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Level structure and deexcitations in ^{220}Ra and their systematic behavior as a function of neutron number

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The level scheme of ^{220}Ra, constructed from ^{208}Pb(^{14}C, $2n\gamma$)^{220}Ra data, shows structure similar to that of ^{218}Ra, with interleaved states of alternating parities connected by enhanced $B(E1)$ deexcitations. The $B(E1)/B(E2)$ ratios (for moderately high spins) are two to three times smaller than in ^{218}Ra; we observe a smooth and rapid increase of the $B(E1)$ values toward shell closures. The systematics of the Ra isotopes are used to examine the alpha cluster model of Iachello-Jackson and the permanent octupole shape model.

Recent experimental[1-6] and theoretical [7-13] studies on light actinide nuclei have stimulated substantial new interest in the structure and behavior of such species. Perhaps the critical observation leading to this new phenomenon has been the long recognized existence[14,15] of low-lying 1^- states in the excitation spectra of the radium and thorium isotopes. In certain of these nuclei, e.g., ^{218}Ra (Refs. 1–4) and ^{222}Th,[5,6] it has been reported that at high spins, the states occur with alternating parity and that the electromagnetic transitions linking them show strongly enhanced $E1$ matrix elements.[4]

These nuclei have been widely discussed[1,5,7-9] in terms of the alpha cluster model of Iachello and Jackson[7] as well as in terms of a model [6,10-13] incorporating a stable octupole deformation. It has recently been shown[16] that although strongly enhanced $E1$ matrix elements provide a characteristic signature for the alpha cluster model, such a model also exhibits intrinsic enhancement of both $E2$ and $E3$ matrix elements; this suggests a connection between the cluster and the octupole models. There are, however, areas in which the model predictions diverge, and we have undertaken a systematic study of the radium isotopes in the hope of resolving some of these divergences and of obtaining information on the underlying physical mechanisms involved.

To study ^{220}Ra, we have used ^{14}C beams from the Brookhaven MP7 tandem at $60 \leq E_{lab} \leq 68$ MeV, just above the Coulomb barrier for ^{14}C on a ^{208}Pb target (50 mg/cm^2). This use of a thick target allowed us to observe gamma radiation from reactions induced by ^{14}C ions ranging down from the maximum beam energy to the Coulomb barrier in a single measurement, and permitted us to see low spin residual states which normally disappear in measurements made nearer to the maximum of the appropriate Ghoshal curve.

We have focused upon the ^{208}Pb(^{14}C, $2n\gamma$)^{220}Ra interaction at an incident beam energy of 68 MeV and have collected 17×10^7 coincidence events using, simultaneously, three high efficiency ($\sim$25%) Ge(Li) detectors, from which data we have constructed the ^{220}Ra level spectrum shown in Fig. 1. Data for certain of the transitions in the vicinity of the 17^- state were extracted from summed gated spectra and are denoted by dashed arrows. Angular distribution data were measured with a Ge(Li), Compton suppressed system. Measurements were carried out at five angles between 0° and 90° at $E_{lab} = 63$ MeV, and 8 h runs at each angular setting were required to provide adequate statistical accuracy for weak transitions. From feeding and deexcitation intensities and conversion coefficient calculations, we have been able to show that the dipole transitions are electric in character.

Alpha particle decay data[15,17] were used to provide unambiguous signatures for the ^{220}Ra nucleus; this identification was confirmed by detailed examination of the excitation function for the ($2n\gamma$) reaction near the Coulomb barrier. Although there is also a known 178-keV line in the deexci-

