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Intermediate and weak coupling in ^{219}Ra

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The level scheme of ^{219}Ra established via a study of the ^{208}Pb(^{14}C,3n)^{219}Ra reaction is presented. The structure of the rotational band based on the ground state is interpreted as reflecting a $g_{9/2}$ valence neutron weakly coupled to a spherical ^{218}Ra core. A non-yrast side band is observed, having tentative $\frac{11}{2}^-$, $\frac{15}{2}^-$, . . . level assignments. An $\frac{11}{2}^-$ state could result from the anomalous $J=j-2$ intermediate strength coupling of a $j_{15/2}$ neutron to the ^{218}Ra core. The relevance of a weak coupling model to the understanding of high spin ($J>j$) parity doublets and the surprisingly different experimentally observed level schemes of $^{219}_{88}$Ra and $^{219}_{89}$Ac are discussed.

Studies of odd-A nuclei have been shown to provide useful information on the structure of the even-even core as well as on the behavior of the valence nucleons. This is particularly the case where weak-coupling phenomena are observed;[1] for example, in $Z>50$ odd-A nuclei. When the core is a prolate spheroid, weak coupling of a valence nucleon in an orbit having total angular momentum j leads to the occurrence of the state $J_{\max}=j+J_{\rm core}$ at a lower excitation than the state having $J=J_{\max}-1$ and to a $\Delta J=2$ band; in contrast, for the case of a valence hole the order of the $J_{\max}$ and $J_{\max}-1$ states is reversed and a $\Delta J=1$ band occurs.[2] The separation of the $J_{\max}$ and $J_{\max}-1$ states is related directly to the diagonal (first order) matrix elements of the quadrupole operator for the core[1-3] and thus provides information on the core structure.

Recently, a number of detailed studies[4-11] on actinide nuclei and subsequent attempts[12-14] at understanding the results on the basis of cluster configurations[12] or static octupole deformations[13,14] have focused attention on the validity and relationship of these two approaches. Comparable success in reproducing the known characteristics of even-even nuclei in this mass region has been obtained with the two approaches; both can reproduce the observed bands of states having alternating parities and strongly enhanced electric dipole intraband deexcitation transitions as collective phenomena. Thus far only the static octupole model has been applied to odd mass nuclei in this region.[15] Both models, in which reflection symmetry is broken in the intrinsic frame, predict parity doublets in odd-A nuclei.

In this short note, a detailed level spectrum for ^{219}Ra is presented. These results are compared with recently published results for the neighboring nuclei ^{217}Ac (Refs. 16 and 17) and ^{219}Ac (Refs. 18 and 19) in order to examine the underlying structure and to seek an appropriate description.

Our study of ^{219}Ra was carried out via the ^{208}Pb(^{14}C, 3nγ)^{219}Ra reaction, using a ^{14}C beam from the Brookhaven MP7 tandem accelerator. Unambiguous identification of ^{219}Ra was achieved in measurements of the excitation function for this reaction over the range $60\leq E(^{14}{\rm C})\leq 78$ MeV using a target comprised of 450 μg/cm^2 of ^{208}Pb on a 225 μg/cm^2 Au backing. Gamma radiation was detected at 90° to the beam in a single Ge(Li) detector. Since detailed information on ^{218}Ra (the 4n channel) and alpha particle decay data for ^{220}Ra (the 2n channel) were available, the excitation function curve measurement, together with x-ray coincidence data, were sufficient to establish the strongest gamma rays deexciting states of ^{219}Ra. The alpha particle decay of the ^{219}Ra ground state to ^{215}Rn has been suggested[20] to yield a gamma ray of ~ 310 keV, which appears to be 316 keV from our study, as well as from a recent alpha-decay measurement of ^{219}Ra (Ref. 21). The 316 keV line observed in our study was used as an additional signature for identifying ^{219}Ra.

Gamma-gamma coincidence data were taken with a thick (50 mg/cm^2) ^{208}Pb target at a beam energy of 68 MeV using three Ge(Li) detectors of high efficiency (approximately 20%). The use of a thick target allowed us to observe reactions occurring at energies down to the Coulomb barrier. This enhanced the population of lower spin states and allowed us to identify a non-yrast side band weakly populated in this reaction. In addition, a large number (2.5×10^8) of coincidence events was accumulated; this allowed us to extend the level spectrum to higher spin states and to establish weak gamma ray branches of intensity only 0.3% of the strongest ground-state transition. The resulting level scheme is shown in Fig. 1. A similar study of ^{219}Ra was reported[22] with consistent results. The results presented herein include an additional side band, which is not included in the study of Ref. 22, as well as several additional high-spin states above 3.5 MeV.

