Possible Mechanism for the Formation of Yrast Traps at Very High Spins

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We discuss a possible mechanism, namely the maximization of the overlap of nucleonic wave functions by alignment, for the formation of isomers in the yrast band in the rare nuclei at very high spin states. Our results indicate that the possibility of existence of such yrast traps is restricted to a few nuclei with special irregularities in the single-particle levels.

With the advent of heavy-ion accelerators it has been made possible to transfer in a fusion experiment angular momenta as large[1] as $\sim 60\hbar$ into compound nuclei. This makes feasible the experimental studies of very high-spin states of the nuclei. The information from these experiments,[1,2] however, is restricted to measurements of the continuum γ rays[1] and γ-ray multiplicities,[2,3] since it is impossible to resolve single γ lines above spin $\sim 22\hbar$. The experimental situation would, therefore, be greatly improved, if an isomeric state at a very high angular momentum (yrast trap) could be found as discussed first by Bohr and Mottelson.[4] The purpose of this note is to suggest more in detail a mechanism for the formation of such yrast traps.

The calculations of the deformation energy surfaces performed in the framework of the liquid-drop model[5] using a rigid-body moment of inertia in the rotational energy indicate that up to spin $\sim 80\hbar$ (rare-earth region) the nucleus is oblate ($\gamma = -60°$) with the symmetry axis coinciding with the rotation axis. Calculations performed with the inclusion of the shell correction[6,7] and microscopic calculations,[8] however, do not yield such shapes for many nuclei. Even so in this note we want to restrict the quantitative considerations to rotation around the symmetry axis preferred by the liquid-drop model. In such a situation a collective rotation is forbidden out of general quantum-mechanical arguments. Any further increase of the total spin can be obtained only from the individual nucleonic excitations. Once such a stage is reached any irregularities on the yrast line may lead to isomeric states.[4]

A possible mechanism for producing isomeric states is the maximization of overlap of nucleonic wave functions by alignment (MONA) of the single-particle angular momenta outside closed shells. This effect is clearly demonstrated for the 18^+ state[9,10] of $^{212}_{84}Po_{128}$ at 2.93 MeV with a half-life of 45 sec. This state is formed by aligning the $(\pi h_{9/2})^2(\nu i_{11/2})^2$ configuration outside the doubly closed ^{208}Pb. Because of the short-range nature of the nucleon-nucleon interaction we have the largest overlap of the nucleonic wave functions for angular momentum $J = 0$. For intermediate angular momenta the overlap is reduced and increased again for the fully aligned configuration. Moreover, Schiffer[11] and Molinari *et al.*[12] found that a suitable normalized effective residual interaction depends only on the angle between the angular momenta: The residual interaction is almost symmetric around 90° and is strongly attractive for 0° and 180°. This property of the effective interaction lowers the $J = 18^+$ state in ^{212}Po below the 16^+ state and one has an isomer. In our calculation we use a quadrupole-quadrupole interaction,[13] which is established as a reasonably good force in the rare-earth region. A detailed analysis[12] shows that it can reproduce quite well the salient features of the Schiffer matrix elements.[11] The quadrupole force is attractive if the quadrupole moments of the interacting particles have both the same sign.

We start with a Slater determinant $|\beta_2\beta_4 J\rangle$ determined by occupying the lowest levels of the cranked Nilsson Hamiltonian

$$h = \sum_a \langle \vec{r}|a\rangle \epsilon_a \langle a|\vec{r}\rangle - \alpha_\tau \hbar\omega_0 r^2(\beta_2 Y_{20} + \beta_4 Y_{40}) - \omega_J j_z \quad (1)$$

under the constraint

$$\langle \beta_2\beta_4 J|J_z|\beta_2\beta_4 J\rangle = J. \quad (2)$$

In this coordinate system the deformation $\gamma_x = -60°$ (defined with the x axis as the rotational axis) corresponds to a negative deformation β_2 with $\gamma_z = 0$. The deformation energy surface is then obtained as

$$E^J(\beta_2, \beta_4) = \langle \beta_2\beta_4 J|H|\beta_2\beta_4 J\rangle + E_{\mathrm{Coul}}(\beta_2, \beta_4) \quad (3)$$

for different values of angular momenta J. The many-body Hamiltonian H (pairing plus quadru-

pole force), the single-particle basis, and the quantity α_τ are given in Ref. 13. The dependence of the oscillator frequency ω_0 on β_2, β_4 is obtained by the volume conservation condition.