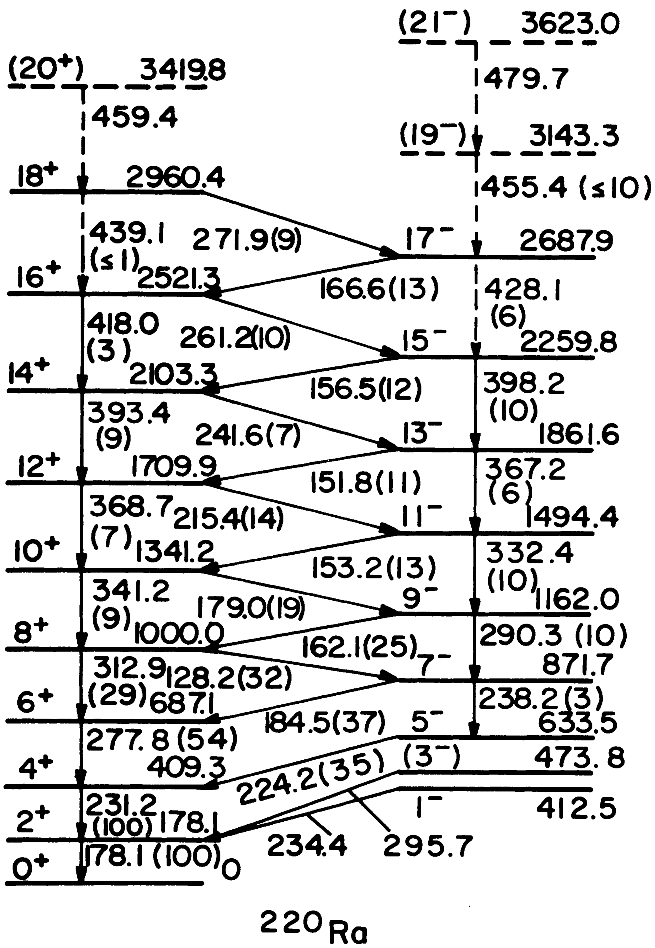

FIG. 1. The level scheme of ^{220}Ra.

tation of ^{219}Fr,[15] we assign the transition at that energy in our study to ^{220}Ra—from the (2n) rather than the (p2n) channel—because we did *not* observe, in our data, the appreciably stronger 192 keV crossover transition that would have accompanied the 178-keV line were it from ^{219}Fr.

We would also note that our data appear to suggest a $4^+ \rightarrow 2^+$ transition different from that previously reported.[15,17] In coincidence with the 178-keV line, we find a strong line at 231 keV (13 173 ± 218 counts) which we identify as this transition. We also find an additional weak coincidence line at 235 keV (150 ± 50 counts), as observed in the alpha decay work and assigned to the $1^- \rightarrow 2^+$ transition. From this, and a crossover transition to the ^{220}Ra ground state observed in the alpha decay work,[17] we can confidently assign the 235-keV line to the $1^- \rightarrow 2^+$ transition, which is expected to be weakly populated in our work at energies close to the Coulomb barrier.[1] We conclude that the earlier misassignment for the $4^+ \rightarrow 2^+$ transition reflects the inadequate energy resolution of the NaI detectors employed previously (see Figs. 33 and 36 of Ref. 17). In our coincidence data, a gate set on the 178-keV $2^+ \rightarrow 0^+$ line also disclosed a line at 296 keV (460 ± 76 counts). Our intensity measurements argue strongly for its assignment to the $3^- \rightarrow 2^+$ transition rather than to $4^+ \rightarrow 2^+$ as earlier reported.[15,17] We conclude then that in the low energy spectrum of ^{220}Ra, the sequence $J^\pi = 0^+, 2^+, 4^+$, and the 1^- state are clearly identified and that there is reasonable evidence for locating the 3^- state at 473.8 keV as shown in Fig. 1. Indeed, ^{220}Ra now appears as the only light actinide for which high spin and 1^- and 3^- low-lying excitations are identified; in the case of ^{218}Ra, the 1^- assignment remains tentative.[1] Two other studies of ^{220}Ra have been reported[18,19] with consistent but more limited results.

The level scheme deduced for ^{220}Ra is compared to those of ^{214}Ra (Ref. 20), ^{216}Ra (Ref. 3), ^{218}Ra (Refs. 1–3), and ^{222}Ra (Ref. 15) in Fig. 2. It can be seen that ^{220}Ra is sharp-

