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Abstract

The experimental log ft. values of the Np^{239} beta decay and Am^{239} electron capture are analysed according to the asymptotic selection rules proposed by Alaga for deformed nuclei. It is found that, with a reasonable choice of state assignments from the Nilsson energy level diagram, a consistent interpretation can be given of the observed log ft. values. All "allowed" transitions are retarded by at least an order of magnitude, whereas the "first forbidden" transitions observed here proceed with normal ft. values. The interesting case of an "allowed" transition with log ft. > 8 is discussed.

Beta Decay and Electron Capture Branching to the Levels of Pu^{239}

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Introduction

Studies of the beta-decay of Np^{239} and Am^{239} have given information about the energies, spins, and parities of the excited states of the Pu^{239} nucleus.[1,2] With these data it has been possible to make several tests[2] of the Bohr-Mottelson nuclear model with regard to rotational level spacings and gamma ray transition probabilities within the rotational bands. the theoretical and experimental results have been found to be in good accord, indicating the applicability of the theoretical description in this region.

However, it was noted in the preceding paper[1] that a consistent picture could not be obtained of the beta and electron capture branchings of Np^{239} and Am^{239} to the states of Pu^{239} by means of ordinary spin and parity selection rules. In particular, the slowness of beta decay of Np^{239} to the members of the ground state rotational band, and the slowness of electron-capture decay of Am^{239} to the 391.8 kev state and to the ground-state rotational band, require explanation. We shall here examine the Np^{239} and Am^{239} log ft values to see if a consistent interpretation of the observed branching ratios can be given in terms of the "asymptotic" beta decay selection rules proposed by Alaga.[3]

Single Particle States in Pu^{239}

In the ordinary spherical shell model, the energies of individual particle states have been calculated by the use of an isotropic potential intermediate between a square well and a harmonic oscillator; with the additional assumption of strong spin-orbit coupling, an order of levels is obtained which reproduces the observed points of major shell closures.[4] In regions of large nuclear deformation such as the lanthanide and actinide elements similar calculations must take account of the fact that the binding field is non-spherical and is dependent upon the amount of deformation. This problem has been considered by several authors,[5,6] but here we shall use only the results of Nilsson.[5] Nilsson has calculated the binding states of nucleons in a modified spheroidal harmonic oscillator potential including the spin-orbit interaction; Fig. 1 is a reproduction of part of the Nilsson energy level diagram, plotted as a function of prolate deformation.[7] In this representation, each level is designated by the spin (Ω) and parity (π), the total oscillator quantum number N, and also by the quantum numbers n_z and λ which are "good" in the limit of large deformation; n_z and λ are respectively the components of N and the particle orbital angular momentum ℓ along the symmetry axis. The value of λ is equal to $\Omega \pm 1/2$ and is even or odd as $N - n_z$ is even or odd. In addition, each rotational band has a quantum number K which is equal to the spin (Ω) of the fundamental level of the band.

In order to use the Nilsson diagram, one must have an estimate of the deformation parameter appropriate to this region of elements. We shall use the value $\eta = +5$ which results from the intrinsic quadrupole moment of Np^{237} (Q_0 = 11 barns) determined by Newton[8] from Coulomb excitation experiments.

The following discussion will make use of information summarized in the level diagram of Pu^{239}, which is Fig. 1 of the preceding paper.

The availability of many close-lying orbitals in the region of 145 nucleons (neutrons) is revealed by an examination of the Nilsson diagram (Fig. 1 of this paper). Among these are two states of $\Omega = I = 1/2$ which might correspond to the Pu^{239} ground state. These are the states $\Omega, \pi, N, n_z, \lambda$ = [illegible] respectively. Strominger[9] has made theoretical calculations of the decoupling parameter a for each of these states and has concluded that only state 1/2+ 6, 3, 1 gives a result consistent with the experimental[2] value a = -0.58. Hence the orbit 1/2 + 6, 3, 1 will be assigned as the ground state.

There is found nearby the state 5/2 + 6, 2, 2 which probably corresponds to the 5/2+ state found at 286 kev.

