Perspective of Nuclear Structure

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***Abstract*-The perspective of nuclear structure throughout the nuclear landscape, regions of structural transition have provided a sensitive structure. In this paper, some aspects of collectivity means of testing our understanding of nuclear and deformation in nuclear structure are presented, using both theoretical and experimental methods.**

***Keywords:* nuclear structure, nuclear chart, nuclear force, energy levels.**

I. INTRODUCTION

A nucleus is microscopic system contains finite number of interacting fermions packed in an extremely small volume. The nature of the force of holding these fermions together in such a small volume is a mystery yet to be understood completely. In the early days, the nucleus was imagined as a point-like particle characterized by its mass and electric charge only. The development of the quantum world telescopes, (the detector arrays of ever increasing resolution) sophisticated experimental techniques and data analyzing systems have revealed the fascinating world of quantum rotations in atomic nuclei, which revolve at the time-scale of the order of baby-second *(10^{-22}s)*. The basic properties of a nucleus are connected with its size and shape, i.e., the spatial distribution of its constituents. At present, there are enormous numbers of quantal states in various nuclei characterized with spherical, prolate, oblate, triaxial etc. shapes of different symmetries.

The study of the nuclear structure with neutron number (N), proton number (Z) and the mass number (A) provides a deep understanding of nuclear interactions. It is a task of nuclear theory to reproduce changes in nuclear structure with N, Z and energy ratio R_4.

Following are the useful measure of collectivity:

II. THE NUCLEAR CHART

Since the famous alpha ray scattering work of Rutherford [1] one knows that all positive charge of the atom and almost all of its mass is confined at its center. This central core of about 10 fm ($=10^{-14}$ m), surrounded by cloud of electrons is called the nucleus. Later, Chadwick [2] discovered the neutron as a constituent of the nucleus. Heisenberg [3] introduced the concept of isospin, viz. that protons and neutrons are merely two different states of the same elementary particle known as nucleon. This concept is formally similar to the concept of intrinsic spin. The isospin of a nucleon is then T = 1/2 and its projection is Tz = +1/2 for neutrons (n) or Tz = -1/2 for protons (p). A two-nucleon system can then have a total isospin of T = 1 (triplet) or T = 0 (singlet). In the triplet state the projected isospin can either have values of Tz = +1, 0 or -1 for the pp-, pn- or nn-system, respectively. However, only the pn system can appear in the singlet state with Tz = 0, so pn has a T = 0 as well as a T = 1 component. The nucleus is then determined by its charge number Z (i.e. its number of protons) and its number of neutrons N (or its mass number A = Z + N). It is usually noted ${}^{A}_{Z}X_{N}$ with X being the chemical symbol. Today, there are nearly 3000 nuclei known, out of which less than 300 are stable. In a nuclear chart (see figure 1), all these nuclei are drawn corresponding to their Z and N values. In figure 1 such a nuclear chart is shown with the valley of stability indicated in black, the area of known nuclei indicated in yellow and the area where the existence of nuclei is assumed, but not yet confirmed indicated in green (the so-called terra incognita). Today nothing known about terra nuclei, neither experimentally nor theoretically, their existence is essential for understanding the production of heavy mass nuclei.

Since in the early universe only the lightest elements like H and He were present, the production of heavier elements has to be explained by several different nuclear processes. Only elements up to iron can be produced by fusion reactions (burning) in stars (e.g. by the famous CNO-cycle in our sun) and later distributed to the interstellar medium. The production of nuclei beyond iron is due to nuclear capture reactions which have to compete with β-decays.

(i) In the slow neutron capture process (s-process) the neutron capture time τn is larger than the corresponding β-decay time $\tau\beta$, hence this process runs through or close to the valley of stability. The abundances of s-process elements are inversely proportional to the neutron capture cross sections, which is consistent with a steady flow of neutrons.

(ii) The rapid neutron capture process (r-process) occurs in environments with high temperatures and extreme neutron fluxes, e.g. core-collapse supernovae. Here, τn is much shorter than $\tau\beta$. Hence, more and more neutrons are added before the nucleus can decay and the r-process runs through the extremely neutron-rich nuclei far from stability. It is significance mentioning here that this process stalls at nuclei with certain (magic) neutron numbers due to their low neutron absorption cross section. The neutron shell closure at $N = 82$ is supposed to be correlated with the $A \approx 130$ peak in the solar-system abundance of heavy elements.