To establish angular distributions, gamma ray data were obtained with two different detectors at six angles at a beam energy of 67 MeV. The first, a planar high-purity germanium detector, was used for transitions having energies below 400 keV; transitions with energies above 400 keV were studied using a Compton-suppression spectrometer consisting of a central high purity Ge n-type detector and a 25.4 cm diameter NaI(Tl) crystal having a central cavity for insertion of the gamma detector. All transitions of dipole character were found to exhibit angular distributions charac-

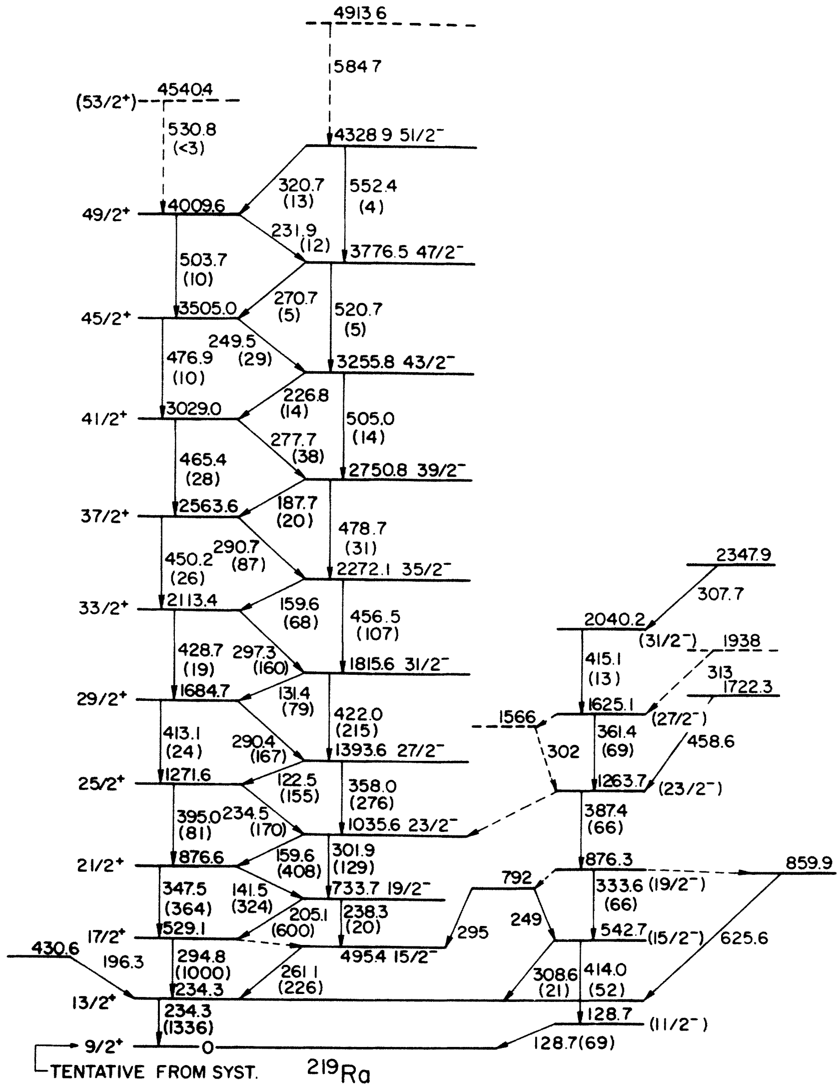

FIG. 1. The level scheme of ^{219}Ra. The ground-state spin is suggested from systematic behavior in this mass region.

teristic of stretched dipole deexcitation, $-0.3 \leq a_2 \leq -0.15$, where $a_2 = A_2/A_0$ in an even ordered Legendre polynomial expansion; in the case of quadrupole transitions the extracted a_2 coefficients were $0.1 \leq a_2 \leq 0.3$.

