^{218}Ra α Reduced Width and Its Consequences for α Clustering in the Heavy Elements

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Nuclei of ^{218}Ra were produced in the reaction ^{208}Pb(^{13}C, $3n$). After being separated from the beam by a velocity filter, they were implanted in a Si(Au) surface-barrier detector and their α-particle decays were observed in the same detector. From these α-decay events the half-life of ^{218}Ra was measured to be 25.6 ± 1.1 μs, almost a factor of 2 greater than the previously reported value of 14 ± 2 μs. The resultant α width fits well into the overall picture of α-decay-rate systematics and weakens one piece of evidence quoted for the existence of α clusters in heavy elements.

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In molecular spectroscopy, reflection asymmetry for rotational bands is characterized by states with spin I and alternating parity connected by enhanced $E1$ transitions. The molecular nuclear model proposed by Bohr implied that nuclear matter also may acquire an asymmetric shape. It, too, would then manifest reflection asymmetry and a rotational band with an I^π sequence in doubly even nuclei of 0^+, 1^-, 2^+, 3^-, 4^+, etc. Because vibrational collective states should also be present, mixing could result in low-lying states with a spin sequence of 0^+, 2^+, 1^-, 4^+, 3^-, etc. Negative-parity levels at low excitations were discovered[1] in even-even nuclei around the radium region thirty years ago. However, after many theoretical endeavors these levels were described[2] as coherent but nonadiabatic vibrations built on few-quasiparticle excitations in the reflection-symmetric representation.

Recent theoretical and experimental evidence for nuclei in the radium region has revived the concept of intrinsic reflection asymmetry.[3] For example, interplay between rotation and octupole shape deformation might account better for the high-spin ^{218}Ra data (see Fernández-Niello *et al.*[4] and Gai *et al.*[5]) than the alignment of an octupole phonon. As an alternative to the microscopic derivation of reflection asymmetry from Strutinsky theory,[6] it has been proposed that the asymmetry arises from α-cluster states that are associated with a molecular dipole degree of freedom.[7-9] Among the evidence cited[7] for this second explanation has been the existence of large α-decay widths for nuclei with neutron numbers just above $N = 126$. As a result, suggestions have been made that α-clustering effects play an important role in heavy nuclei as they do in the ^{16}O and ^{20}Ne mass region (see, e.g., Gai *et al.*[10]). An especially strong case has been made for ^{218}Ra whose width is the largest one reported for isotopes in this mass region, exhausting[5] some 75% of the Wigner-sum-rule limit.

Figure 1 shows a plot against neutron number of reduced widths for *s*-wave (or ground-state to ground-state) α transitions connecting even-even nuclei with $78 \leqslant Z \leqslant 100$. Here the formalism developed by Rasmussen[11] has been used. In it a relative decay probability is represented by the reduced width δ^2, defined by $\lambda = \delta^2 P/h$, where λ is the decay constant, h is Planck's constant, and P is the penetrability factor for the α particle to tunnel through a barrier. One sees the regularity of the widths as a function of N with the extremely sharp break at $N = 126$. This discontinuity has been shown (see, e.g., Mang[12]) to be a shell-structure effect. (A less pronounced minimum can be seen at the $N = 152$ subshell.) The indication in Fig. 1 is that only the ^{218}Ra width (open point at $N = 130$ identified as ^{218}Ra) is out of line when relative α-decay widths are examined. It is about a factor of 2 greater than the δ^2 value expected from systematics.

To calculate the reduced width for an α transition the decay energy and half-life are needed. Two α-decay energies, in agreement with one another, are available for ^{218}Ra, i.e., 8392 ± 8 keV (Torgerson[13]) and 8385 ± 8 keV (Valli[14]), but only one value has been measured[14] for the half-life, i.e., 14 ± 2 μs. We decided to remeasure the half-life of ^{218}Ra to see if its α width is indeed anomalously large.

