E. K. Warburton, L. Hildingsson, M. A. Quader, and D. B. Fossan, *ibid.* **32**, 1888 (1985).
[7]A. Celler, Ch. Briancon, J. S. Dionisio, A. Lefebvre, Ch. Vieu, J. Zylicz, R. Kulessa, C. Mittag, J. Fernandez-Niello, Ch. Lauterbach, H. Puchta, and F. Riess, Nucl. Phys. **A432**, 421 (1985).
[8]W. Bonin, M. Dahlinger, S. Glienke, E. Kankeleit, M. Krämer, D. Habs, B. Schwartz, and H. Backe, Z. Phys. A **310**, 249 (1983).
[9]D. Ward, G. D. Dracoulis, J. R. Leigh, R. J. Charity, D. J. Hinde, and J. O. Newton, Nucl. Phys. **A406**, 591 (1983).
[10]W. Bonin, H. Backe, M. Dahlinger, S. Glienke, D. Habs, E. Hanelt, E. Kankeleit, and B. Schwartz, Z. Phys. A **322**, 59 (1985).
[11]P. Schüler, Ch. Lauterbach, Y. K. Agarwal, J. DeBoer, K. P. Blume, P. A. Butler, E. Euler, Ch. Fleischmann, C. Günther, E. Hauber, H. J. Maier, M. Marten-Tölle, Ch. Schandera, R. S. Simon, R. Tölle, and P. Zeyen, Phys. Lett. **174B**, 241 (1986).
[12]A. Chevallier, J. Chevallier, B. Haas, S. Khazrouni, and N. Schulz, Z. Phys. A **308**, 277 (1982).
[13]P. D. Cottle, M. Gai, J. F. Ennis, J. F. Shriner, Jr., D. A. Bromley, C. W. Beausang, L. Hildingsson, W. F. Piel, Jr., D. B. Fossan, J. W. Olness, and E. K. Warburton, Phys. Rev. C **33**, 1855 (1986).
[14]Carl Phillip Ruiz, Ph.D. dissertation, University of California, Berkeley, 1961 (University of California, Berkeley Report UCRL-9511, 1961).
[15]R. S. Hager and E. C. Seltzer, Nucl. Data **A4**, 1 (1968).
[16]D. Dragoren, Z. Plagner, and F. Schmutyler, Nucl. Data Tables **A9**, 119 (1971).
[17]W. Kurcewicz, N. Kaffrell, N. Trautmann, A. Plochocki, T. Zylicz, K. Stryczniewicz, and I. Yutlandov, Nucl. Phys. **A270**, 178 (1976).

[18]W. Kurcewicz, N. Kaffrell, N. Trautmann, A. Plochocki, T. Zylicz, M. Matul, and K. Strycziewicz, Nucl. Phys. **A289**, 1 (1977).

[19]W. Lourens and A. H. Wapstra, Z. Phys **247**, 147 (1971).

[20]L. K. Peker, J. H. Hamilton, and J. O. Rasmussen, Phys. Rev. C **24**, 1336 (1981).

[21]Y. Gono, K. Hiruta, T. Nomura, M. Ishihara, H. Utsunamiya, T. Sugitate, and K. Ieki, J. Phys. Soc. Jpn. **50**, 377 (1981).

[22]D. Horn, O. Häusser, B. Haas, T. K. Alexander, T. Faestermann, H. R. Andrews, and D. Ward, Nucl. Phys. **A317**, 520 (1979).

[23]*Tables of Isotopes,* 7th ed., edited by C. M. Lederer and V. S. Shirley (Wiley, New York, 1978).