Parity assignments were established by measuring conversion electrons with a Si(Li) detector and a mini-orange magnetic spectrometer with permanent cobalt samarium magnets. Conversion coefficients could be extracted for several of the $E2$ band transitions and also for the stronger dipole transitions within the ground-state band. Because of the large difference in conversion coefficients between $E1$ and $M1$ transitions in this region, the electric dipole nature of these transitions could be established. As an example the measured ratio $\alpha_L(205)/\alpha_K^{E2}(295) \leq 0.27$ can be compared with 0.20 if the 205 keV transition were $E1$ and 4.47 if it were $M1$. In addition, parity assignments could, in some cases, be made using intensity arguments, as will be discussed below.

Only tentative spin and parity information could be extracted for the weakly populated side-band members, involving the 128, 414, . . . keV deexcitation transitions, from the angular distribution data. The results obtained are, however, supported by the intensity arguments. We note, for example, that an assignment of positive parity to the 128 keV level (i.e., $J^\pi = \frac{11}{2}^+$ state at 128 keV) leads to a 128 keV dipole transition intensity which is at least a factor of 3.4 larger than the intensity of the 414 keV feeding transition. The highly converted and unobserved $(\frac{23}{2}^-) \rightarrow \frac{23}{2}^-(M1)$ transition, on the other hand, provides support for a negative parity assignment to this $\frac{11}{2}^-$ state at 128 keV in ^{219}Ra. Since these intensity arguments are crucial for these assignments we report these spin-parity assignments in parenthesis.

The spin parity of the ground state of ^{219}Ra is not known, nor of excited states of ^{219}Ra from radioactivity measurements. A tentative ground-state spin and parity of ^{219}Ra can be deduced from the systematics of assignments to the ground states of neighboring nuclei. The $N = 131$ isotones $^{215}_{84}$Po and $^{217}_{86}$Rn are measured to have ground-state spin parities of $(\frac{9}{2})^+$ and $\frac{9}{2}^+$, respectively.[20] We note that in the neighboring $N = 133$ isotones[20] $^{219}_{86}$Rn and $^{221}_{88}$Ra, as well as in the $N=135$ isotones $^{223}_{88}$Ra and $^{225}_{90}$Th, the measured ground-state spin-parities are identical within an isotonic chain ($J^\pi=\frac{5}{2}^+$ for $N=133$ and $J^\pi=\frac{3}{2}^+$ for $N=135$ isotones). We, therefore, have assumed that the ground state of ^{219}Ra is $\frac{9}{2}^+$.

The assumed $\frac{9}{2}^+$ ground-state spin and parity of ^{219}Ra are also consistent with the $g_{9/2}$ neutron state as observed in ^{209}Pb (Ref. 20), and thus it is of interest to examine whether the ^{219}Ra spectrum contains the other relatively pure single neutron states that are known in the low-lying spectrum of ^{209}Pb. Since the 128 keV $\frac{11}{2}$ state has negative parity, we conclude that the observed low-lying positive parity $i_{11/2}$ state of ^{209}Pb is not observed (in this work) in ^{219}Ra, suggesting that this state is pushed to higher energies above the yrast line. In the case of the low-lying negative parity $j_{15/2}$ state, two candidate $J^\pi=\frac{15}{2}^-$ states are available at 495 and 542 keV in ^{219}Ra. For the higher state we find $B(E1)/B(E2)=1.3\times10^{-7}$ fm^{-2}: With a realistic estimate[23] of $B(E2)=50$ W.u. this implies a hindered $E1$ deexcitation, with $B(E1)=2.2\times10^{-4}$ W.u. This suggests that the high-lying $\frac{15}{2}^-$ state arises mainly from the $j_{15/2}$ neutron orbit and thus would be expected to show a weak $E1$ deexcitation to the $\frac{13}{2}^+$ state which is a member of a band built on a different single particle orbit. The lower $\frac{15}{2}^-$ state belongs to a negative-parity band which shows enhanced $E1$ deexcitation with an average value $B(E1)/B(E2)=2.1\times10^{-6}$ fm^{-2} [i.e., $B(E1)=3.5\times10^{-3}$ W.u. for a realistic estimate[23] of $B(E2)=50$ W.u.]. The lower $\frac{15}{2}^-$ state most probably results from the weak coupling of the 3^- state of ^{218}Ra (Ref. 5) to a $g_{9/2}$ neutron. Similar states arising from the $g_{9/2}$, $i_{11/2}$, and $j_{15/2}$ single particle neutron states are observed in ^{217}Ra (Ref. 24). Again in ^{217}Ra the members of the $j_{15/2}$ negative-parity band also decay with weak $E1$ transitions to the members of the $g_{9/2}$ band. Assuming[23] $B(E2)=20$ W.u. in ^{217}Ra, we extract, on the average, $B(E1)=7.3\times10^{-4}$ W.u. for these weak $E1$ deexcitations in ^{217}Ra (Ref. 24), similar to the decay of the second $\frac{15}{2}^-$ state observed in our work on ^{219}Ra.

