SHAPE ISOMERS AS CANDIDATES FOR THE GAMMA RAY LASER STORAGE STATE

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ABSTRACT

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Three Dimension Nuclear Hartree-Fock calculations have been performed for isotopes of Osmium, Mercury, and Tungsten. Many of the calculated potential energy surfaces show a second minimum at large prolate deformation indicating the possibility of shape isomeric states. Several are at sufficiently low energy to be possible candidates as storage states for the gamma ray laser.

1. INTRODUCTION

The most promising scheme for the development of a gamma ray laser involves initially creating an energy inversion through populating an appropriately long lived storage state. Conventional wisdom would identify this state as one of the class of nuclear spin isomers. We believe this wisdom may very well prove ingenuous.

Spin isomers are well studied states and until a few years ago the only nuclear levels called "isomers". They have lifetimes ranging from micro-seconds to years. Their atypical life times come about through their anomalous angular momentum relative to "normal" nuclear states at adjacent or lower energy. The necessity of changing angular momentum by a large quantity combined with the relatively low energy of the transition inhibits their electro-magnetic decay. Moreover, their origin lies in the nuclear shell model of the atomic nucleus in which a single particle orbital of high angular momentum is displaced in energy. Hence their electro-magnetic strength arises from a single particle orbital transiting to another state that is at best another single particle state. Hence, a spin isomer can have a transition strength of at most one single particle unit. Most typically this strength is one to three orders of magnitude smaller. Moreover, they are at relatively low energy in the nuclear spectra and in a region of relatively low level density. This means that finding another nuclear state some where near the isomer in energy which could serve as a lasing state is at least improbable and by our arguments one would have a very difficult time transiting to it if found.

Nevertheless, at present these are the only existent storage states and a cottage industry has come into being to find new ones and measure their properties. A prudent program of research leading to a gamma ray laser would support this effort, pedestrian as it may be. Our effort is in a different and more speculative direction. Namely, to predict, using the techniques of nuclear theory, the existence of a class of isomers which would be specifically very useful as gamma ray laser storage states. These are shape isomers which decay only electro-magnetically.

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This other form of isomerism, alternatively called shape isomerism or fission isomerism, was first discovered in the observation of delayed fission in actinide elements¹. The theoretical explanation of the anomalous life time of these nuclear states is in the hypothesized complexity of structure in the potential energy surface of these nuclei². This is illustrated in Fig 1, where a schematic drawing displays a second minimum in a "prolate cut" through this multi-dimensional (in nuclear collective coordinates) potential energy surface. The delay in the decay of this state is due to the necessity of tunneling through the barrier to the right to fission or to the left to emit a photon. Perhaps fifty of these states are known, all in the actinides, all decaying entirely by fission and with lifetimes ranging from milli to nano seconds.

Our speculation is that these states will exist in nuclei that do not fission. This inference is drawn from the observation that the shape isomer found are not theoretically existent because they are in the fissioning nuclei. These nuclei provide a vehicle for their observation through the "accident" of their excitation energy being comparable to their fission barriers. If either of these quantities were different by a factor of ten the discovery of this phenomena would perhaps not have occurred.

The relevance of this supposition to the problem of gamma ray storage states lies in rather pedestrian inferences on the probable electro-magnetic properties of these hypothesized states. As distinguished from spin isomers, shape isomers are highly collective states. They have very low angular momentum. Therefore, causing a transition from such a storage state to a lasing state does not have to overcome the inhibition of a large transfer of angular momentum as would be the case in a spin isomer. This is particularly important as all known schemes for the transfer are electro-magnetic in origin which has a particularly difficult time changing angular momentum by more than one or two units. Lastly, it is likely they will be at least high enough in energy to be in region of high nuclear level density for normal levels. Hence, finding a possible lasing state energetically "adjacent" to the storage state literally becomes many orders of magnitude more probable than for spin isomers.

The set of probable difficulties in using these states for the gamma ray laser, beyond the obvious one of their entirely speculative existence, is certainly not empty. Foremost, is the problem of finding them. Secondly, once found will they be at energies inconsistent with their use as gamma ray laser storage isomers? Thirdly, will they have useful lifetimes? Lastly, will they be in nuclei so far from stability that useful quantities cannot be produced? These questions will be addressed in the following sections. We will not address the question of the actual transfer mechanism and the relevance of these states to it, leaving that for another paper⁴

2. PREDICTING THE STATES

Our immediate goal in this research, therefore, was to examine the general problem of the existence of second minima in the potential energy surfaces of atomic nuclei. The experimental difficulty of looking for such a subtle and difficult phenomena precludes a purely experimental approach.

