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Alternating parity structure in doubly odd ^{218}Ac

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States in doubly odd ^{218}Ac have been studied using in-beam α-, γ-, and e^--spectroscopy techniques mainly through the ^{209}Bi(^{12}C,$3n$) fusion-evaporation reaction. ^{218}Ac shows a band structure, with interleaved states of alternating parities connected by enhanced $B(E1)$ transitions, which is strikingly similar to the one in its isotone ^{217}Ra.

Heavy transitional translead nuclei lying between the doubly magic ^{208}Pb and the deformed Th-U region have recently attracted the interest of several high-spin spectroscopy groups.[1-7] This interest mainly derives from the finding of phenomena which seem to indicate that a reflection asymmetric degree of freedom is playing an important role.[1-9] Quite a number of even-even[1,2,4,7] and odd-mass[5,7] nuclei of this part of the chart of nuclides have already been studied revealing structures with possibly both quadrupole and octupole (or more generally odd multipole) collectivity. On the other hand, very little is known on doubly odd nuclei in this region and it is important to investigate if they consistently fit into the same picture. As a step in this direction and within the frame of our program[10] to study collective phenomena in doubly odd nuclei, we present here first results obtained for ^{218}Ac.

This nucleus was produced through the ^{209}Bi(^{12,13}C,$3n$ and $4n$) fusion-evaporation reactions with the TANDAR accelerator of the Argentine Atomic Energy Commission. ^{218}Ac is in the region of the shortest-lived α emitters of the whole chart of nuclides and hence allows the use of powerful in-beam α spectroscopy techniques in addition to more conventional γ and conversion electron (e^-) measurements. Actually, the only previously known information on ^{218}Ac was the existence of an α-emitting state ($E_\alpha = 9.21$ MeV) of $T_{1/2} = 1.12$ μs (Ref. 3). This state is most likely of low spin [$I^\pi = (1^-)$] since it decays exclusively to the (1^-) ground state of ^{214}Fr with a hindrance factor which fits the systematics.[3] Most of the experiments were performed with the ^{209}Bi(^{12}C,$3n$) reaction which gives a better peak-to-background ratio (this background coming mainly from fission). In addition to γ-ray excitation functions, cross-section measurements detecting the ground-state α decay were performed in the 64- to 82-MeV bombarding energy range. The production of ^{218}Ac maximizes at $\simeq 68$ MeV with a cross section of 160 ± 40 mb. The fission limitation of the fusion-evaporation cross section is already important, but not as strong as in the compound nuclei of Th and heavier elements. Figure 1 shows an in-beam α-particle spectrum at 70-MeV ^{12}C bombarding energy (at which higher spins in ^{218}Ac are favored) measured with several large area ($\simeq 10$ cm^2) surface barrier Si detectors looking at an Al catcher placed $\simeq$5-cm downstream from the target in which the recoils are implanted, in coincidence with γ rays measured at the target position with a 40% HpGe detector. The main competing channel at this energy is the $4n$ leading to ^{217}Ac which subsequently decays to the ground state of ^{213}Fr (Ref. 11). The α line coming from the short-lived ground state of ^{218}Ac provides us with an ideal signal to select and unambiguously identify the prompt γ (and e^-) radiation which belongs to ^{218}Ac. The E_α-E_γ-$t_{\alpha\gamma}$ experiment yields a set of new lines in ^{218}Ac and also another value for the half-life of its ground state: $T_{1/2} = 1.31 \pm 0.12$ μs (see Figs. 1 and 2). The consistency of this procedure has been checked, making use of the previous knowledge[12] on ^{217}Ac (here we have obtained a half-life of 70 ± 6 ns in excellent agreement with the published[12] value of 69 ± 4 ns). A γ-γ coincidence experi-