The nuclide was produced in the reaction ^{208}Pb(^{13}C, $3n$) by bombardment of a 200-μg/cm^2-thick ^{208}Pb target with 67-MeV ^{13}C ions from the Holifield Heavy Ion Research Facility tandem accelerator. Forward-recoiling compound-nuclear products were separated from the ^{13}C beam by use of the accelerator's velocity filter,[15] and were implanted in a Si(Au) surface-barrier detector. The deposited recoils provided a start signal for a time-to-amplitude converter (TAC) while the α-particle decays furnished the stop signal. Details of this novel experimental technique are being prepared for publication.[16] Energy

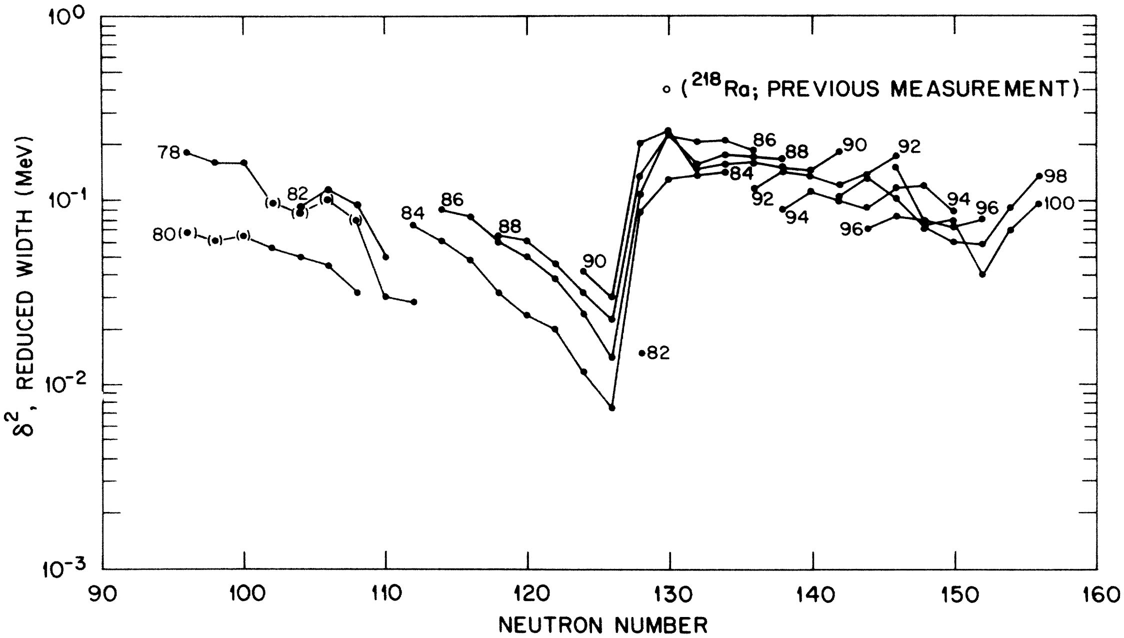

FIG. 1. Reduced widths for *s*-wave α transitions plotted as a function of neutron number for nuclei with atomic numbers from 78 to 100. The open point at $N=130$, labeled as ^{218}Ra, is the width calculated by use of the previously available (Ref. 14) half-life, 14 ± 2 μs, for this isotope. The width for the same nucleus calculated by use of our measured half-life, 25.6 ± 1.1 μs, essentially coincides with that of ^{216}Rn. Values enclosed in parentheses for $Z=78$ and $Z=80$ are based on estimated α branches.

scales for the recoil and α-particle spectra (measured with two different amplifiers) were calibrated with a ^{244}Cm α source and a precision pulser. Calibration of the TAC was accomplished by use of a commercial time calibrator. Energy and time information was stored in an event-by-event mode on magnetic tapes; histograms were generated on-line as the experiment progressed. The incident energy was selected to maximize the (^{13}C,$3n$) cross section. In addition, the 2-μs flight time through the velocity filter and the 80-μs range of the TAC provided further diminution of undesired α-emitting isotopes.