The purpose of this note, however, is not to emphasize the quantitative calculation of the yrast traps but to show that in principle MONA can lead to isomers even at very high spin states. (We should not forget that the single-particle basis used may be too small for the larger deformation and that we restricted ourselves to $\gamma_x = -60°$. The model character of this study is further stressed by the fact that we use a many-body Hamiltonian[13] the parameters of which have been adopted to ground-state properties without the inclusion of the Coulomb repulsion.)

Figure 1 gives the yrast energies and total mass quadrupole moments. The ratio $(\beta_4/\beta_2)_{J=10}$ is determined in this figure by minimizing the total energy (3) for angular momentum $J=10$ with respect to β_2 and β_4. This ratio is kept fixed for a given nucleus. The equilibrium β_2 for every J is then determined by minimizing (3) as a function of β_2 with $\beta_4(J) = (\beta_4/\beta_2)_{J=10}\beta_2(J)$.

The nuclei shown in Fig. 1 are the only ones showing yrast traps by MONA. The appearance of these traps therefore does not seem to be a common feature.

Figure 1 also shows that the appearance of isomers is connected with maxima in the absolute value of the quadrupole moment. This can be understood by the mechanism leading to these yrast traps. The single-particle part of the total energy is an increasing function of the angular momentum J. The expectation value of the quadrupole force, however, is an oscillating function of J, its value being dependent on the expectation value of the quadrupole operator. A drastic increase of the quadrupole moment may then lead to an yrast trap. The traps found in this work are all connected with a pecularity in the Nilsson spectrum (Fig. 2) near neutron number 108. An increase of angular momentum forces, for example, nucleons from the levels $[521]-\frac{1}{2}$ ($q=0.25$ fm^2), $[602]-\frac{5}{2}$ ($q=0.97$ fm^2), $[521]-\frac{3}{2}$ ($q=0.17$ fm^2), $[523]-\frac{5}{2}$ ($q=0.29$ fm^2) into the levels $[615]+\frac{11}{2}$ ($q=-1.59$ fm^2), $[615]+\frac{9}{2}$ ($q=-1.18$ fm^2), $[602]+\frac{3}{2}$ ($q=-0.93$ fm^2), and $[613]+\frac{7}{2}$ ($q=-1.47$ fm^2). (As an estimate for the single-particle quadrupole moment q one can also consider the slope of the Nilsson levels in Fig. 2.)

We conclude that the MONA may lead to yrast traps at very high spin states. (They should not be mixed up with shape isomers.) The stability

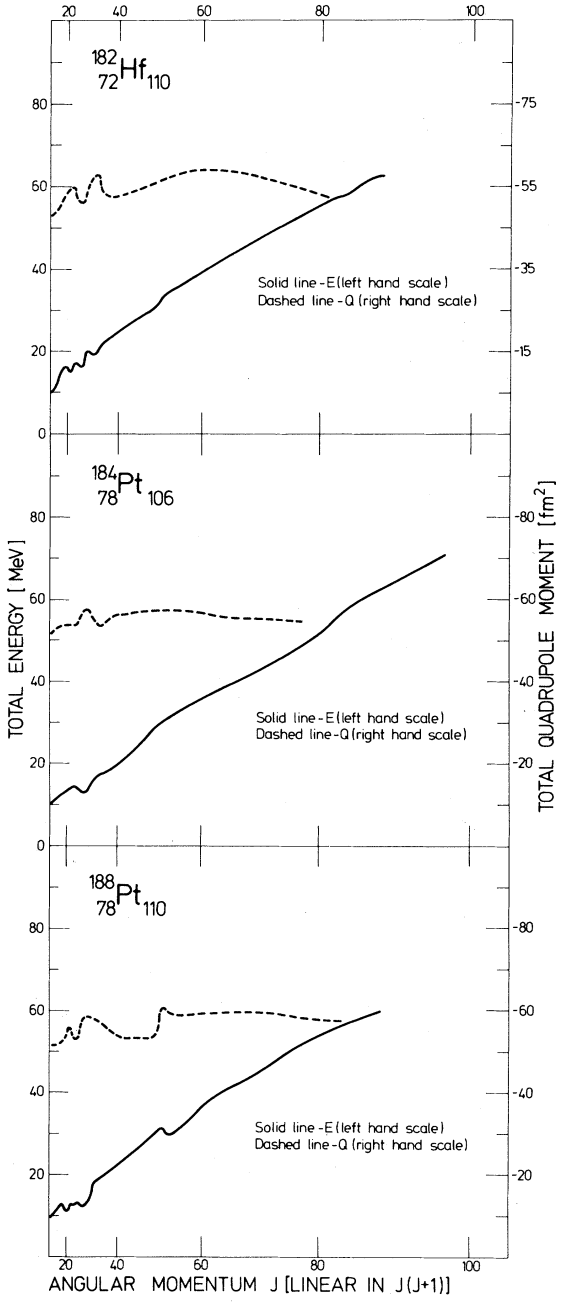

FIG. 1. Yrast energies and mass quadrupole moments in ^{182}Hf, ^{184}Pt, and ^{188}Pt as functions of the total angular momentum.

