A Unified Approach for Nuclear Structure

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Abstract : The nuclear physics area is plagued by variety of sophisticated models based upon initial ideas of liquid drop model or independent particle shell model. One set of models are used to understand binding energy and fission mechanism while the others are used to understand the nuclear shell structure and its implications. Further, some of the basic assumptions required for these models are apparently contradictory to each other. These models have their limited application area and can be used to account certain nuclear properties only. In present work, an unified approach for nuclear structure is proposed which can account the nuclear binding energy along with the nuclear shell structure for all ranges of nuclei. This model is based upon recent observations and do not use arbitrary assumptions like spin-orbit coupling term. It can be used to calculate various nuclear properties like binding energy, nuclear magnetic moments, quadrupole moments, similar excitation levels for mirror nuclei, emergence of new magic numbers for neutron rich nuclei or correlated two proton/neutron emission. Interestingly, it provides an straightforward explanation for asymmetric/symmetric fission fragment distribution in spontaneous/low-energy fission events for heavy nuclei. Although, the proposed model is supported by many experimental evidences, further suggestions are given for verification of the approach.

1. Introduction

Soon after the discovery of neutron, there had been a 20 years rapid progress phase in the area of nuclear physics. It resulted in development of liquid drop model and shell models which provided important insight into the nucleus properties and shaded some light on nucleon-nucleon interaction. But these models have their limited phase-space of applications and even for a single nucleus, different models are required to account for the different nuclear properties. The unsatisfactory state of affair in nuclear physics is reflected by the wide range of different competing nuclear models, appearing to explain some of the nuclear properties with their own set of parameters and assumptions [1]. Sometimes, even the basic set of assumptions, required to formulate these models, are contradictory to each other. For example, liquid drop model allows very small or no nucleonic motion while independent particle shell model requires smooth nucleonic motion for well defined quantum orbits. The independent particle shell model assumes independent protons and neutrons moving in average nucleonic potential while one of basic assumption of Interactive Boson Model (IBM) is the formation of valence nucleonic bosons [2] i.e. nucleons are not moving independently but in form of boson pairs. On the other hand, many of the basic assumptions required to formulate apparently successful nuclear models have never been explained properly. For example, the origin of spin-orbit coupling term used in independent particle model can not be related to the magnetic moment of nucleons due to very low magnetic moment of protons and neutrons (which is lower by a factor of 10^3, compared to electrons). Similarly, very long mean free path required for formation of well defined shells in independent particle model is not supported by experimentally observed very low mean free path of nucleons inside nuclear medium [3].

The basic reason for large number of nuclear models is the poorly understood, complex nucleonic interaction. The widespread expectation that the progress in particle physics would illuminate the nucleonic interaction was never fulfilled. Further, there is growing set of unexpected observations which are not explained (and were not anticipated) by any of these nuclear models. These new observations are not only illustrating the limitations of present array of nuclear models, these are providing the vital clues for the underlying nucleonic interactions and structure too. Some of these observations are discussed in section 2 and are used for motivating a different but realistic approach for nuclear structure in section 3. The proposed new approach for nuclear structure can be implemented to understand various nuclear properties and phenomena. The proposed approach can be used to understand the binding energy per nucleon curve, mirror nuclei properties, appearance of new magic numbers for neutron rich nuclei, magnetic dipole moments, quadruple moments etc.

Interestingly, the present approach can be used to understand the nature of spontaneous (or initiated by low energy) fission fragment distribution for different nuclei. Even after 70 years of research and modeling, mass and charge distribution of fission fragments is still a unresolved problem in nuclear physics [3,4,5]. A simple application of the model can provide accurate prediction about the mass and proton distribution of fission fragments for all fissionable nuclei. The asymmetric fission of Actinide nuclei [3,4], the transition from symmetric to asymmetric fission with variation for neutron number for Actinide nuclei [4], symmetric fission for nuclei below Actinide range [5] and unexpected observations of asymmetric fission for Hg^{180} nucleus [6] can be understood as simple implications of the model.

Although, the present approach for nuclear structure is verified by range of observations, further possible observations are suggested in section 5. These observations can provide further insight into nuclear forces and nuclear structure. Finally, the summary and future outlook are discussed in section 6.