Figure 2 shows the spectra of heavy recoils [Fig. 2(a)] and α particles [Fig. 2(b)] recorded during a 12-h run with a beam intensity of ~ 10 particle nA. The three α groups in Fig. 2(b) are ^{218}Ra, its α-decay daughter ^{214}Rn, and a peak which encompasses events wherein both α energies are summed because of the short (0.27 μs) half-life[13,14] of ^{214}Rn. As a result of the flight time in the velocity filter most of the short-lived ^{214}Rn nuclei have to result from ^{218}Ra decay rather than from independent production, and, since the α branch of ^{214}Rn is 100%, this is indeed reflected in the essentially equal intensities of the two α groups in Fig. 2(b). In contrast to data from ordinary α-particle sources the ^{218}Ra and ^{214}Rn peaks show little degradation because the radioactive nuclei have been implanted in the Si(Au) detector. However, tailing does occur on their high-energy sides and on the low-energy side of the sum peak. These tails are a necessary consequence of the fact that the α emitters are located near the front face of the detector and are caused by α particles ejected from the detector, leaving only a fraction of their total energy (these points will be discussed in more detail in the forthcoming manuscript[16]).

Within uncertainties all three peaks had the same half-life, which was almost a factor of 2 larger than the 14-μs value reported[14] for ^{218}Ra. Figure 2(c) represents the time distribution for all α decays recorded in Fig. 2(b) spread over the 80-μs TAC range. The decay curve generated by setting gates only on the three peaks is shown in Fig. 2(d); the resultant half-life is 25.6 ± 1.1 μs. [The shorter-lived component seen in Fig. 2(c) is due mainly to ^{217}Ra produced in the (^{13}C,$4n$) reaction.] From the 25.6-μs half-life we deduce a δ^2 value of 0.23 MeV. This width is indistinguishable from the ^{216}Rn point in Fig. 1 and is well below the 0.42-MeV value (open point) based on the 14-μs half-life. Our measurement removes the ^{218}Ra discrepancy *vis-à-vis* α-decay rates in the heavy-element region. Nevertheless, the importance of α clusters in accounting for low-lying levels in nuclei with N around 130 needs to be explored because their reduced widths are larger than those of isotopes with $N \leq 126$.

In a discussion of clustering effects, one should remember the recent discovery of ^{14}C emission from