The next intrinsic state observed experimentally is the 392 kev level which has odd parity and a spin of 5/2 or 7/2. A 5/2- state lying near the 1/2+ and 5/2+ states on the Nilsson diagram is that one designated 5/2- 7, 5, 2. There is also a 7/2- state available, 7/2- 7, 4, 3.

The 512-kev level in Pu^{239} has even parity and spin 5/2 or 7/2. A near lying 7/2+ state on the Nilsson diagram is the 7/2+ 6, 2, 4 state while somewhat farther away there is the 5/2+ 6, 3, 3 state.

States available to the parent isotopes Np^{239} and Am^{239} can be found on the diagram by counting up from the 82 proton shell. In the region of 93 and 95 protons there are three states, 5/2+ 6, 4, 2; 5/2- 5, 2, 3; and 3/2- 5, 2, 1. The first of these can be assigned as the ground state of Np^{239} while the second is probably the ground state of Am^{239}. The even parity 5/2 state is chosen for Np^{239} in analogy to the ground state of Np^{237} while the odd parity ground state of Am^{239} is analogous to the 5/2- ground state of Am^{241}. (The spin and parity assignments of Np^{237} and Am^{241} have been discussed by Hollander, Smith, and Rasmussen.)[2]

The spin value 5/2 has been assigned to the ground state of Np^{239} in spite of its measurement as 1/2 by optical hyperfine structure[10] because of the difficulty in reconciling the latter value with the Np^{239} beta decay data. In this connection it is interesting to observe that there is no Nilsson state with $\Omega = 1/2$ near 93 protons. A redetermination of the Np^{239} spin would be of obvious interest in view of this question.

The Alaga Selection Rules

Selection rules for beta decay of strongly deformed nuclei have been given by Alaga.[3] Beta transitions are classified as "unhindered" or "hindered" according to whether they obey or violate the following rules:

Allowed transitions: $\Delta I = 0,1$ no

$\Delta N = 0,\ \Delta n_z = 0,\ \Delta\Lambda = 0$

First forbidden transitions: (a) $\Delta I = 0,1$ yes

$\Delta N = 1,\ \Delta n_z = 0,\ \Delta\Lambda = 1$

$\Delta N = 1,\ \Delta n_z = 1,\ \Delta\Lambda = 0$

(b) $\Delta I = 2$ yes

$\Delta N = 1,\ \Delta n_z = 0,\ \Delta\Lambda = 1$

The analysis by Alaga[3] of beta decay log ft values in the rare-earth element region has indicated that those beta transitions which violate the asymptotic selection rules are in general retarded by about a factor of ten. Since these selection rules have not yet been tested in the heavy element region, it is of interest to make such a comparison in the case of the beta and electron capture decays to Pu^{239}, where log ft values are known and also definite assignments of the asymptotic quantum numbers have been made to some of the states by use of the Nilsson diagram.

Table I lists the experimental log ft values and the quantum number changes which occur in the various beta transitions. The spin and parity changes are listed first to denote the general classification of the transition as allowed or forbidden. Then the changes in K, N, n_z, and Λ are given. A discussion of these transitions follows:

Np^{239}, The transition to the ground-state A is expected to be second forbidden and unobservable. Transitions to states B, C, and D are of the allowed type but are known to be very slow (log ft > 9.1). This retardation may be explained by the operation of the strong K-selection rule, by which these transitions are forbidden since ΔK exceeds the multipolarity.

Table I

Np^{239} Beta Transitions

Final State	ΔI, $\Delta \pi$ Type	ΔK, ΔN, Δn_z, $\Delta \Lambda$	Asymptotic Classification	Expt'l log ft
A	2 no, 2^{nd} forb.	---	---	--
B	1 no, allowed	$\Delta K = 2$	K forb.	≥ 9.1
C	0 no, allowed	$\Delta K = 2$	K forb.	≥ 9.1
D	1 no, allowed	$\Delta K = 2$	K forb.	≥ 9.1
E	0 no, allowed	0, 0, 2, 0	hindered	7.0
F	1 no, allowed	0, 0, 2, 0	hindered	>6.5
G	0 yes, 1st forb.	0, 1, 1, 0	unhindered	6.5
H	1, 0 no, allowed	1, 0, 2, 2	hindered	6.8
		0, 0, 1, 1	hindered	6.8