2. Motivations for a new approach:

Most of the present nuclear models are based on independent particle model in which protons and neutrons are considered to be moving, independently, in a mean field created by all other nuclei. On the other hand, many experimental and theoretical developments in nuclear physics area are clearly advocating for a new approach for the nuclear structure. Some of these observations are discussed below.

1. Short Range Correlation of Nucleon: From earlier models of nuclear structure, it is expected that nucleon are moving independently in different shells and there can not be any correlation in their space-time locations inside nuclei and even if there exists a small nucleon-nucleon correlation, it would be quite similar for n-p, n-n or p-p cases. Direct measurements for nucleon-nucleon correlations have been carried out at Brookhaven National Laboratory [7] using proton beam and Thomas Jefferson National Accelerator Facility using about 5 GeV electron beam [8,9]. Interestingly, Brookhaven analysis demonstrated that the removal of a proton from the carbon nucleus is 92 % (+8 to -18%) of the time accompanied by the emission of a correlated neutron that carries momentum roughly equal and opposite to the initial proton momentum [7]. Even cleaner experiments of Jefferson Lab have demonstrated that at least 95% protons and neutrons are forming short-ranged correlated pairs in nuclei ranging from carbon to lead [8,9]. However, in these experiments only n-p and p-p correlations can be measured and n-p-n or p-n-p correlations measurements have not been performed [8,9].

Using the above discussed measurements, It is straightforward to infer that the large fraction of nucleons are in strong short-range correlations inside nuclei and n-p short-range correlated pairs are the most dominating one. In fact, observed fractions of p-p or n-n short-range correlated pairs are almost zero with some experimental uncertainties. Fraction of experimental measured n-p and p-p correlated pairs are compared in figure 3 of [9], where it can be seen that almost all of correlated pairs are in n-p form and p-p fraction is almost negligible. Hence, it can be concluded from these measurements that protons and neutrons are not moving independently inside nuclei but rather as n-p short-ranged quasi-particles. In these measurements, three nucleon n-p-n correlation was not measured.

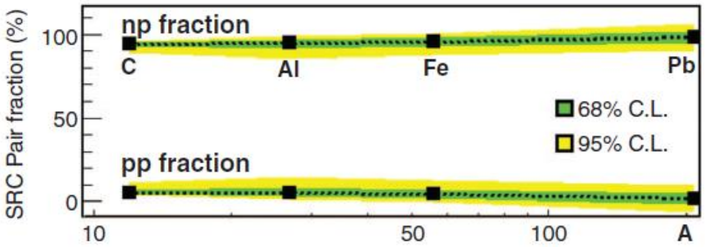

Figure-1: Measured n-p and p-p correlated fraction for C, Al, Fe and Pb nuclei. The n-p fraction form almost 100% of the observed correlated pairs. The green and yellow bands reflect 68% and 95% confidence levels. Figure is taken from [9].

Another indirect indication about the non-availability of independently moving protons (or existence of short-ranged n-p or possibly, n-p-n correlated quasi-particles) inside nuclei comes from experimental observations of unexpectedly low cross-section in A(e, e'p)A-1valance shell knock-out reaction at electron scattering facilities like NIKHEF and SACLAY [10,11]. The independent particle model calculations result in significantly higher cross-sections for single proton knock-out reactions compared to measured one. Continuous existence of protons in n-p or n-p-n states may be a plausible reason behind these observation which would increase the ejection of two (in correlated n-p) or three nucleon (in correlated n-p-n) while suppressing single proton ejection.

2. EMC effect : In independent particle shell model, free nucleons are assumed to be moving non-relativistically under the influence of a mean field generated by mainly NN interactions. Hence, in the rest frame of the nucleon, the partonic structure functions of free and bound nucleons should be identical. The parton structure functions measured by the Deep Inelastic Scattering (DIS) experiments should be quite similar for all the nuclei (except for additional Fermi motion effects). Contrary to this expectation, parton structure functions of the bounded nucleon were found to be significantly different from that of unbound nucleons or from nucleons inside loosely bound Deuteron. This effect was first discovered by European Muon Collaboration and hence named as EMC effect [12].

