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Alpha decay hindrance factors and reflection asymmetry in nuclei

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All available hindrance factors of alpha transitions to low-lying negative-parity states in doubly even nuclei, to odd-A parity doublets and to doubly odd parity doublet bands, are used to study the systematics of reflection asymmetry in the $A\sim 218-230$ region. Special attention is given to the polarization effect of the odd particle in increasing reflection asymmetry and therefore decreasing hindrance factors to the opposite parity states of octupole bands.

I. INTRODUCTION

The evidence is strong for stable reflection asymmetry (RA) in the region from $A\sim 218-230$. In doubly even quadrupole-octupole deformed nuclei there is a displacement of the two bands of opposite parities, i.e., $I^{\pi}=0^{+},2^{+},4^{+},\ldots$ and $I^{\pi}=1^{-},3^{-},5^{-},\ldots$ with even spins favored energetically. The formula of Nazarewicz *et al.* [1] gives the energy difference between the positive- and negative-parity bands and what would be expected if they were to fit the rotational $I(I+1)$ relationship. When this energy difference is plotted against the spin of the rotational band, one can see whether or not the energy systematics is tending toward stable RA, and at what spin. Plots of this type are given, for example, in Ref. [2]. Furthermore, RA systematically improves the agreement between experimental and theoretical masses where they differ significantly in the $A\sim 218-230$ region [3].

In odd-A nuclei, the evidence for RA is (a) the level systematics of the bandheads is correctly described by the octupole deformed model but not by the Nilsson model, (b) the rotational bands have approximately degenerate parity doublets, (c) the decoupling parameter a has approximately the same absolute value but opposite sign for $K=\frac{1}{2}^{\pm}$ bands, and (d) the magnetic moment μ for parity doublets is approximately the same.

One additional factor which should significantly show the effect of RA is the hindrance factor (HF) in alpha decay. This should be important for doubly even nuclei, for odd-A nuclei, and presumably for odd-odd nuclei. To see the relationship between RA and the HF, consider a parity-mixed state of an odd-A parent, e.g., $\Omega^{+}[Nn_z\Lambda]\otimes\Omega^{-}[N'n_z'\Lambda']$ which alpha decays to the parity doublet bandheads Ω^{+} and Ω^{-} in the daughter nucleus with the same quantum numbers as the parent. The allowed unhindered alpha transitions between states of the same parity and between states of opposite parity give the same HF's in the limiting case where the barrier between the mirror octupole minima is very high. In practice, the most favored alpha transitions between states of the same parity have HF's which are always lower than those involving alpha decay between opposite parity states.

If one had a complete systematics of HF's, it could obviously tell us a great deal about the extent of the region of RA and its general characteristics. Even though the systematics of HF's is incomplete, we can learn about the systematics of RA using the available HF's.

II. SYSTEMATICS OF HF'S IN DOUBLY EVEN AND ODD-A NUCLEI

For the most part, the source of the HF's which we use in our work is the *Table of Isotopes* of Lederer and Shirley [4]. In even-even nuclei, the ground-state to ground-state transitions have HF=1 by definition. Using these HF's in a Geiger-Nuttal-type plot [4] one determines the HF's for odd-A and doubly odd nuclei by interpolation or extrapolation. Additional data pertaining to the HF's and the parity doublets of ^{218}Rn, ^{219}Fr, ^{221}Fr, ^{223}Fr, ^{221}Ra, ^{223}Ra, ^{225}Ra, ^{224}Ac, ^{225}Ac, ^{227}Ac, ^{225}Th, and ^{234}U are from Refs. [5–16], respectively.

The empirical HF's for all available alpha transitions to the low-lying 1^{-} states in double even nuclei are summarized in Table I. The available HF's for favored alpha transitions to odd-A and odd-odd nuclei parity doublets are given in Table II. These HF's have been renormalized so that the allowed unhindered alpha decay to the daughter state of the same parity is defined to have HF=1 as in the case for even-even nuclei.

