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Alpha Decay of Even-Even Nuclei

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A possible correlation between trends in the hindrance of alpha transitions to members of the ground-state rotational band of even-even nuclei and variations in the availabilities of various states in the nuclear surface is discussed

I. INTRODUCTION

MOST alpha transitions to the excited states of even-even nuclei are slower than expected from the simple barrier penetration theory. The decay hinderance is generally larger for emission of alpha particles of higher angular momentum. As the formation of alpha clusters of high angular momentum requires constituent nucleons of high angular momentum, the high angular momenta of the constituent nucleons possibly contribute to the decay hinderance. It is therefore of interest to study the dependence of the decay hindrance on the angular momenta of the constituent nucleons. In this paper we shall discuss a possible correlation between trends in decay hindrance and availabilities of states of various Ω's, Ω being the projection quantum number for particle angular momentum along nuclear symmetry axis, in the nuclear surface.

II. AVAILABILITY OF STATES

As a measure of the availability of states of a definite Ω, we shall use the number of orbitals with this Ω present among the highest few filled orbitals. Moreover, we shall take the same number of highest filled orbitals for both protons and neutrons. This procedure neglects the following effects. (a) In nuclear surface the number of available neutron states may be different from that of available proton states. So it is possible that we should take different numbers of highest filled orbitals for neutrons and protons. (b) Configurations containing unfilled orbitals in the unperturbed ground-state configuration may be mixed into the ground state. Thus the availabilities of states may be affected. (c) The extent of penetration into the nuclear surface by nucleons in a particular orbital varies from nucleus to nucleus. In fact, the same orbital may be more available in the surface region if it is, or nearer in energy to, the last filled orbital.

In deciding on how many highest filled orbitals are to be used in estimating the availabilities of states, the following points are considered. First, due to the short-range residual forces the Fermi surface is dissolved over an energy region of about 1 MeV. We expect that only nucleons in levels lying within this region are capable of being scattered. As the average level spacing in heavy odd nuclei is between 0.1 and 0.2 MeV, we may conclude that nucleons in the highest several filled orbitals make most of the contributions to alpha cluster formation. Secondly, from a classical viewpoint, alpha clusters of higher orbital angular momentum can be formed from nucleons of lower kinetic energy only at less dense region of the nucleus. Therefore we expect that orbitals of lower energies contribute less to the formation of clusters of higher orbital angular momentum, because their wave functions either penetrate the outer region of the nucleus less or have smaller Ω.

III. NILSSON ORBITAL ASSIGNMENTS

Table I (Table II) lists the highest seven filled proton (neutron) orbitals for heavy even-even nuclei with $230 < \text{mass number} < 250$. The last filled proton (neutron) orbital of an even-even nucleus is assumed to be the same as that of the odd proton (neutron) of an odd nucleus of the same proton (neutron) number. The classification of the energy levels of odd nuclei was reported by Stephens and others.[1] Other filled orbitals are obtained from the Nilsson energy-level diagram.

TABLE I. Nilsson proton orbital assignments. The orbitals are identified by Ω, parity and three numbers in brackets referring, respectively, to the total number of nodes in the wave function, the number of nodal planes perpendicular to the symmetry axis and the component of orbital angular momentum along the symmetry axis. Column 2 lists the last filled orbitals, and succeeding columns list other filled orbitals below the last filled orbitals in the order of decreasing energy.

Isotope	I	II	III	IV	V	VI	VII
Th	3/2+ (651)	11/2+ (505)	1/2+ (660)	3/2+ (532)	1/2− (541)	1/2+ (400)	3/2+ (402)
U	1/2− (530)	3/2+ (651)	11/2− (505)	1/2+ (660)	3/2− (532)	1/2− (541)	1/2+ (400)
Pu	5/2+ (642)	11/2− (505)	1/2− (530)	3/2+ (651)	1/2+ (660)	3/2− (532)	1/2− (541)
Cm	5/2− (523)	5/2+ (642)	11/2− (505)	1/2− (530)	3/2+ (651)	3/2− (532)	1/2+ (660)
Cf	3/2− (521)	5/2− (523)	5/2+ (642)	11/2− (505)	1/2− (530)	3/2+ (651)	3/2− (532)
Fm	7/2+ (633)	3/2− (521)	5/2− (523)	5/2+ (642)	11/2− (505)	1/2− (530)	3/2+ (651)

[1] F. S. Stephens, F. Asaro, and I. Perlman. Phys. Rev. **113**, 212 (1959); I. Perlman, *Proceedings of the International Conference on Nuclear Structure* (The University of Toronto Press, Toronto, 1960), p. 547.

TABLE II. Nilsson neutron orbital assignments. The orbitals are identified by Ω, parity and three numbers in brackets referring, respectively, to the total number of nodes in the wave function, the number of nodal planes perpendicular to the symmetry axis and the component of orbital angular momentum along the symmetry axis. Column 2 lists the last filled orbitals, and succeeding columns list other filled orbitals below the last filled orbitals in the order of decreasing energy.