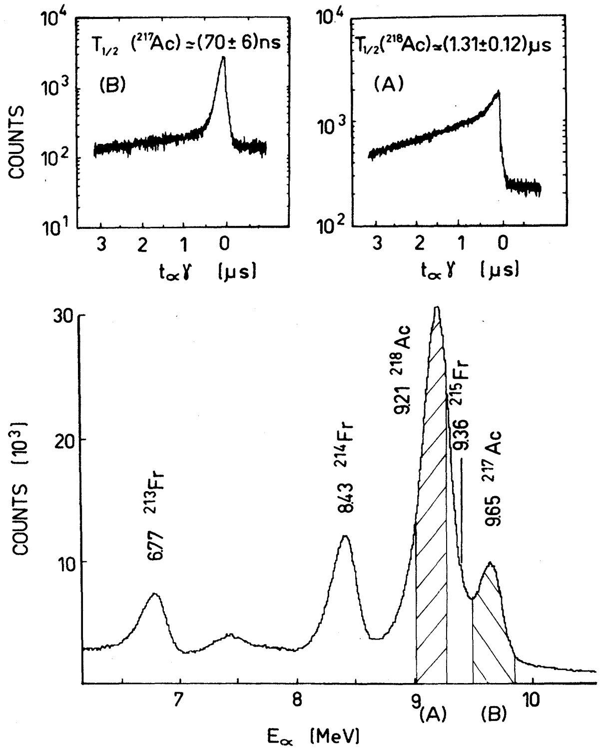

FIG. 1. The lower part shows an in-beam α-particle spectrum in coincidence with γ rays for the ^{209}Bi(^{12}C,$3n$) reaction at 70 MeV. The upper part shows the time distributions of the α particles coming from the ground-state decay of (A) ^{218}Ac and (B) ^{217}Ac. The more prompt component in (A) comes from the ^{215}Fr α-particle tail in the ^{218}Ac peak.

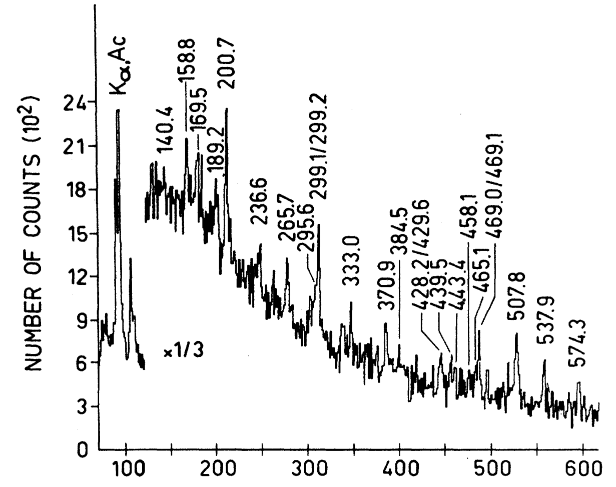

FIG. 2. γ-ray spectrum in coincidence with the α-particle ground-state decay line of ^{218}Ac [gate (A) of Fig. 1].

ment using two HpGe detectors of 30% and 40% efficiency placed face to face at 90° to the beam direction allowed us to construct the partial-level scheme shown at the center of Fig. 3. The relative parity of the states follows from the conversion coefficient determinations for the transitions connecting them. In this mass region it is a relatively simple matter to distinguish between $E1$ and $M1$ transitions. These measurements were made with a BaFe permanent magnet minorange spectrometer in conjunction with a LN_2-refrigerated Si(Li) (200 $\mathrm{mm}^2\times 2$ mm) detector.

Now the tentative spin-parity $I^\pi=(9^-)$ assignment to the "band-head" state in ^{218}Ac has to be briefly discussed. There is a systematic occurrence[11] of two α-emitting isomers in many doubly odd nuclei of this region, namely $I^\pi=(1^-)$ and (9^-) states which mainly arise from the coupling of the two lowest-lying single-particle orbits ($\pi h_{9/2}$ and $\nu g_{9/2}$) above the double-shell closure at $Z=82$ and $N=126$. The splitting between these two states decreases steadily[11] from ^{210}Bi, where it is 271 keV, to its isotone ^{216}Ac, where[13] it has most likely collapsed to 37 keV as the $h_{9/2}$ shell is being filled and the proton changes from particle to a mixed particle-hole (quasiparticle) character. These states are certainly purest in terms of the $\pi h_{9/2}\otimes\nu g_{9/2}$ configuration for ^{210}Bi and the (particle-particle) matrix elements of the p-n force can be extracted from the lowest-lying $I^\pi=J^\pi=0^-,1^-,\ldots,9^-$ multiplet (where J is the two-particle angular momentum) giving[14] the typical inverted-parabola shape for the matrix elements $V_J=\langle(\pi h_{9/2}\otimes\nu g_{9/2})_J|V_{p\text{-}n}|(\,)_J\rangle$. In ^{210}Bi the lowest-lying members of this multiplet are[11] the 1^- (ground state), the 0^- (46.5 keV), and the 9^- (271 keV). Moving up in proton number to the isotone ^{212}At, one finds that the gap between the 1^- and 9^- has diminished[15] to 223 keV and furthermore that the 2^- and 3^- states have moved into the gap and that the 5^- state has