Am^{239} Electron Capture Transitions

A,B,C,D	2,1,0,1 yes, 1st forb.	$\Delta K = 2$	K forb.	?
E	0 yes, 1st forb.	0, 1, 0, 1	unhindered	5.9
F	1 yes, 1st forb.	0, 1, 0, 1	unhindered	?
G	0 no, allowed	0, 2, 3, 1	hindered	>8
H	1 yes, 1st forb.	1, 1, 0, 1	unhindered	6.0

Transitions to states E and F are of the allowed type $\Delta I = 0, 1$; $\Delta K = 0$; $\Delta \pi$ = no, but are somewhat slow (log ft > 6.5). This is consistent with the fact that the asymptotic rule in Δn_z is violated. The retardation in this case is a factor of ~10-30. (There can of course be no unhindered allowed transitions in this region with $\Delta I = 0$ since these would have to be mirror beta decays).

The transition to state G is of the first-forbidden type [illegible] or 1 since state G can have either spin 5/2 or 7/2. Because the log ft value (6.5) seems rather low for a transition of the Δ I = 1 yes type, we prefer spin 5/2 for state G. In either case the beta transition is unhindered according to the asymptotic rules.

State H can have spins 5/2+ or 7/2+. There are Nilsson states available with both these spins: 7/2+ 6, 2, 4 and 5/2+ 6, 3, 3. In either case the beta transition, "allowed" by Δ I and Δ K selection rules, is "hindered" by a violation of the Δn_z and $\Delta\Lambda$ rules. The hindrance factor again is of the order of 10 to 30.

<u>Am^{239}</u>. The ground-state spin of Am^{239} has been assigned as 5/2-, for which the Nilsson state designation is 5, 2, 3.

A change of two occurs in the K value for electron-capture transitions to the ground rotational band, hence only those transitions with Δ I $\geq$ 2 are expected to proceed normally. Since a "normal" Δ I = 2 yes transition exhibits a log ft value in the neighborhood of 8.5, these transitions would be expected to contribute only a few percent of the Am^{239} decays. Unfortunately, the exact amount of branching to the ground state band is not known experimentally, but it is surely weak.

Electron capture to state E takes place with a log ft of 5.9 (this is actually a lower limit because the amount of branching to the lower levels is not known). According to the asymptotic selection rules this transition should be an unhindered first forbidden type, which agrees with the observed log ft of ~6.

A very interesting situation occurs in the case of the electron-capture to the odd parity state G which was assigned the spin value 5/2- or 7/2-. In either case this transition is expected to be "allowed", with Δ I = 0 or 1, no.

However, experimentally it is found that this transition is very slow; in fact it has not been observed in Am^{239} decay and a lower limit on its log ft has been set at 8. Thus, one has an "allowed" transition in both I and K which has been considerably retarded, by at least a factor of hundreds. A natural explanation for this unusually large hindrance is perhaps at hand from the asymptotic selection rules because here the initial and final states in the transition differ by two in principal oscillator quantum numbers; the parent state 5, 3, 2 arises from the fifth oscillator shell whereas the final state 7, 5, 2 (or 7, 4, 3) arises from the seventh shell. The lack of overlap between two such states is evidently quite serious.

The electron-capture transition to state H is of the $\Delta I = 0$ or 1, yes type, with log ft ~6.0. In this case none of the selection rules are violated, hence the transition is fast. A log ft value of 6 seems more reasonable for an unhindered $\Delta I = 0$ yes transition than for the slower $\Delta I = 1$ yes type, so perhaps the assignment 5/2+ 6, 3, 3 is preferable to 7/2+ 6, 2, 4 for state H.

SUMMARY

It has been shown that the log ft values of the Am^{239} and Np^{239} beta decays, anomalous according to ordinary ΔI and ΔK selection rules, can be fitted into a consistent picture by means of the Alaga "asymptotic" selection rules. Such a comparison helps to demonstrate the applicability of these rules and the Nilsson energy level scheme to odd-A nuclei in this region. The large hindrance of transitions with $\Delta N = 2$ is particularly interesting.

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Figures and Tables

Fig. 1. Nilsson energy level diagram for prolate deformation.

Table 1. Analysis of Np^{239} and Am^{239} beta transitions.