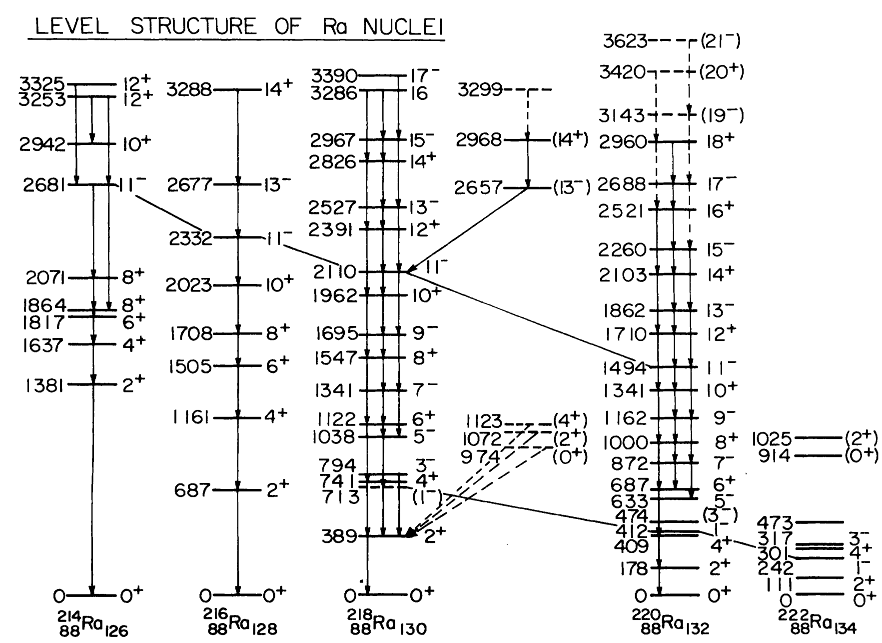

FIG. 2. Energy systematics of the Ra isotopes. Note the low-lying 1^- and high-lying 11^- states, as discussed in text. The data are from Refs. 1–3,13,18.

ly more rotational than ^{218}Ra. In fact, for both the positive and negative parity levels in ^{220}Ra, the energy spacings increase smoothly with spin consistent with a gradual increase of the moment of inertia. In ^{218}Ra, the positive parity levels are not rotorlike, while the negative parity states show rotor characteristics up to the $J^{\pi}=11^{-}$ state; thereafter, the band locus on an E_{γ} vs J plot changes slope discontinuously, indicating that noncollective features are involved above the $J^{\pi}=11^{-}$ state.

Two-quasiparticle $J^{\pi}=11^{-}$ states are influential in the structure of the light ^{214,216}Ra isotopes.[3,20] In fact, the high spin seniority two 11^{-} and, in addition, the seniority four 17^{-} states of the $h^{5}_{9/2}i_{13/2}$ configuration have been identified via their g factors and $B(E3)$ values in ^{214}Ra.[20] In ^{218}Ra, a second negative parity band appears to feed the 11^{-} state, as shown in Fig. 2. We thus suggest that the two-quasiparticle band based on an 11^{-} state affects the negative parity states in ^{218}Ra and that it is this change which is reflected in the discontinuous slope changes above $J^{\pi}=11^{-}$. No such discontinuous effects are found in ^{220}Ra. This may suggest that the two-quasiparticle states and the yrast negative parity states are more widely separated at ^{220}Ra, so that the collective properties of the band are less affected.

The $B(E1)/B(E2)$ ratios in ^{220}Ra have been extracted from the observed relative braching intensities. These ratios are shown in Fig. 3, along with those for ^{218}Ra (Refs. 1,3) and ^{226}Ra.[21] For the high spin states ($J^{\pi}\geq 11^{-}$) in ^{218}Ra, both data of Refs. 1 and 3 show a decrease in the $B(E1)/B(E2)$ ratios; the data of Ref. 2 appear inconsistent with the data of both Refs. 1 and 3. As shown in Fig. 3, the points at $J=14$, 15, and 16 are below the points at $J=8$ and 9. On the other hand, for high spin states in ^{220}Ra, the $B(E1)/B(E2)$ ratios appear, on the average, to increase with increasing spin. As we shall discuss below, it appears