Usually, DIS cross section ratio of nuclei relative to deuterium as a function of Bjorken x_p (or X_B) are plotted to estimate the EMC effect. The measured ratio is found to differ from the expected ratio (taking into account only Fermi motion of nucleons inside heavier nuclei). Since the nucleon Fermi motion effect are considered to be negligible up to x_p ~ 0.7, a ratio of unity, up to x_p ~ 0.7, is expected. The experimental results indicate that the structure function of free nucleon and of nucleon bounded in nuclei (except loosely bound nuclei like Deuteron) are significantly different [13]. These results can not be explained by usual independent shell models where pion exchange model would not affect nucleon structure functions. Interestingly, linear relation between the EMC effect and short-range correlations has been found [13] which indicates that EMC effect may be due to formation of n-p (or probably due to n-p-n also, if these also exist) quasi-particles inside nucleus.

It appears that neutron and protons are not moving independently in effective potential but are paired (in n-p and n-p-n quasi-particles) and those pairs are moving in effective Coulomb potential due to all other n-p and n-p-n quasi-particles

3. Neutrino Interaction with nuclei : Another independent confirmation of presence of correlated nucleons inside nuclei (and absence of single or independent nucleons) comes from quasi-elastic scattering of neutrino from different nuclei. The measured quasi-elastic scattering cross-section and its variation with neutrino energy is significantly different from the cross-section calculations based upon independent particle shell model [14,15]. The discrepancy disappears, after considering the possibility of multi-nucleon ejection into the neutrino interaction models [15]. Hence, energetic neutrino knock-out not just single nucleon (which should have been the case if independent particle model would have represented the reality of nucleonic motion inside nucleus) but more frequently, at least two nucleons are ejected [15] simultaneously, indicating about the formation of short-range correlated nucleon quasi-particles.

4. Independent Boson Model: Although, Independent Boson Model (IBM) has very different set of motivation [2] and complex parameterization, underlying success of variant of IBM model (IBM1, IBM2, IBM3, IBM4) is the assumption of formation of boson like structures by valance nucleons for even A nuclei. Interestingly, for odd A nuclei, additional interaction term between bosons and fermions H_{BF} term is added to the Hamiltonian. Physically, these assumptions are equivalent to formation of two particle (for even A) and three particle (for odd A) short-range correlated quasi-particles.

5. Correlated nucleon emissions from proton and neutron rich nuclei: Correlated emission of proton pairs are reported from proton rich nuclei [16]. Similarly, correlated neutron pair emission are also observed from neutron rich nuclei [17]. These measurements also indicate about the existence of short-ranged nucleonic correlation inside nuclei.

6. Binding energy per nucleon curve : Variation of binding energy per nucleon with increasing number of nucleon also provide strong indication about the underlying mechanism of nuclear forces. The binding energy per nucleon curve saturates quickly, reaches at maximum for Fe and Ni and after that, it decreases due to increasingly higher Coulomb energy for higher Z nuclei. Successful binding energy modeling for different nuclei is carried out using liquid drop model which consider main contribution proportional to number of nucleon and other terms dependent on nucleus surface, Coulomb energy, energy due to asymmetry in proton and neutron number and pairing energy [18]. Vary good agreements between calculated binding energy using liquid drop model and measurements is quite striking. The measured binding energy deviation from liquid drop model predictions are quite small even for magic nuclei. These results are strange because nucleus is inherently quantum system and almost same amount of binding energy (after taking care of Coulomb energy) is not expected for a wide range of nuclei for A = 4 to 238. In independent particle models (which uses a mean field potential approach), shells are separated by significant energy (of the order of few MeV) and nucleons are filled progressively. Hence, almost same binding energy, from He to Uranium isotopes, can not be explained using independent particle models. It can be concluded from the success of liquid drop model (and from the failure of independent particle shell model) in explaining the nuclear binding energy that most of the binding energy for the nucleons is independent of the particular shell of the nucleon. Nucleon can be in s, p, d, f or g shell, still it is bounded by almost similar amount of energy. This simple fact demands for an alternative approach for the nuclear forces and nuclear structure.