The assumptions used in the gathering of the HF's are the following.

(1) The HF's for both ^{218}Rn and ^{220}Rn are given in parentheses because the 1^{-} states of these nuclides are not identified in the *Table of Isotopes* [4]. However, the spin-parity assignments can be inferred from the gamma transitions from the 645.4-keV state of ^{220}Rn and from the 840-keV level of ^{218}Rn to the 2^{+} and 0^{+} states of the ground-state bands. There is a serious discrepancy [4,16] in the HF for populating the $K=0,1^{-}$ state in ^{234}U. We have chosen the more recent Ref. [16]. Whereas the HF's to many states in the odd-A nuclei have been determined

TABLE I. HF's for alpha transitions to the low-lying 1^- states in doubly even daughter nuclei. Data are from Refs. [4, 5, 16].

Daughter nucleus	N	A	HF
$_{86}$Rn	132	218	(4.7)
	134	220	(4.1)
	136	222	4.4
$_{88}$Ra	132	220	2.0
	134	222	5.0
	136	224	11
	138	226	39
$_{90}$Th	134	224	9.4
	136	226	20
	138	228	120
	140	230	260
$_{92}$U	140	232	160
	142	234	33
	144	236	61
$_{94}$Pu	144	238	170
	146	240	460

[4], in many cases the appropriate spin parities have not been correctly deduced in the *Table of Isotopes*. Recently, the correct spin parity has been deduced for the parity doublets in a number of odd-A and odd-odd daughter nuclei involving allowed unhindered alpha decay (see Refs. [6–15]). Thus it has been possible to determine normalized HF's for many additional odd-A and odd-odd nuclei. In those cases where there is uncertainty regarding the spin-parity assignments, the normalized HF's are given with parentheses.

(2) We have not taken into account the spin barrier which is expected to affect the relative HF's to the 0^+ ground state and the 1^- octupole state in even-even nuclei. However, we note that the HF to the 2^+ member of the ground-state band (0.96 for ^{220}Ra, 0.96 for ^{222}Rn, 1 for ^{224}Th, 1.1 for ^{230}Th) is very similar to the ground state HF=1 in the region $220 \leq A \leq 230$. We expect the spin-barrier effect on the HF's to be even smaller to the 1^- state and have neglected this effect.

TABLE II. Ratio of HF's for the alpha population of the parity doublet band heads in the daughter nuclei with approximately the same configurations as the parent. The ratio is that for populating states with the same parity as the parent to that with the opposite parity of the parent. Data are from Refs. [4,6–15].

Daughter nucleus	N	A	HF ratio
$_{86}$Rn	133	219	(1.3)
$_{87}$Fr	132	219	3.4
	134	221	(3.4)
	136	223	(4.1)
$_{88}$Ra	133	221	7.9
	135	223	2.5
	137	225	(10.7)
$_{89}$Ac	134	223	2.8
	135	224	1.7
	136	225	4.2
	138	227	18.3
$_{90}$Th	135	225	(5.3)
$_{92}$U	137	229	5.3
	143	235	85.2

III. DISCUSSION OF ENERGY AND HINDRANCE FACTOR SYSTEMATICS

In order to see where we can expect the RA region, we examine first the data of the excitation energies from the lowest-lying $K=0,1^-$ states in doubly even nuclei [17]. It is necessary to do this because the energy systematics is more complete than that of HF's. Data on the energy of the lowest negative-parity excited states known in even-even Rn, Ra, Th, U, and Pu nuclei are compiled in the form of a contour plot of Fig. 1. A similar plot was first published in Ref. [18]. The most pronounced minimum occurs at $N=136$ in the Ra-Th region. This is where RA is expected. There is also a secondary minimum at $N=146$ along the beta stability line for the heaviest elements. Due to the lack of a number of crucial experimental HF's in the RA region it is, unfortunately, not possible to construct similar contour plots for HF's.