of the yrast states against γ degree of freedom has not been investigated. This may lead to a further reduction of the number of possible MONA isomers. The only examples where we found the traps correspond to nuclei with neutron number $N=106, 110$. Around the deformation values at which the traps appear a group of Nilsson levels

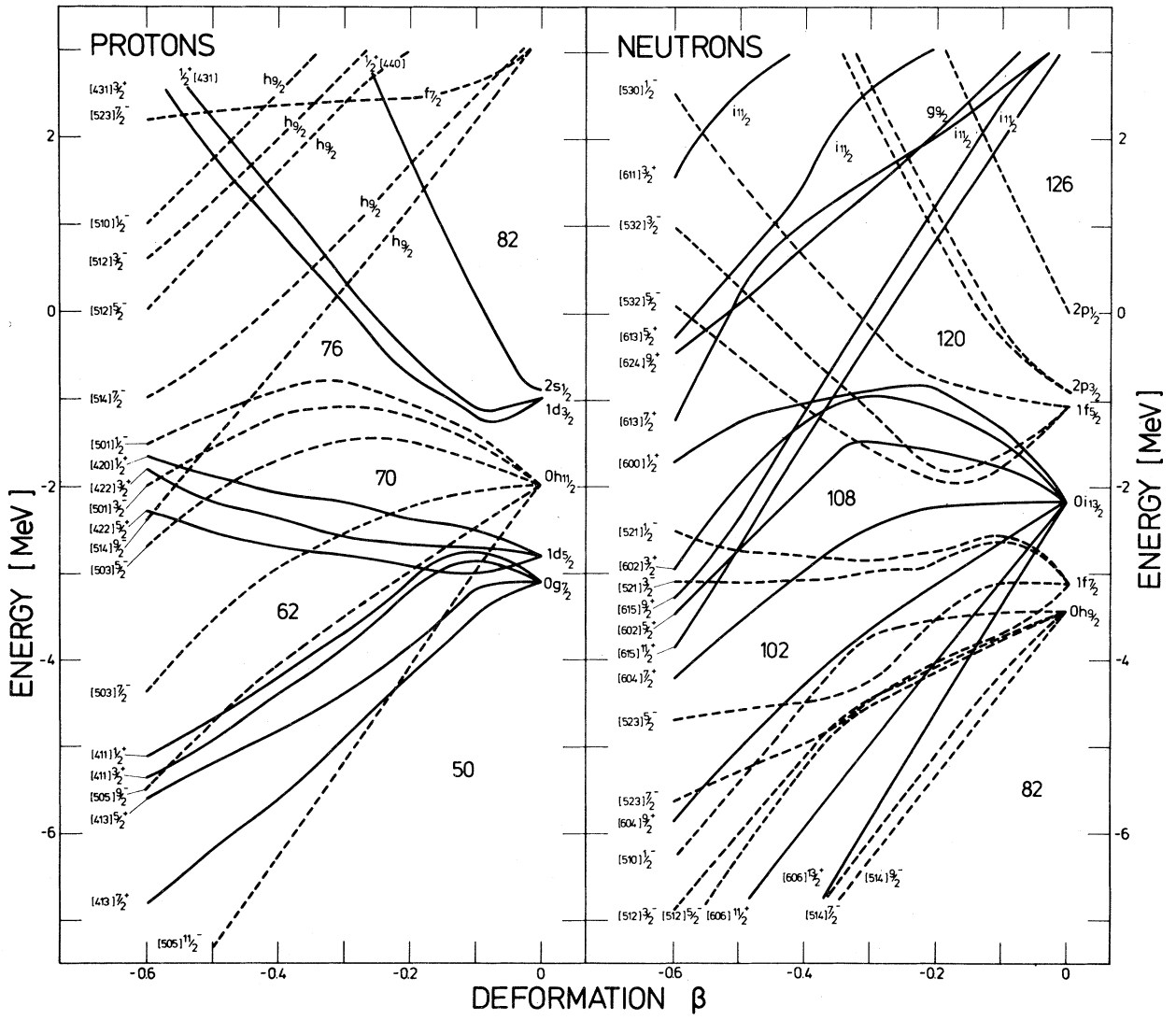

FIG. 2. Nilsson-level diagram for negative deformations β_2 and $\beta_4 = 0$.