There are many other important clues about the nature of nuclear interaction. There is only one nucleus with two nucleon (Deutron), containing one proton and one neutron with spin 1 and binding energy per nucleon just above 1 MeV. There are two nuclei for A = 3, He^3 and H^3, with almost similar binding energy per nucleon (less than 3 MeV/nucleon). But, for He^4, binding energy per nucleon becomes more than 7 MeV/nucleon. Taking clue from short-range correlation measurements (and other independent sources as discussed above), it can be inferred that the He nucleus can be assumed as system of two n-p quasi-particles. The neutron-proton binding in Deuteron and in He^4 nucleus is quite different. In Deuteron, neutron and proton wavefunctions are moving around the center of mass of two nucleon system but in He^4, n-p quasi-particles are also moving in average Coulomb well due to second n-p quasi-particle. The presence of Coulomb well in He^4 is localizing the wavefunctions of proton and neutron, resulting in better overlapping of nucleonic wavefunctions in n-p quasi-particles. This results in much higher binding energy/nucleon in He^4. The wavefunction localization and efficient overlapping of nucleonic wave-functions resulting in formation of strongly bounded n-p quasi-particles, would happen in heavier nuclei too.

3. Model and its implication on nuclear properties

Using the above discussed experimental and theoretical developments, some assertions can be drawn which can be used to form a unified approach for the nuclear structure

(a) Neutrons and protons do not move independently inside nucleus. They always form (depending upon number of protons and neutrons) n-p, n-p-n and p-n-p type quasi-particles. These quasi-particles move inside the overall Coulomb well (due to all other moving quasi-particles). At least one proton and one neutron is required to form a stable quasi-particles inside nucleus. So, quasi-particles like p-p, n-n do not exist inside nucleus. But, more than two neutron can attach with a proton (of course, with significant lower binding energy per nucleon in this case) to form heavier quasi-particles (for example, 3n-1p quasi-particle can be formed by three neutron and one proton). Spin of n-p quasi-particle is 1, while for n-p-n and p-n-p quasi-particles spin is 1/2.

The main contribution of nucleonic binding energy is coming from the formation of tightly bound short-range correlated nucleonic quasi-particles inside overall Coulomb well of nucleus. This would result in similar amount of binding energy/nucleon for a wide range of nuclei except for low mass nuclei where insufficient Coulomb well results in lower binding energy/nucleon. The overall binding energy per nucleon of a nuclei will depend on Coulomb energy and pairing of quasi-particles too (pairing energy).

Further, it appears that binding per nucleon is highest in n-p quasi-particle, followed by n-p-n and p-n-p (where extra Coulomb energy comes into picture) quasi-particles. This would be equivalent to an asymmetric energy term of liquid drop model in neutron rich (or in proton rich) nuclei where many n-p-n (p-n-p) quasi-particles would be formed.

The formation of these quasi-particles may be due to the internal charge structures of neutron and proton [18]. Net negative and positive charge structures of neutron (due to moving charged partons inside), invite us to consider the possibility of electromagnetic interaction with charged partons making proton structure. It is a wrong to consider that the nuclear forces can not be of electromagnetic in nature because neutron is neutral. If two neutral molecules can have van der Waals interaction, two neutral atoms can form covalent bonds, proton and neutron (with their extended charged parton structures) can certainly have strong electromagnetic interaction. Since the sizes of proton and neutron are of the order of $\sim 10^{-15}$ m (with even smaller sizes for constitute partons), electromagnetic coupling of charged structures inside proton and neutron can be a viable reason for their strong coupling and high binding energy. Moreover, just like van der Walls force in atoms and molecules, such a force would be a complicated function of direction and would depend on higher powers of separation distance between neutron and proton which is in accordance to the observations for nuclear forces. Further, n-p-n and p-n-p quasi-particles are also viable (with slightly lower binding energy for p-n-p, due to higher Coulomb energy). It is interesting to note that, such a mechanism can provide qualitative reasoning behind EMC effect without any additional assumption. The nucleonic structure function inside Deuteron and heavy nuclei will be different because rearrangement of partons (inside nucleon) is necessary for higher binding energy in heavy nuclei.

The role of overall Coulomb well is quite critical in nuclei. It help in localization of n-p, n-p-n or p-n-p quasi-particle wave functions leading to efficient overlapping of neutron and proton wavefunctions. This results in higher neutron and proton binding energy in n-p quasi-particles (compared to Deuteron). Moreover, it stops the leaking of alpha particles, formed by pairing of two n-p quasi-particles.

(b) If even number of quasi-particles are present inside a nucleus, they will pair to give 0 spin and magnetic moment values. For odd number of quasi-particles, last unpaired quasi-particle will decide the spin and magnetic moment of nucleus. There are four possible combinations of proton and neutron for different nuclei.