The HF's for alpha transitions to the low-lying 1^- states in doubly even nuclei and to the states of opposite parities but the same spins in odd-A and odd-odd nuclei are presented in Figs. 2 and 3. These figures are semilogarithmic plots of HF vs neutron number and proton number, respectively. The question mark symbol in Figs. 2 and 3 indicates that there are no experimental HF values for ^{229}Th, ^{227}Th, ^{226}Ac, and ^{221}Rn in Fig. 2 and for ^{226}Pa in Fig. 3.

The HF's reach a minimum in the region of RA similar to the minimum in the energies of the 1^- states (Fig. 1). The minimum seems to be at a somewhat lower neutron number 133 or 135 rather than at 136 as in Fig. 1. However, the incompleteness of the data makes it more

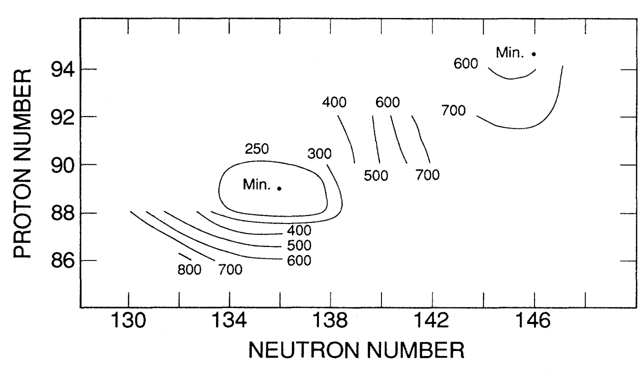

FIG. 1. Contour plot for 1^- energies in keV in doubly even Rn, Ra, Th, U, and Pu nuclei versus neutron and proton numbers.

difficult to define exactly the borders of the region of RA. Furthermore, the obvious presence of an odd-even effect in Figs. 2 and 3 complicates the HF systematics. The task of defining the region of RA might better be left to a combination of 1^- energy systematics, HF systematics, and especially the comparison of the ground-state spins of odd-A nuclei with various models. It is well known that reflection asymmetric odd-A nuclei have in general different spins than those expected in the Nilsson model. Furthermore, these spins are predicted in a strong-coupling RA model [19]. Therefore, deviations of spin from the Nilsson model and agreement with the octupole model can be a useful criterion to define the region of octupole deformation. This technique has recently been successfully applied [20,21].

Perhaps the most interesting factor in Figs. 2 and 3 is the odd-even effect which is most pronounced in the Ra-Th region. The observed HF to the 1^- state, e.g., 4.4 for ^{222}Rn, means that the alpha transition to this state is 4.4 more hindered than the ground-state transition. Similarly, the observed normalized HF to the opposite parity member of the parity doublet band, e.g., 2.8 for ^{223}Ac, indicates that the alpha decay to this state is 2.8 more hindered than the alpha transition to the member of the parity doublet band with the same parity as the alpha decaying parent. From the HF plots, we see clearly that the odd-A nuclei have lower HF's (4.2 for ^{225}Ac) than corresponding even-even nuclei (11 for ^{224}Ra, 20 for ^{226}Th).

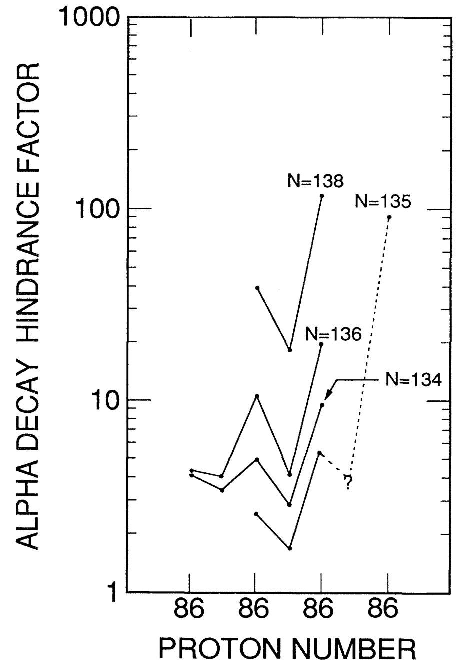

FIG. 3. Hindrance factors for alpha transitions to the low-lying 1^- states in even-even nuclei and to the state of opposite parity but same spin in odd-A and odd-odd nuclei plotted against proton number.