Moreover, given several thousand known nuclei a methodical search would be most improbable of success this millennium. Our goal was to make theoretical calculations predicting these states. The technique chosen exploited a technology that had been developed over several years⁵ a collaboration with several researchers in Europe. Together, we had developed the western world's most advanced capacity for three dimensional nuclear Hartree-Fock calculations and had used it to study many of the properties of nuclei.

It is crucial to what follows to recall that "Hartree-Fock" is the leading term in a theory as distinguished from a model. As such it can be embedded in a coherent sequence of approximations. The calculations were performed with two variants of the Skyrme type of effective forces, SKI1 and a modern version of it called SKM*. The non-linear equations to be solved are

$$-\frac{\hbar^2}{2m} \Delta \varphi_i(r) + \sum_{j=1}^A \int dr' v(r, r') \cdot \varphi_j^*(r') \varphi_j(r') \varphi_i(r) - \varphi_i(r) \varphi_i(r') = \epsilon_i \varphi_i(r) \quad (1)$$

where $V =$

$$\begin{aligned} & t_0 [1 + x_0] \rho_\sigma \delta + \frac{1}{2} t_1 [1 + x_1 \rho_\sigma] (k^2 \delta + \delta k^2) \\ & + t_2 [1 + x_2 \rho_\sigma] k \cdot \delta k' + \frac{1}{6} t_3 \rho^2 \delta + i W (\sigma_1 + \sigma_2) \cdot k \times \delta k' \end{aligned} \quad (2)$$

The parameters have been fitted to the ground states of certain spherical nuclei which includes their binding energies and sizes. In our work we must also include nuclear-pairing and this is accomplished in the constant matrix element approximation.

As examples of our results, Fig 2. shows the prolate axis of the potential energy surface for three nuclei, Os¹⁸⁰(a), Os¹⁹⁰(b) and Os²⁰⁰(c). The curves were calculated with the SKI1 potential and with the pairing strength⁶ previously adjusted to that of Os¹⁹². We have calculated maps for all of the even Osmium in this range. The ordinary or first well ground state occurs in the range of 1500 fm squared and is indicative of a large well defined prolate minimum. The experimental consequences are a rotation spectrum built upon the ground state. Our results are consistent with known experiments and is the subject of a report intended for a nuclear physics audience⁷. More pertinent to the gamma ray laser problem, one sees in (a) an ordinary nucleus, sans second minimum. In (b) and (c) one sees "maps" which display secondary minima in their potential energy curves. This is indicative of the likelihood that a set of states built upon this extremely large deformation exist. The lowest will be a shape isomer.

A more complete study is nearly concluded for the Mercury isotopes⁸. Figure 3 shows the depth of the second well (relative the height of the barrier between the first and second well) for the even isotopes of Mercury between 188 and 218. These calculations were performed for both the standard SKI1 potential and the more modern SKM* potential. While there are no

qualitative differences, the quantitative differences could have profound effects on the measured properties of these states. Figure 4 displays some of the same information and also the energy difference between the first, or ground state minimum, and the second minimum. In the static approximation we have been employing, this is the excitation energy of the isomer relative to the ground state. These calculations have been tested for stability with respect to the value of the strength of the pairing force and with respect to Octopole Deformation. The results were insensitive and must be considered robust.

3. RESULTS

One sees that nuclear theory predicts a plethora of second minima in this region of the periodic table. It is also clear that there is a systematic prediction of variation of the excitation energy of these states along with the dependence on the particular parameterization of the effective nuclear force. The smaller the excitation energy of the hypothesized isomer the more likely it will have a long life time. In Hg^{194} and Hg^{218} one sees nuclei with secondary minima quite similar that of the known fission isomers but of course without a fission channel. Hg^{194} being "nearly stable" would be a most interesting nucleus to study particularly to see the increase in isomeric lifetime from removal of the fission channel. The fact that it "lives" many seconds in its ground state would make it available by current techniques.

We have also predicted secondary minima in several nuclei in the region around Zn^{70} . However, the plethora of minima in the Mercury-Osmium-Tungsten region (several isotopes of the latter also having been studied) makes this a more interesting region to propose as places for experimental test of our theoretical predictions, with Hg^{194} as the most interesting for practical and applied reasons. There are several physical observables in consequence of this structure in the potential energy surface of these nuclei. Besides direct observation of an isomer by delayed gamma emission, they will also cause predictable changes in atomic spectra (analogous to the atomically observed isotope shift but many times larger) and in the gamma ray cascade spectrum in the second well. The latter have been calculated for several nuclei and are displayed in Table I.