Even-even nuclei : For even-even nuclei, all the neutrons and protons are in the form of n-p and n-p-n quasi-particles which themselves will form pairs with spin 0. The extra energy due to pairing and symmetry will results in higher binding energy. For example, O^{16} will have 8 n-p quasi-particles (2 in 1s and 6 in 1p sub shell), Si^{28} will have 14 n-p quasi-particles, Si^{30} will have 12 n-p quasi-particles along with 2 n-p-n pairs, Ca^{40} will have 20 n-p quasi-particles and Ca^{48} will have 12 n-p and 8 n-p-n quasi-particle. The first excitation energy for these nuclei will be higher as addition energy will be required for breaking pairs of n-p or n-p-n quasi-particles. Since similar amount of energy will be required to break a n-p quasi-particle pair in a different even-even isotopes of a nucleus, it can be reflected in quite a similar first excitation levels for those isotopes. For example, many even-even isotopes of Sn and Cd have very similar first excitation states. Major portion of the excitation energy is due to the pairing energy of n-p quasi-particles, resulting in almost similar amount of first excitation states for even-even isotopes of Sn.

Odd-even nuclei : In these nuclei, last odd proton will be bounded in a n-p-n quasi-particle. For example, Al^{27} will have 12 n-p and 1 n-p-n quasi-particle. Low level excitations for such a nuclei should be due to last n-p-n quasi-particle.

Even-odd nuclei : This type of nuclei must have one unpaired p-n-p as and will be less favored compared to even-even nuclei. For example, C^{13}, B^{9}, Si^{29}, Fe^{57} etc.

Odd-odd nuclei : These nuclei must have unpaired n-p quasi-particle and thus be least stable. Only few of the stable odd-odd nuclei exist.

It is interesting to see the variation of relative number of proton and neutron for heavier nuclei. Up to Z = 20, many nuclei with equal number of proton and neutron are stable but beyond ^{40}Ca, there is no stable isotope with equal number of neutron and proton and additional neutrons are found in heavier stable nuclei. Apparently, after ^{40}Ca, addition of n-p quasi-particle in new shell is avoided, while n-p-n quasi-particle is preferred. The lower mass unpaired n-p quasi-particle in last sub-shell would have much higher probabilities for Coulomb barrier penetration (due to exponential dependence on mass of particle) compared to n-p-n and hence avoided. The higher mass nuclei need to have more and more n-p-n quasi-particles or higher neutron/proton ratio for stability. For example, Sn have stable isotopes between ^{112}Sn to ^{124}Sn (or extra neutrons between 12 to 24), while Pb have stable isotopes between ^{204}Pb to ^{208}Pb (or extra neutrons between 40 to 44). Interestingly, after Pb, even n-p-n quasi-particles find it difficult to sustain in new shells (due to increasing higher Coulomb repulsion from core) and next island of stability appears around ^{238}U, which is simply addition of 10 n-p-n quasi-particles to ^{208}Pb nuclei (probably, fully filled d-shell is added to ^{208}Pb nucleus). It is really surprising that there are same number of n-p quasi-particles in ^{112}Sb, ^{208}Pb and ^{238}U (38 in each).

The n-p wavefunction in Coulomb well will be more spread (or less localized) due to lower mass of n-p quasi-particle compared to n-p-n, thus, an unpaired n-p-n quasi-particle will be preferred over n-p for an unpaired last proton in a odd Z nuclei. Hence, Most of the stable odd Z nuclei will come with even number of neutrons. Similarly, extra pairing energy in even-even nuclei will lead to more stable nucleus. Hence, odd-numbered elements tend to have fewer stable isotopes compared to even Z nuclei. There are 25 odd Z nuclei which have only one stable isotope, while only one even Z nucleus have single stable isotope (Be^{9}). All of these 25 stable isotopes for odd Z nuclei have even number of neutron, indicating better stability for unpaired n-p-n, compared to n-p quasi-particle. Similarly, no odd-numbered element has more than two stable isotopes, while every even-numbered element (with stable isotopes), except for helium, beryllium, and carbon, has at least three stable isotopes.