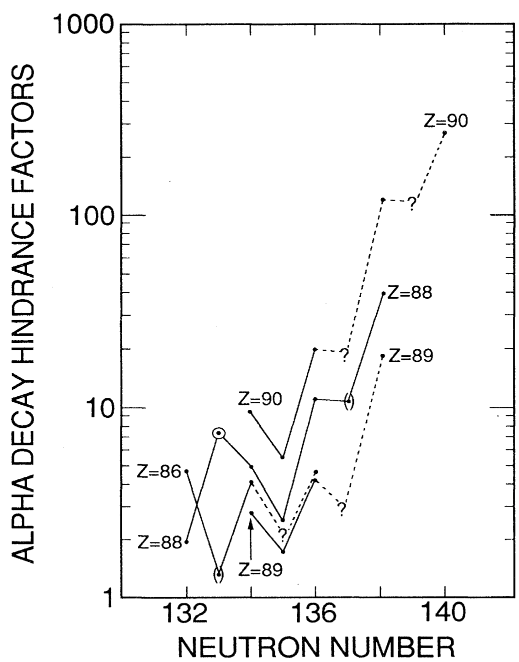

FIG. 2. Hindrance factors for alpha transitions to the low-lying 1^- states in even-even nuclei and normalized hindrance factors to the state of opposite parity but same spin in odd-A and odd-odd nuclei plotted against neutron number. The normalized hindrance factor for ^{221}Ra is anomalous. See the text for more details.

Moreover, we observe that the HF to the opposite member of the parity doublet band, e.g., 1.7 for ^{224}Ac, is even smaller than the values observed to the octupole bands in the neighboring odd-A nuclei (2.8 for ^{223}Ra and 5.3 for ^{225}Th). There is one exception to the odd-even effect in this HF systematics. That is for the nucleus ^{221}Ra. Figure 2 shows quite clearly that the HF for ^{221}Ra is larger than for ^{220}Ra and ^{222}Ra in contrast to all other odd-even effects in Figs. 2 and 3. This anomaly is probably related to the fact that the $K=\frac{3}{2}^{\pm}$ bands in ^{221}Ra are considerably mixed with $K=\frac{1}{2}^{\pm}$ bands as implied in their rotational structure [9]. The mixing would then be expected to cause anomalies in the HF ratio. For this reason the point corresponding to ^{221}Ra in Fig. 2 is encircled.

A possible explanation for the odd-even effect in Figs. 2 and 3 is the polarization effect (PE). Indeed, it is known that the odd particle polarizes the core toward greater RA. Let us therefore describe an attempt to quantify the PE. We calculate the hypothetical HF for even-even nuclei with odd mass number by drawing a straight line between the even-even isotopes in Fig. 2 and the even-even isotones in Fig. 3. The interpolated value of the HF at the odd neutron number (Fig. 2) and odd proton number (Fig. 3) then becomes the hypothetical HF for even-even nuclei with odd mass number. The difference between this HF and the actual HF for the odd-A nucleus is defined as the PE. A similar treatment is also applied in going from even-even to odd-odd nuclei and from odd-A to odd-odd nuclei. Table III summa-

TABLE III. Polarization effect (PE) in odd-A and odd-odd nuclei. (See the text for a description of the procedure used in determining the PE.)