Neutron number of isotope	I	II	III	IV	V	VI	VII
140	5/2− (752)	3/2+ (631)	13/2+ (606)	3/2− (761)	3/2+ (642)	1/2+ (640)	1/2− (770)
142	5/2+ (633)	13/2+ (606)	3/2+ (631)	5/2− (752)	3/2− (761)	3/2+ (642)	1/2+ (640)
144	7/2− (743)	13/2+ (606)	5/2+ (633)	3/2+ (631)	5/2− (752)	3/2− (761)	3/2+ (642)
146	1/2+ (631)	13/2+ (606)	7/2− (734)	5/2+ (633)	3/2+ (631)	5/2− (752)	3/2+ (642)
148	5/2+ (622)	1/2+ (631)	13/2+ (606)	7/2− (734)	5/2+ (633)	3/2+ (631)	5/2− (752)
150	7/2+ (624)	5/2+ (622)	1/2+ (631)	13/2+ (606)	7/2− (734)	5/2+ (633)	3/2+ (631)
152	9/2− (734)	7/2+ (624)	5/2+ (622)	1/2+ (631)	13/2+ (606)	7/2− (734)	5/2+ (633)

IV. DISCUSSION

In Table III we tabulate the number of orbitals with $\Omega=\frac{1}{2}$ present in the highest seven neutron and highest seven proton orbitals, the number of orbitals with $\Omega=\frac{3}{2}$ present in the highest four neutron and highest four proton orbitals, and the number of orbitals with $\Omega=\frac{5}{2}$ present in the highest four neutron and highest four proton orbitals. We first note that nucleons with $\Omega=\frac{1}{2}$ become less available as we go to heavier nuclei. This trend is also noticeable if we take into account only six highest proton and six highest neutron orbitals. This suggests that the increasing trend in the hindrance factors for transitions to the 2+ states of the ground state rotational band of even-even nuclei[2] as the proton number increases may be attributed to the decreasing availability of states with $\Omega=\frac{1}{2}$. We further note that orbitals with $\Omega=\frac{3}{2}$ become more available as we go to nuclei either lighter or heavier than Cm nuclei, and orbitals with $\Omega=\frac{5}{2}$ become more available as we go to heavier nuclei. The minimum in the availability of orbitals with $\Omega=\frac{3}{2}$ disappears when several more orbitals are included, but the increasing trend, as we go to nuclei lighter than Cm nuclei, remains. The increasing trend in the availability of orbitals with $\Omega=\frac{5}{2}$ is also present when several more orbitals are included. It is therefore tempting to attribute the trends in the hindrance factors for transitions to the 4+ (6+) state of the ground-state rotational band to the variations in the availability of orbitals with $\Omega=\frac{3}{2}$ $(\frac{5}{2})$. These correlations, if real, would mean that nucleons with $\Omega=\frac{1}{2}$ are the major constituents in the formation of $l=2$ alpha clusters; nucleons with $\Omega=\frac{3}{2}$ the major constituents in the formation of $l=4$ alpha clusters; nucleons with $\Omega=\frac{5}{2}$ the major constituents in the formation of $l=6$ alpha clusters. This proposition, together with the fact that decay hindrance is generally larger for the emission of alpha particles of higher angular momentum, would suggest that the formation probability of alpha clusters is a decreasing function of the Ω's of the constituent nucleons.[3]

TABLE III. Availabilities of states of various Ω's.

Isotope	Ω=1/2	Ω=3/2	Ω=5/2
Cf^{250}	2	1	3
Cf^{246}	2	1	3
Cm^{244}	3	0	3
Cm^{242}	3	0	3
Pu^{242}	4	1	2
Pu^{240}	4	1	2
Pu^{238}	3	2	2
Pu^{236}	4	2	3
Pu^{234}	5	3	2
U^{238}	5	1	1
U^{236}	4	2	3
U^{234}	5	2	2
U^{232}	6	3	1
Th^{232}	4	3	2
Th^{230}	5	4	1

The calculations of Mang and Rasmussen[4] show that the contribution of nucleon orbitals to alpha groups of different angular momenta do not show any clear trend in its dependence on the Ω's of the orbitals. In their method the alpha transition probability is essentially determined by the overlap of the wave function of the parent nucleus and that of the alpha particle plus the daughter nucleus. We feel that there is a need to study the role played by internucleon forces in determining alpha transition probability.

[2] G. C. Hanna, *Experimental Nuclear Physics*, edited by E. Segre (John Wiley & Sons, Inc., New York, 1959), Vol. III, p. 55.

[3] In a previous communication [F. C. Chang, Phys. Rev. Letters **6**, 414 (1961)], it was tentatively concluded that pairing energies of high-Ω nucleons are generally larger than those of low-Ω nucleons, and thus a monotonic dependence of formation probability of alpha clusters on the Ω's of the constituent nucleons follows. Recent calculations of pairing energies in deformed nuclei show that pairing energies in deformed nuclei do not seem to possess a monotonic dependence on Ω. [P. E. Nemirovsky and Yu. V. Adamchuk, Nucl. Phys. **39**, 551 (1962); S. G. Nilsson and O. Prior, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **32**, No. 16 (1961)].

[4] H. J. Mang and J. O. Rasmussen, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter **2**, No. 3 (1962).