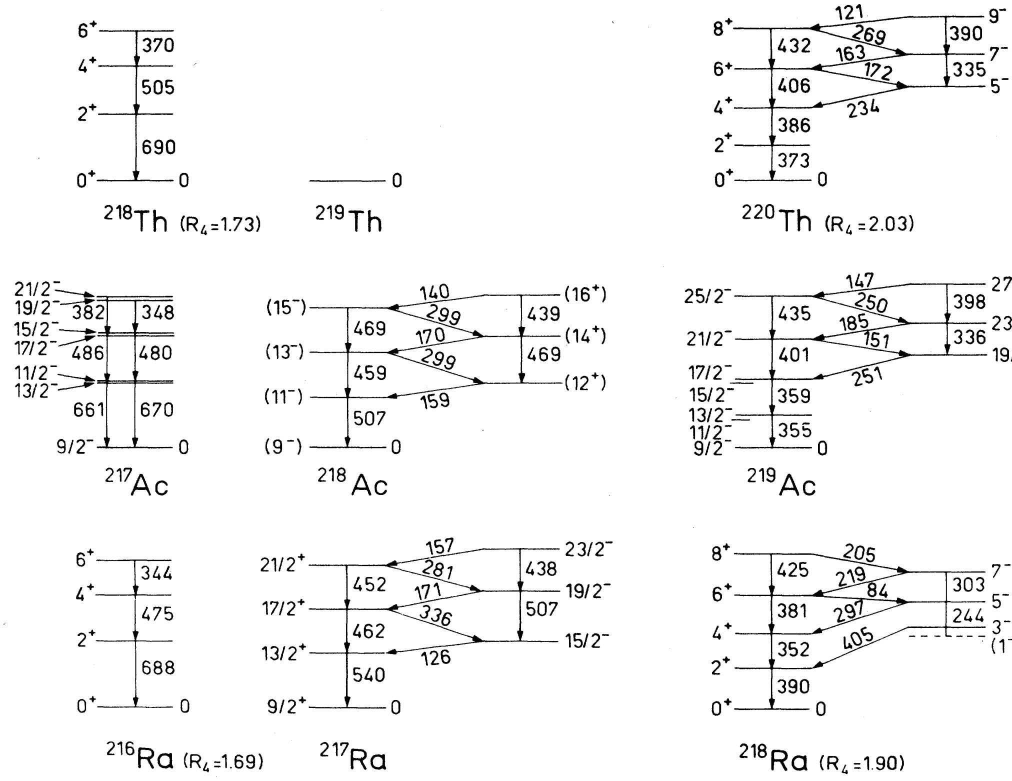

FIG. 3. Comparison of partial-level schemes of even-even ^{216,218}Ra and ^{218,220}Th, odd N ^{217}Ra, odd Z ^{217,219}Ac, and odd-odd ^{218}Ac (see text).

come down to 275 keV (in addition, it has been suggested that the 7^- lies just above the 9^- state[15]). This pattern also repeats itself for the known $N=129$ isotones (Ref. 11 for ^{212}Bi and Ref. 16 for ^{214}At). In contrast to this situation, no α-emitting high-spin isomeric state seems to exist in ^{218}Ac. One can envisage a situation in which, for instance, the 5^- and the 7^- cross the 9^- state and hence it may decay to the 1^- ground state through a cascade of very low-energy highly converted transitions loosing its α-emitting character. An example of such a low-energy $E2$ transition is the $5^- \rightarrow 3^-$, 70-keV isomeric ($T_{1/2}=32$ ns) line[15] in ^{212}At. The Weisskopf estimate for the half-life of a low-energy ($\lesssim 100$ keV) $E2$ transition corrected for internal conversion reaches[11] an approximately constant value of less than 100 ns. Hence the lifetime for the ground state of ^{218}Ac as obtained here may be somewhat enlarged with respect to the true value. Since the 9^- state is expected to be low lying, it will be on the yrast line receiving strong feeding in the heavy-ion–induced reaction (the maximum angular momentum brought into the compound system by the 70-MeV ^{12}C beam is about $24\hbar$). As the $h_{9/2}$ proton quasiparticle character becomes more pronounced, the residual p-n force is expected to diminish[17] because it becomes an average between the particle-particle (attractive) and the particle-hole (repulsive) matrix elements. Actually, if the $g_{9/2}$ neutron can be considered predominantly particle (namely, $u_n=1$, $v_n=0$ in terms of the usual BCS occupation amplitudes), and the proton is approximately at midshell (which means $u_p \simeq v_p$), the expression[17] for the effective p-n interaction becomes $V_J^{\text{eff}}=u_p^2V_J+v_p^2V_J^{-1}$, where V_J^{-1} is the particle-hole matrix element. Since V_J^{-1} tends to be of similar magnitude but opposite sign than V_J, the J multiplet tends to become degenerate.