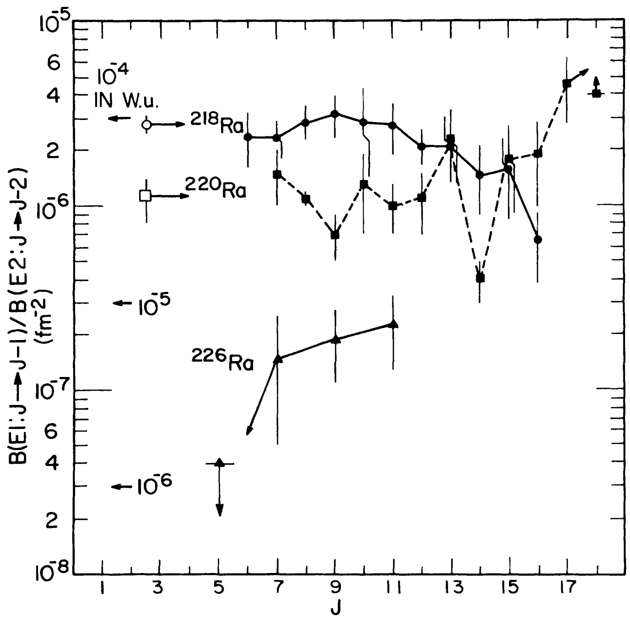

FIG. 3. Ratios of $B(E1)/B(E2)$ for ^{218}Ra, ^{220}Ra, and ^{226}Ra. The average values for ^{219}Ra and ^{220}Ra for $J^{\pi}\leq 11^{-}$ are denoted by open symbols. The ratios are expressed in fm^{-2}, and equivalent values are shown when the $B(E\lambda)$ are in Weisskopf units.

that these decreases of the $B(E1)/B(E2)$ ratios in ^{218}Ra most likely reflect some decrease in the $E1$ reduced matrix elements. The observation of correlated changes in both the moment of inertia and $E1$ deexcitations of negative parity states in ^{218}Ra, together with the absence of these effects in ^{220}Ra, suggests that the two-quasiparticle states are responsible for these changes in ^{218}Ra.

The importance of such two-quasiparticle states just above shell closures is worth noting; they produce a phenomenon reminiscent of the familiar backbending and loss of collectivity in quadrupole bands with an additional apparent systematic decrease in the $E1$ strength. The decrease in the $E1$ strength is similar to the decrease in $E2$ strength which is usually observed in nuclei displaying backbending phenomena; this has a corollary which implies that the $E1$ enhancement in this mass region is of a collective origin.

In the spin regime $J\leq 11$, the $B(E1)/B(E2)$ ratios are essentially constant as a function of spin and parity for ^{218}Ra and ^{220}Ra, but show an increase with increasing spin for ^{226}Ra. The average ratio for each nucleus, indicated in Fig. 3 on the left by open symbols, decreases steeply with N; the ratio for ^{220}Ra and ^{226}Ra relative to that for ^{218}Ra decreases by factors of 2.5 and 20, respectively. Recent measurements[4] of the $B(E2)$ values in ^{218}Ra have been made via recoil-distance-method (RDM) techniques utilizing the ^{13}C(^{208}Pb,3nγ) ^{218}Ra reaction at 5.3 MeV/u. For moderately high spins ($J\leq 11$), preliminary results indicate large values in ^{218}Ra of $B(E2)\approx 150$ W.u. If the above observed change in $B(E1)/B(E2)$ ratios was to be attributed to the $B(E2)$ value alone, this would suggest in ^{220}Ra an unphysical value of $B(E2)\approx 400$ W.u. For this reason, our conclusion is that the $E1$ matrix elements are somewhat smaller in ^{220}Ra, are dependent on N, and that they are largest in ^{218}Ra. Thus, the decrease in $B(E1)$ together with the steep behavior of the alpha particle hindrance factors[15] of the 1^{-} states as a function of N provide interesting and sensitive tests of any model proposed to explain the structural phenomena of this mass region.

The vibron model[7] provides a convenient framework within which to make calculations concerning these $B(E1)/B(E2)$ ratios.[9] The vibron calculations do, indeed, reproduce the increase in these ratios with increasing spin in ^{226}Ra, with similar preliminary results for ^{220}Ra. Furthermore, our experimental results for ^{220}Ra support the suggestion[1] of a monotonic increase in the $B(E1)$ in moving toward the region immediately above shell closure, as suggested in the cluster model.[7]

The nuclei discussed here have also been interpreted with a model that assumes a stable octupole shape for the nucleus.[10,11] In this model, the $E1$ transitions arise from the fact that the octupole shape causes polarization[12,13] of the nucleus; thus the center of charge is displaced from the center of mass. This effect has been qualitatively studied,[12,13] but no quantitative calculations concerning the $B(E1)/B(E2)$ ratios are available. However, one specific prediction of an octupole deformation model is the absence of backbending;[11] both the negative-parity and positive-parity states in ^{220}Ra show a smooth upbending and are consistent with this feature of the model. Since the two models are obviously closely related, it would be most interesting to further study the relationship between these two ideas.

We conclude that these new data provide further evidence for a new form of dipole collectivity, which may be related to alpha particle clustering in these heavy systems.[7] However, many systematic features are emerging for which no current model provides any obvious reproduction. More and better data are urgently required, as is a more fundamental understanding of the relationship between the vibron and octupole models for this mass region.

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