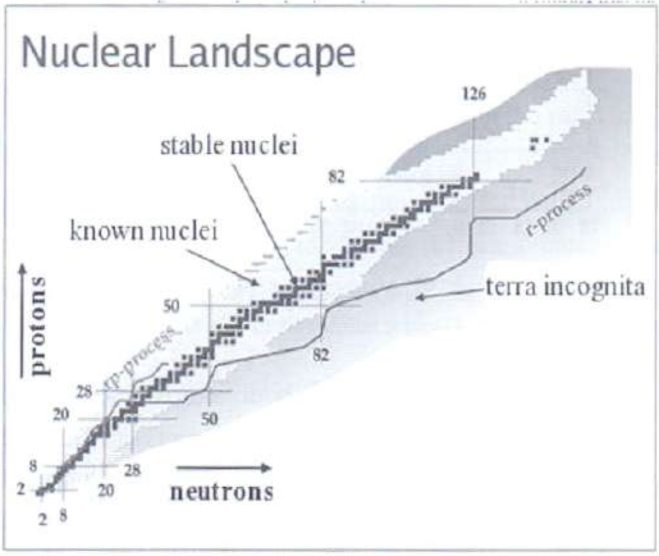

Fig. 1: The nuclear landscape with the valley of stability. Taken from the nndc website [4].

(iii) The rapid proton capture process (rp-process) can occur especially in hydrogen rich environments at high temperatures (Wallace and Woosley, 1981). It is considered to play a substantial role in the production of nuclei on the neutron-deficient side of stability, e.g. it explains very well the observed abundances of neutron-deficient nuclei with $A \leq 100$ (Schatz et al., 1998).

Among the most important nuclear properties for understanding and modeling these processes are nuclear half-lives, separation energies (or masses) and neutron capture cross sections. Since experimental data far of stability is insufficient these properties often have to be deduced from nuclear models. The aim of nuclear structure physics is then to improve these models by gathering further experimental data on these nuclei, describing and interpreting nuclear properties and by probing the interaction between nucleons.

There are two complementary approaches to describe the nucleus:

(i) A microscopic approach, where nucleons are treated as independent particles moving in a central potential arising from the interaction of each nucleon with all other nucleons. One of the simplest such models is the so-called Fermi gas model in which the nucleons are considered as non-interacting particles in a 3-dimensional square well potential. This leads to energy eigen values $E\alpha(n/d)^2$ where n is the radial quantum number and d the size of the well. The total kinetic energy of this system is then $E_{tot}\ \alpha\ (N-Z)^2$ which is consistent with the stable nuclei having $N \approx Z$. For $A \geq 40$ the repulsive Coulomb interaction between the protons leads to a neutron excess. This model can be seen as predecessor of the successful shell.

(ii) A macroscopic approach where the nucleus is treated like a macroscopic (or geometric) object. One of the earliest nuclear models, the liquid drop model (first described by Gamow, 1930), belongs in this category. There, the nucleus is described similar to a drop of an incompressible liquid. The observed masses and binding energies can be well deduced from it (von Weizsacker, 1935). In this model the nucleus has a surface and a shape and excitations can be described in terms of collective vibration and rotation. These ideas are also essential in the collective model by Bohr and Mottelson (1975).

III. PROPERTIES OF NUCLEI AND NUCLEAR FORCE

From the fact that bound nuclei exist it can be seen that there must be an attractive interaction between the nucleons which is stronger than the repulsive Coulomb force between the protons is called the nuclear force. On the other hand, it is known from scattering experiments that the nuclear density is nearly constant. This shows that there must be a repulsive core at very short distances. The volume of the nucleus then has to increase as $V \alpha A$, hence the mean nuclear radius can be defined as $R = R_0 \cdot A^{1/3}$ with R_0 being a constant between 1.2 fm and 1.3 fm. The mass of a nucleus can be expressed as the sum of the masses of the nucleons minus its binding energy

$$M = Z \cdot m_p + N \cdot m_n - E_b.$$

It is interesting to note that for $A \geq 20$the binding energy per nucleon i.e. E_b/A saturates to about 8 MeV (see figure 2). This can be explained by assuming that nucleons interact only with their nearest neighbours, i.e. the range of the nuclear force is only of the order of 1 fm.