with large negative quadrupole moments intersects the levels of small or even positive quadrupole moments. For neutron number 108 we do not find such pronounced traps as for $N = 106$ and 110 nuclei. This is connected with the fact that the absolute value of the deformation β_2 is farther away from the intersection point for $N = 108$. Another mechanism for producing yrast traps is to construct particle hole excitations over the sloping Fermi surface. This method has been used by Nilsson.[14]

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Observations of Population Inversion between the Λ-Doublet States of OH

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Inverted population distribution between Λ-doublet states of OH produced in the reaction $H+NO_2 \rightarrow OH+NO$ has been observed in a beam maser and in a molecular-beam electric-resonance spectrometer. The observed inversions are of the order of 4–6% for the $^2\Pi_{3/2}$, $J=\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$, and the $^2\Pi_{1/2}$, $J=\frac{1}{2}$ states, and less than 1% for the $^2\Pi_{1/2}$, $J=\frac{3}{2}, \frac{5}{2}, \frac{7}{2}$, and $\frac{9}{2}$ states.

Nonequilibrium population distributions of hydroxyl radicals have been reported for several types of production processes.[1-3] In all these cases the population distributions can be described by some positive excitation temperature. Population inversion between rotational states of the electronic ground state ($X^2\Pi$) of OH has been obtained by Ducas *et al.*[4] in their infrared OH laser. In the present investigation population inversion between the Λ-doublet levels has been observed for the OH radicals produced in the reaction[5]

$$H+NO_2 \rightarrow OH+NO. \quad (1)$$

Although this is the first report of "natural" inversion between closely spaced doublet levels, such inversions might be occurring in a wide range of reactive and collisional processes. The present results may be of direct importance for the understanding of reactive interactions involving diatomic $^2\Pi$ molecules. They might also contribute to the understanding of the elusive problem of the origin of the maser emission by the interstellar OH sources. Although a number of possible inversion mechanisms based on pumping by radiation[6] and by collisional[7] or reactive processes[8] have been proposed, no laboratory investigations in this field have been reported so far.

The measurements have been performed in a beam maser and in a molecular-beam electric-resonance (MBER) spectrometer. A description of the MBER spectrometer has been given elsewhere.[9] Details of the OH beam maser will be published in a forthcoming paper. The basic outline of the two spectrometers is schematically shown in Fig. 1. In both spectrometers the OH radicals were produced by the reaction (1) for which the atomic hydrogen was obtained from an electrodeless discharge at 2.45 GHz in H_2O. The reaction took place near the end of the flow tube where the NO_2 was injected via a capillary glass array or through a concentric ring of small holes. The reaction products were streaming freely into the source chamber. The molecular beam was formed by a hole with a diameter of 2–3 mm at a distance of a few millimeters from the end of the flow tube.

In the beam maser the Λ-doublet transitions were detected in two microwave cavities tuned to different transitions. The measurements have been performed on the Λ-doublet transitions in the rotational $J=\frac{3}{2}$, $\frac{5}{2}$, and $\frac{7}{2}$ states of the electronic $^2\Pi_{3/2}$ level. In normal operation, state se-

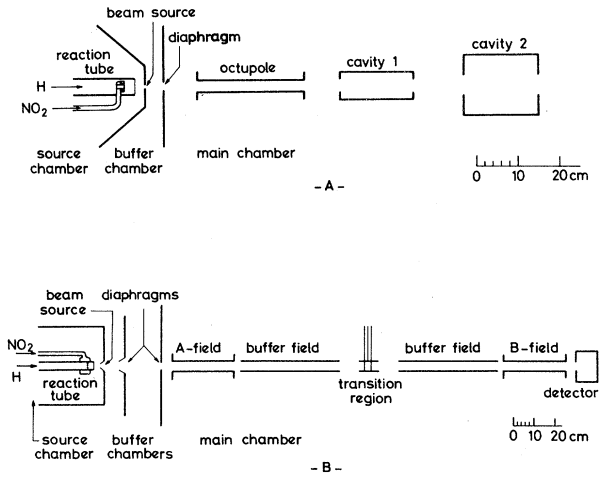

FIG. 1. Diagram of the molecular beam maser and the MBER spectrometer.