The level spectrum of ^{219}Ra shows a striking similarity to that of the neighboring even-even ^{218}Ra (Refs. 4 and 5) and ^{220}Ra (Refs. 8–10) nuclei, with two interleaved major bands of opposite parity showing enhanced $E1$ intraband deexcitations. The average $B(E1)/B(E2)$ ratio in ^{219}Ra ($=2.1\times10^{-6}$ fm^{-2}) is intermediate between the corresponding values of 2.7×10^{-6} fm^{-2} in ^{218}Ra and 1.2×10^{-6} fm^{-2} in ^{220}Ra. The nuclei ^{218}Ra and ^{220}Ra appear to be only slightly deformed in their low energy excitation region. The ratios $E(4^+)/E(2^+)$, for example, are 1.9 and 2.3 in ^{218}Ra and ^{220}Ra, respectively, very close to the value of 2.0 expected for vibrational nuclei. All of these considerations suggest that the yrast states of ^{219}Ra arise from a $g_{9/2}$ neutron weakly coupled to a ^{218}Ra core, including both positive and negative-parity states.

In such models, quadrupole-quadrupole coupling of the single particle to the core (with no odd multipole terms) is assumed. This results in a rich spectrum of spin multiplets associated with each core state. Because of the selective nature of (HI,xn) reactions, primarily the $J_{max}=j_c+j$ and $J_{max}-1$ members of the spin multiplets are usually observed. In ^{219}Ra only the J_{max} member of the spin multiplet is seen, as shown in Fig. 2. For a particle state the $J_{max}-1$ state is expected to appear at excitation energies higher than that of the corresponding state of the even-even core,[3] as observed systematically in the odd-A $_{53}I$ nuclei,[1] and thus the remaining states lie far above the yrast line and cannot be observed in (HI,xn) reactions.