The neutron (proton) separation energies S_n (S_p) are related to the binding energy. It is defined as the energy needed to remove a neutron (proton) from a nucleus $^{A}_{Z}X_{N}$ to infinity. Hence, they are equal to the difference in binding energies between $^{A}_{Z}X_{N}$ and $^{A-1}_{Z}A_{N-1}$ ($^{A-1}_{Z-1}A_{N}$). In general, the separation energies decrease with an increasing number of like nucleons and increase with an increasing number of unlike nucleons (figure 3). For certain values of Z or N the separation energies show large and sudden drops. These values turn out to be the so-called magic numbers.

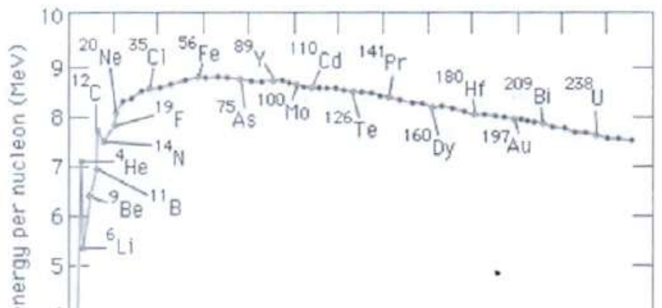

Fig. 2: The variation of nuclear binding energy per nucleon (E_b/A) vs. mass number (A). The saturation and its slight decrease above iron can be seen (2007 Encyclopedia Britannica, Inc.).

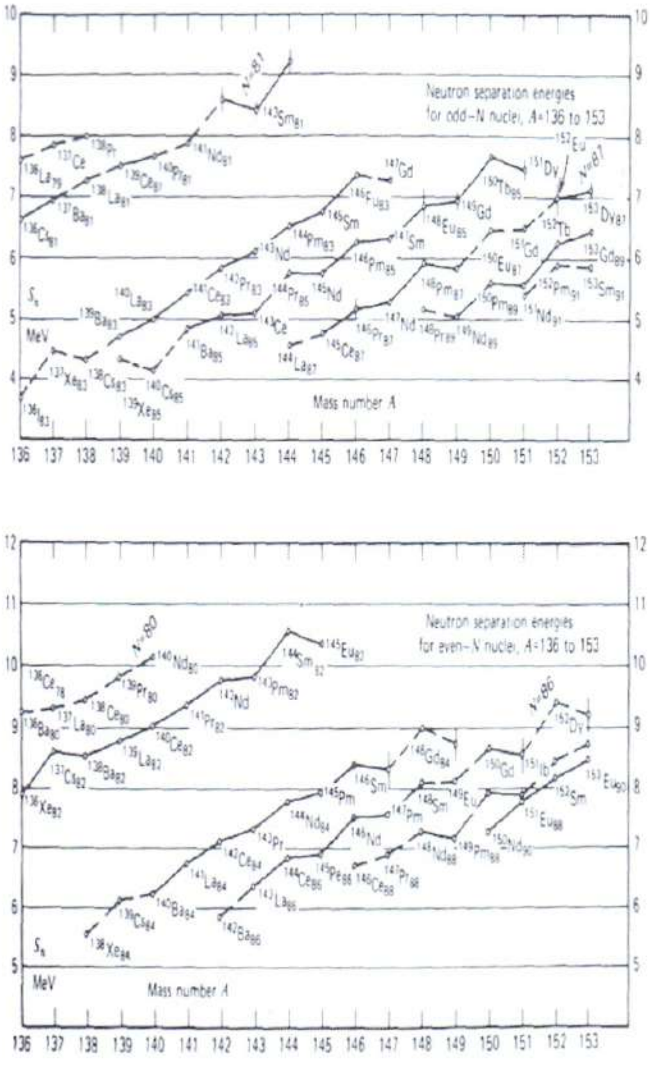

Fig. 3: Neutron separation energies for odd N, and even N, A= 136-153; near the N=82 magic number taken from Casten [5].

A lot of knowledge about atoms was gained by studying their excited states; a lot about nuclear structure can be learned by studying nuclear excited states, their energies, spins and parities. For example, the energies of the first excited states are highest for nuclei with magic nucleon numbers and reach their minimum in the mid-shell region which is another evidence for magicity in nuclei. The behaviour of the separation energies shows that there is a strong attractive p-n-interaction, whereas the residual interaction between like nucleons is repulsive.