Also from the point of view of the particle-core (quadrupole-quadrupole) coupling, the 9^- state is expected to lie low in energy. The coupling of the $h_{9/2}$ proton to the core is weak since its quadrupole moment is quenched (by the u^2-v^2 factor) due to its quasiparticle character. This means that the orientation of the proton angular momentum j_p with respect to the core spin R is energetically indifferent, which leads to the quasidegeneracy of the first $\frac{11}{2}^-$ and $\frac{13}{2}^-$ states[6,12] in ^{217,219}Ac. On the other hand, the neutron Fermi level lies at the beginning of the $g_{9/2}$ shell. This clearly privileges the aligned coupling of j_n and R which maximizes the overlap between particle and core quadrupole moments (in a deformed shell model language this corresponds to a decoupling situation). This means that, for instance, the "unfavored" $\frac{11}{2}^+$ state is pushed up in energy with respect to the aligned $\frac{13}{2}^+$ state, being consistent with its nonobservation[5] in ^{217}Ra. Hence the yrast states in the doubly odd nucleus ^{218}Ac will be of the type $I=j_p+j_n+R$ while the unfavored ones of the type $I=(j_p-1)+j_n+R$ should lie very near in energy. Similar arguments should also hold for the octupole-octupole coupling.

Figure 3 shows a striking similarity between the level schemes of ^{218}Ac and ^{217}Ra (Ref. 5), suggesting that the addition of the odd $h_{9/2}$ proton does not significantly influence the structure already developed in ^{217}Ra, which undoubtedly displays collective features. In particular, the excitation energies of the first negative parity states in both nuclei are identical. This speaks strongly in favor of a collective interpretation of these states.

In fact, the transition between a spherical shell model (or single particle) and a collective regime[18,19] seems to occur precisely at $N=129$. The even $N=128$ isotones, ^{216}Ra (Ref. 20) and ^{218}Th (Ref. 7), have $R_4(=E_4^+/E_2^+)$ ratios less than the critical value 1.82 in a Mallmann plot[18,19,21] showing a compression of the transition energies as one goes up the ground-state band, while ^{217}Ac is essentially an $h_{9/2}$ proton weakly coupled to ^{216}Ra. On the other hand, the even $N=130$ isotones, ^{218}Ra (Refs. 1 and 2) and ^{220}Th (Ref. 7), clearly show collective features; their R_4 ratios lie beyond $R_4=1.82$ and R_6 and R_8 fall nicely on the collective branch of the variable moment of inertia curves.[18,19,21] The development of quadrupole collectivity is accompanied by the appearance of interleaved negative parity states most likely connected to the presence of reflection asymmetry.[8,9] It is interesting to note that the first transition energy both in ^{217}Ra (540 keV) and ^{218}Ac (507 keV) coincides with the average of the first transition energies of its neighboring isotopes, namely $(688+390)/2=539$ keV and $(661+355)/2=508$ keV, respectively.

The $B(E1)/B(E2)$ ratios found here in ^{218}Ac [$(1.7+0.3)\times10^{-6}$ fm^{-2}] lie, on average, between those of ^{217}Ra and ^{219}Ac [(1.1 ± 0.2) and $(3.2\pm0.3)\times10^{-6}$ fm^{-2}, respectively].

Summarizing, excited states of ^{218}Ac have been studied through a complete set of combined α, γ, and e^- spectroscopy measurements. This work has revealed the existence of a band structure with interleaved states of alternating parities connected by enhanced $B(E1)$ transitions, which is strikingly similar to the one in its isotone ^{217}Ra. Both nuclei seem to be right on the edge of a phase transition to deformed, reflection asymmetric shapes.

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