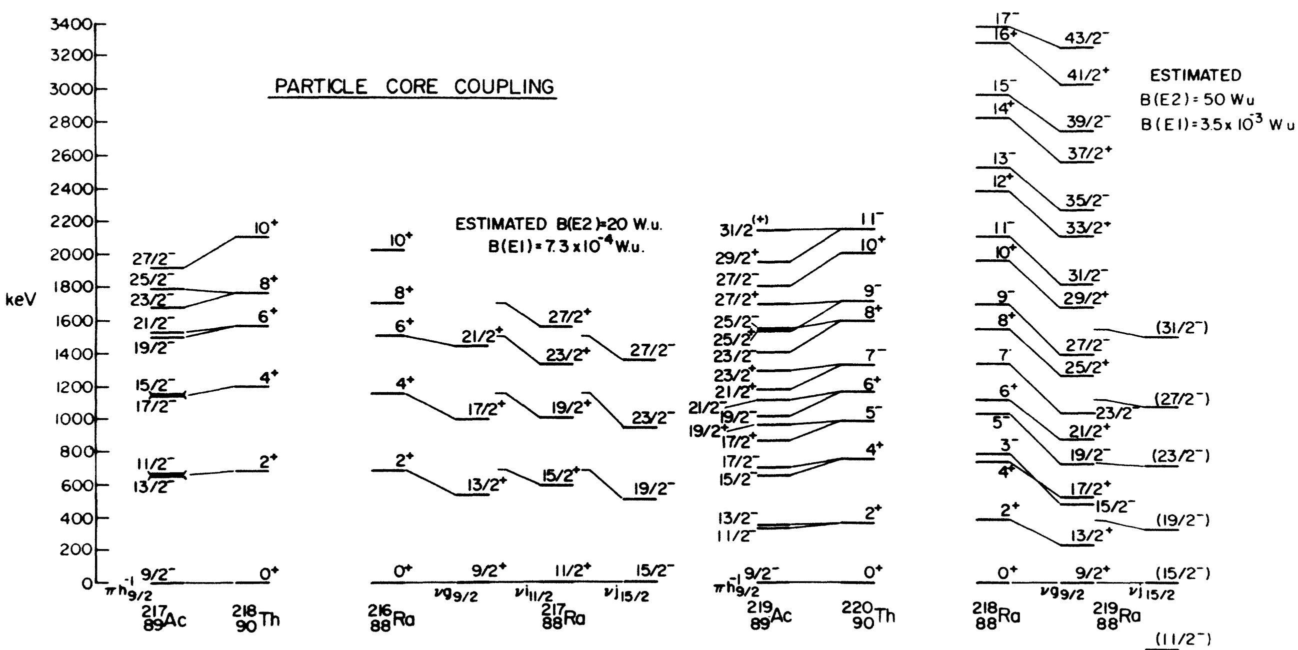

FIG. 2. A weak-coupling scheme for ^{219}Ra and neighboring odd-A nuclei. For a particle state (^{219}Ra) the J_{max} state ($=J_{core}+j$) appears below the $j_{max}-1$ state, and for a hole state (^{219}Ac) the opposite ordering is expected (Ref. 2); this accounts for the differences in the ^{219}Ra and ^{219}Ac spectra. Data are from Refs. 16–19, 24, and the present work. Note that the J_{max} and $J_{max}-1$ states of "2^+ and 4^+ multiplets" in ^{217}Ac are degenerate, corresponding to a very small quadrupole matrix element of the corresponding core states.

For a hole state, as we have noted above, the $J_{max}-1$ state appears below the J_{max} state (for cores with modest prolate deformation). In such cases we find, in general, two close lying states of opposite parities and identical spin. These are the J_{max} and $J_{max}-1$ members of different spin multiplets arising from two core states of angular momentum differing by one unit. Such a mechanism for creating so called "parity doublets" is accidental in nature and different from the mechanism associated with the breaking of reflection symmetry in the intrinsic system.[13,15] The nuclei ^{217}Ac and ^{219}Ac show a weak-coupling spectrum arising from an $h_{9/2}$ proton hole coupled to the even-even Th core, as shown in Fig. 2. At higher spins the $J_{max}-1$ state appears below the J_{max} state, as expected for an $h_{9/2}$ proton hole state, and thus states of the same spin and opposite parity which are almost degenerate are found in ^{219}Ac. This feature does not occur in ^{219}Ra which involves neutron particle states. We note that for low-spin states in ^{217}Ac and ^{219}Ac the quadrupole moment of the core appears to be vanishingly small so that the J_{max} and $J_{max}-1$ states are nearly degenerate. This simple weak-coupling (like) model accounts for the surprisingly different level schemes of $^{219}_{88}$Ra and $^{219}_{89}$Ac, even though both nuclei involve very similar core nuclei. It should be emphasized that the predictions of a weak-coupling model[3] are almost independent of the j of the single particle involved, and therefore the conclusions suggested in this paper are largely independent of the spin of the ground state of ^{219}Ra.

The tentative assignment of an $\frac{11}{2}^-$ state at 128 keV in ^{219}Ra is intriguing, since the band built on this state is a $\Delta J=2$ band and therefore of particle nature. The only available neutron particle negative-parity orbit is $j_{15/2}$. This $\frac{11}{2}^-$ state can be interpreted as the $J=j-2$ anomalous state of the $j_{15/2}$ orbit.[25-27] In core-particle coupling models such as PTQM[26] and interacting boson-fermion approximation[27] one finds that for slightly deformed nuclei the effect of the Pauli principle is to lower the $j-2$ state below the j state. Such a phenomenon has been observed in ^{75}Se (Ref. 26) and ^{103}Tc (Ref. 27) for the $g_{9/2}$ orbital. We note that the low-lying $\frac{7}{2}^+$ state in ^{219}Ra observed in the recent alpha-decay study of ^{223}Th (Ref. 21) could be the predicted $j-1$ state of the $g_{9/2}$ neutron orbit in ^{219}Ra. The ground state of ^{221}Ra, measured[28] to be $\frac{5}{2}^+$, could then be the $j-2$ anomalous state of the $g_{9/2}$ neutron orbit.

We conclude that the level scheme of ^{219}Ra and the neighboring Actinium nuclei can be well reproduced by a weak-coupling model invoking a quadrupole-quadrupole force with no assumptions regarding the nature of the core or odd multipole interactions. In such a description the data on odd-A nuclei do not distinguish between octupole or cluster phenomena, since no explicit assumption concerning the core is necessary in weak-coupling models.

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