No.	Even-even nuclei	Odd-A nuclei	Even-even nuclei	PE log	PE linear
1.	$^{220}_{86}Rn_{134}$	$^{221}_{87}Fr_{134}$	$^{222}_{88}Ra_{134}$	1.1	1.2
2.	$^{222}_{88}Ra_{134}$	$^{223}_{89}Ac_{134}$	$^{224}_{90}Th_{134}$	4	4.7
3.	$^{222}_{86}Rn_{136}$	$^{223}_{87}Fr_{136}$	$^{224}_{88}Ra_{136}$	2.7	5.2
4.	$^{224}_{88}Ra_{136}$	$^{225}_{89}Ac_{136}$	$^{226}_{90}Th_{136}$	10.6	12.3
5.	$^{226}_{88}Ra_{138}$	$^{227}_{89}Ac_{138}$	$^{228}_{90}Th_{138}$	49.7	61.2
6.	$^{222}_{88}Ra_{134}$	$^{223}_{88}Ra_{135}$	$^{224}_{88}Ra_{136}$	3	5.5
7.	$^{224}_{88}Ra_{136}$	$^{225}_{88}Ra_{137}$	$^{226}_{88}Ra_{138}$	10.3	14.3
8.	$^{224}_{90}Th_{134}$	$^{225}_{90}Th_{135}$	$^{226}_{90}Th_{136}$	8.7	9.4
	Even-even nuclei	Odd-odd nuclei	Even-even nuclei	PE log	PE linear
9.	$^{222}_{88}Ra_{134}$	$^{224}_{89}Ac_{135}$	$^{226}_{90}Th_{136}$	8.2	10.8
10.	$^{224}_{88}Ra_{136}$	$^{224}_{89}Ac_{135}$	$^{224}_{90}Th_{134}$	8.2	8.5
	Odd-A nuclei	Odd-odd nuclei	Odd-A nuclei	PE log	PE linear
11.	$^{223}_{89}Ac_{134}$	$^{224}_{89}Ac_{135}$	$^{225}_{89}Ac_{136}$	1.7	1.8
12.	$^{223}_{88}Ra_{135}$	$^{224}_{89}Ac_{135}$	$^{225}_{90}Th_{135}$	1.9	2.2

rizes the results obtained from Figs. 2 and 3. Since the logarithms of the HF's are plotted in Figs. 2 and 3, the polarization effects assume a logarithmic relationship in the method described immediately above. If a linear plot had been used instead, somewhat higher values for PE would be obtained. Both logarithmic and linear values for PE are given in Table III.

It is interesting to note that the PE is often quite large in going from doubly even nuclei to odd-A nuclei but still larger in going from doubly even to doubly odd nuclei (compare 4 and 10, Table III). On the other hand the PE is larger in going from doubly even to odd-A nuclei than in going from odd-A to doubly odd nuclei (compare 2 and 8 with 11 and 12, Table III).

The PE suggests that the region of RA is somewhat larger for odd-A than for even-even nuclei and still larger for odd-odd nuclei. If one recognizes that the HF's are largest at the borders of the region of RA, the HF for even-even nuclei will then be much larger than for odd-A nuclei in these borders. As a consequence, the PE will be greatest in the borderline region. This is exactly what is observed in Table III.

IV. SUMMARY AND CONCLUSION

We have come to the conclusion that the experimentally determined HF's are not only a tool for the study of the nuclear states involved in alpha decay, but also are important experimental factors in exploring RA. The HF curves reach a minimum in the same region of the nuclear Periodic Table as the minimum in the energies of the 1^- states of even-even nuclei, but at slightly lower neutron number. The incompleteness of the HF data and the odd-even effect make it more difficult to define exactly the borders of the region of RA.

However, the odd-even effect which results because the polarization of the odd particle is driven toward greater RA suggests that the region of RA is somewhat expanded for odd-A nuclei and slightly still more expanded for odd-odd nuclei. It is, unfortunately, difficult to see the effect of RA in doubly odd nuclei because of the lack of experimental HF's and spin-parity assignments in doubly odd nuclei in the $A \sim 220-230$ region. It should therefore stand as a challenge to experimentalists to more nearly complete the spectroscopy of the doubly odd quadrupole-octupole deformed actinide nuclei.

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