However, looking closer at Sn (Sp), an oscillation between odd and even numbers of neutrons (protons) can be seen. This hints to an attractive pairing interaction coupling neutrons (protons) to $I^{\pi} = 0+$. Hence, the ground state in even-even nuclei is always $I^{\pi} = 0+$. More information on the nucleon-nucleon-interaction can be gained from data on mirror nuclei. These are nuclei where the proton and neutron number exchange, e.g $^{27}_{13}Al_{14}$ and $^{27}_{14}Si_{13}$. The similarity of their level schemes (energies, spins and parities of their excited states) suggests that the nuclear force is charge independent, i.e. p-p-, p-n and n-n-interactions are equal. However, this is only true for triplet state (T = 1).

The T = 0 component of the nuclear interaction can be very different. With the example of the deuteron it can be shown that the interaction of two unlike nucleons is more attractive in the T = 0 state than in the T = 1 state [Casten (2000)].

IV. COLLECTIVE BAND STRUCTURE

The low-lying energy levels of the deformed even-even nuclei can be grouped into three bands, namely, ground state rotational band with $I^{\pi} = 0+, 2+, 4+, 6+ ....$, the β - vibrational band with $I^{\pi} = 0+, 2+, 4+, 6+ ....$ and γ - unstable band with $I^{\pi} = 2+, 3+, 4+, 5+, 6+, 7+, 8+ .....$

The Energy Ratio R_4

The energy ratio of nucleus is equal to the ratio of 4^+ state ground energy of the nuclei E_4^+ to the 2^+ state ground energy of the nuclei E_2^+ and denoted by $R_4 = E_4^+ / E_2^+$. The nuclei are divided into different categories depending upon the R_4 values (see fig. 4)

For vibrational nuclei or U(5)	R_4=2.0
For E(5) symmetry	R_4=2.2
For γ-soft nuclei or O (6)	R_4=2.5
For X(5) symmetry	R_4=2.9
For rotational nuclei or SU(3)	R_4=3.33

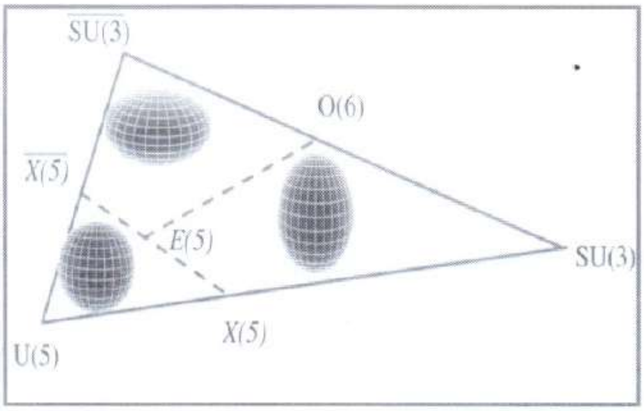

Fig. 4 Casten's symmetry triangle taken from ref. 5.

B. Deformation parameter β

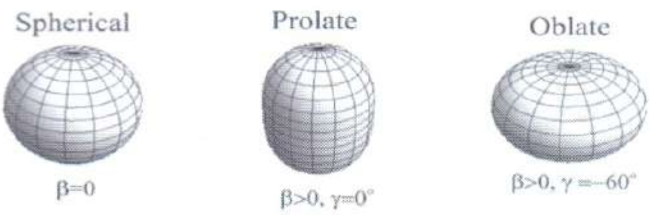

Table 1 Nuclear shapes for different values of γ.

θ	Shapes	Symmetry Axis
0	Spheroid - Prolate	3 - axis
π	Spheroid - Oblate	3 - axis
2nπ/3	Spheroid – Prolate	1 or 2 -axis
(2n+1)π/3	Spheroid - Oblate	
≠ n π/3, where n= integer	Ellipsoid (3 unequal axes along principal axes)	

Three main types of collective structures are discussed here: the spherical vibrator (β = 0), the axially symmetric rigid rotor β > 0, γ = 0°, and the gamma-soft rotor (β > 0, with a flat potential in γ) (see fig. 5). Spherical vibrators are typically found close to the closed shells, and have the ratio R_4= 2. The nuclear shapes for different values of asymmetry parameter (γ) are given in Table. 1

V. CONCLUSION

In this paper, we studied the perspective of nuclear structure in different regions of nuclear landscape and find quick point of view of collectivity and triaxiality of nuclei using the observables; nuclear force, energy ratio(R_4), deformation parameter (β), and asymmetry parameter (γ) through the nuclear landscape.

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