Lastly, it is interesting to speculate on the possible relationship between these secondary minima and the recently discovered "super-deformed" bands found in several nuclei. At first blush they might have a different origin as the latter exist only at high angular momentum where the centrifugal stretching has altered the mean field so as to support this region of large deformation at high angular momentum. However, they are both characterized by similar "betas" of approximately 0.6 and therefore have similar shape. The connection is not academic as understanding the one will help us understand the other in such a way as to further predict the existence of shape isomers, whether or not they require rotation to be stabilized.

4. FUTURE WORK

While we will continue static calculations not only to complete the above work but also to look for other regions of secondary minima based upon insights to be gained from analyzing our present results, future calculations are planned in two disparate directions. Calculation of the fission barriers of the actinide elements is technically very difficult but only quantitatively so from our present work. Extending our calculation to that region is not only intrinsically interesting to nuclear physics but also will provide a bench-mark to test the observed fission (shape) isomers against our predictions. However, it is more interesting and potentially more valuable to extend our work beyond the limitations of static Hartree-Fock theory.

There are several ways of including nuclear dynamics as the next stage in this theory. The least subtle and most direct is via a so-called Hill-Wheeler wave function or equivalently Configuration Interaction⁹. In essence, we will assume a more accurate representation of the exact wave function can be reached by choosing a linear combination of Hartree-Fock solutions. Adroitly chosen, these can restore broken symmetries, i.e. restore precise quantum numbers such as angular momentum or in regions where there is no well defined Hartree-Fock minimum, construct a meaningful solution.

In terms of some collective degree(s) of constraint, we will construct

$$\Psi = \int dQ f(Q) \psi(Q) \quad (3)$$

and then extract the expansion coefficients by diagonalizing the two body Hamiltonian

$$H = \sum_{\gamma\beta} t_{\gamma\beta} A_Y^+ A_\beta + \frac{1}{4} \sum_{\gamma\beta\delta} \langle \gamma\beta | v_A | \delta\gamma \rangle A_Y^+ A_\beta^+ A_Y A_\delta \quad (4)$$

This theory subsumes projection and obviates the necessity for the construction of inertial parameters for (quasi) stationary states. With it we will be able to calculate many of the properties of predicted shape isomers. These will include more precise energies, life times and transition rates. Combined with an experimental program enabling us to check and, if necessary, refine these calculations the precise nature of these states will be elucidated and their hypothesized application tested.

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Table 1.

Mass of Hg Isotopes	1st Minimum		2nd Minimum			
	$I_x[\text{u}^2\cdot\text{MeV}^{-1}]$	$E_{2+0}[\text{MeV}]$	$E_{4+2}[\text{MeV}]$	$I_x[\text{u}^2\cdot\text{MeV}^{-1}]$	$E_{2+0}[\text{MeV}]$	$E_{4+2}[\text{MeV}]$
194	96	0.031	0.073	123	0.024	0.057
198	97	0.031	0.072	126	0.024	0.056
202	100	0.130	0.070	130	0.027	0.054
206	105	0.029	0.067	133	0.023	0.053
210	109	0.028	0.062	135	0.022	0.051

Ridged body moments of inertia and predicted rotational band cascade energies for the 1st and 2nd wells of typical Mercury isotopes. While the ridged body moment of inertia is known to be inaccurate for ground state bands, it is accurate for the one second minimum measured [10^4].

Gamma ray shape isomers

Fig. 1. Schematic diagram of the potential energy surface of an idealized actinide nucleus with a fission isomer.

OSMIUM 180-SKIII

Fig. 2. Potential energy surfaces of three Osmium isotopes calculated in the Hartree-Fock approximation. Displayed are cuts along the prolate axis of symmetry. (a) shows Osmium 180 with a well defined highly deformed ground state minimum. (b) shows Osmium 190 also with a deformed ground state and also a second minimum which will likely support a shape isomeric state. (c) is similar to (b) for Osmium 200.

OSMIUM 190-SKIII

$\gamma = 0$ degrees

OSMIUM 200-SKIII

gamma = 0 degrees

Fig. 3. Depth of second minima for several Mercury isotopes whose potential energy wells exhibit the secondary minima shown in Fig. 2-b and 2-c. These have been calculated with two variants of the effective nuclear force, SKIII and SKM* (see reference 5)

Fig. 4. Depth and Excitation energy of the secondary minima in the Mercury Isotopes calculated for SKIII and SKM*. Each nucleus is represented by a double column, the left most SKIII, the right for SKM*. Several exhibit minima a excitation energies well below the particle emission threshold and are candidates for possible long live states with only electro-magnetic decay.