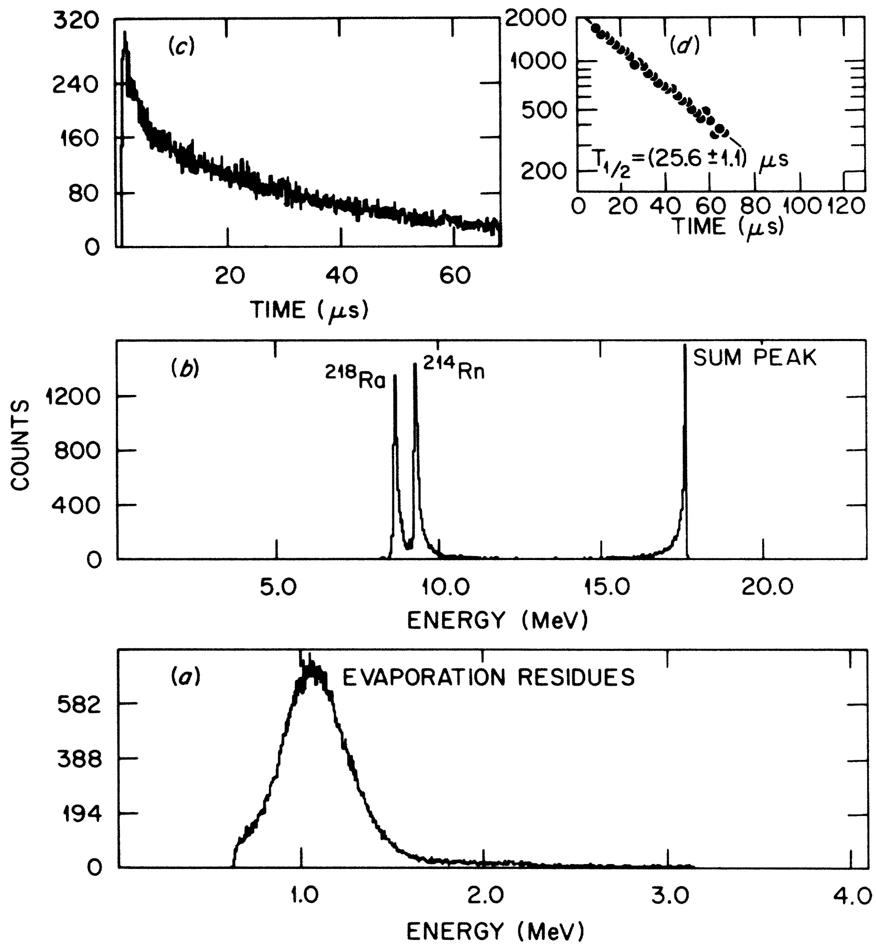

FIG. 2. Energy spectra measured (a) for product nuclei stopped in a Si(Au) surface-barrier detector and (b) for subsequent α-particle decays registered in the same detector. (c) Time distribution of all recorded α decays; (d) decay curve deduced from the time distribution gated by just the three α peaks in (b), i.e., ^{218}Ra, ^{214}Rn, and their sum peak.

^{223}Ra (Rose and Jones,[17] and Gales[18]) and from ^{222}Ra and ^{224}Ra (Price *et al.*[19]). These data suggest the presence of ^{14}C (or other heavy) clusters at the nuclear surface. Current deformed-shell–model calculations support this speculation. Chasman[20] has pointed out that a ^{14}C bulge induces a shape similar to the octupole-deformed Strutinsky equilibrium shape. Leander *et al.*[21] have found that an α cluster and a reflection-symmetry core do not account for the decoupling factors—or the $K=\frac{1}{2}$ ground state—of ^{225}Ra; the Strutinsky equilibrium shape or a large cluster, such as ^{14}C, is required. The generally smooth trend of δ^2 values for $N \geqslant 130$ seems to eliminate arguments that α-cluster configurations rather than the cranked Strutinsky equilibrium shapes are more appropriate for describing the lighter radium isotopes. In fact, while the calculated Strutinsky equilibrium shape is spherical for the ^{218}Ra ground state, in the cranked-shell-model calculations of Nazarewicz *et al.*[22] it acquires an octupole deformation at finite spins so that the yrast spectroscopy in this nucleus can also be accounted for.

To conclude we now consider *s*-wave reduced widths of rare-earth α emitters. Following their sharp drop at $N=126$ the δ^2 values shown in Fig. 1 increase as N decreases in the direction of the 82-neutron shell; as in the case of the heavy elements, widths in the rare earths reach a maximum (see, e.g., Nazarewicz and co-workers[23]) for nuclei with about four neutrons above the shell closure. On the basis of a measured[24] α-branching ratio of $(21 \pm 6)\%$ for ^{156}Yb this $N=86$ nucleus appeared[23] to have an extremely large width, a point that was interpreted[25] as a possible indicator for α clustering. However, a search[25] for new low-lying negative-parity levels in ^{156}Yb and ^{158}Yb revealed none. While not specifically looking for such states, an earlier study[26] of ^{156}Yb and a recent investigation[27] of ^{158}Yb also did not report low-spin negative-parity levels. The ^{156}Yb α branch has been remeasured[28] to be $(9 \pm 2)\%$ (a ratio confirmed in Ref. 25); this new branch lowers the reduced width to 0.19 MeV, a number consistent with δ^2 values of other $N=86$ isotopes. The width, however, is large enough to be comparable to those in the radium region that we have already discussed. It seems that large α widths are not related to the existence or nonexistence of enhanced dipole transitions in nuclei.

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