Unification of Liquid Drop and Shell Model approaches : The above discussed approach provides an unified approach for nuclear structure. It can be used to estimate the binding energy per nucleon as well as the nuclear properties dependent on shell formation. Since the main contribution of binding energy is coming from formation of quasi-particles of nucleon (n-p, n-p-n or p-n-p), very similar binding energy per nucleon is expected from He to heaviest know nuclei, with systematic corrections due to Coulomb energy and pairing term (due to pairing of quasi-particles). Moreover, slightly lower value of binding energy per nucleon for n-p-n quasi-particles, compared to that of for n-p quasi-particle can result in asymmetric energy term. The spikes in binding energy per nucleon in low mass nuclei are expected as addition of extra nucleon affects the overall quantum well significantly, thus affecting the extent of overlapping of nucleonic wavefunctions in quasi-particles and hence, affects the binding energy per nucleon value. These binding energy spikes are iron out in heavier nuclei where additional nucleon do not produce a significant change in the overall Coulomb well. Higher per nucleon separation energy is expected for completely filled shells due to symmetric wavefunction, thus leading to magic nuclei behavior for certain nuclei. moreover, the last unpaired quasi-particle should decide the magnetic moment and spin of nuclei.

Mirror Nuclei: Mirror nuclei have very similar excitation levels and binding energy (after taking care of Coulomb energy). For example, ${}_{17}Cl^{35}$ and ${}_{18}Ar^{35}$ are two mirror nuclei with odd A. Since the binding energy and spin of last unpaired quasi-particles is similar for these nuclei (n-p-n in Cl and p-n-p in Ar), excitation levels and their spin will also be very similar. Similar reasoning can be applied for other mirror nuclei. Excitation levels for even A mirror nuclei, for example C^{14} and O^{14}, will be also similar due to similar number of quasi-particles. C^{14} will have 4 n-p and two n-p-n quasi-particles while O^{14} will have 4 n-p pairs and 2 p-n-p pairs.

Magic number for neutron rich nuclei: The closure of a particular shell will result in extra binding energy for n-p as well as n-p-n quasi particles. For example, O^{16} will be a magic nuclei. The 1s, 1p shells can accommodate 8 n-p quasi-particles, resulting in 8 as magic number. Interestingly, 16 can be a magic number for neutron in Oxygen nuclei as 8 n-p-n quasi-particles will also form a closed shell. Similarly, 14 can also be a semi-magic number for neutron in Oxygen as this will be equivalent to 2 n-p in 1s shell while 6 n-p-n in 1p shell (closed). These simple implication of present model have been confirmed by measurement [19]. Similarly, 20 will be a magic number for Ca^{40} (20 n-p quasi-particles) but 20 will not be magic number for ${}^{32}Mg$ as it will be equivalent to 4 n-p and 8 n-p-n quasi-particles with 4 n-p quasi-particles in 1s and 1p, shells will not be closed (if 8 n-p-n are filled in1s and 1p shells, remaining 4 n-p quasi-particles will make it non-magic). This is confirmed by measurements also [20]. Similarly, ${}^{42}Si$ (with 28 neutrons) will not be a magic nuclei [21] as it has 14 n-p-n quasi-particles which are not filled in closed shells. Hence, present model can provide a straightforward explanation for new magic numbers in neutron rich nuclei without introduction fictitious terms like spin-orbit coupling.

Higher magic numbers like 50, 82 and 126 should be due to completely filled shells of n-p and n-p-n quasi-particles and must be produced without additional assumptions like spin-orbit terms etc. But the detailed shell configurations can be assigned only after solving Schrodinger equation for the effective Coulomb well (due to all n-p and n-p-n quasi-particles). This problem is not considered in the present work.

Magnetic moments: As expected, magnetic moment of even-even nuclei will be zero while the magnetic moment of odd-even, even-odd and odd-odd nuclei will be due to the unpaired n-p-n, p-n-p and n-p quasi-particles respectively. Since, total mass and charges of these quasi-particles are different, g_l factors for these quasi-particles will be different. On the other hand, g_s factor would be the net magnetic moment of nucleons inside a quasi-particles. Since proton and neutron spins are aligned in n-p quasi-particle, g_s factor for n-p quasi-particle should be about 1.76 (sum of proton and neutron g_s factors), if there is no significant rearrangement of partons inside neutron and protons when they are bounded in quasi-particles. The neutrons (protons) spin in n-p-n (p-n-p) quasi-particles are apposite, thus canceling their magnetic effect. It would lead to g_s factors of 5.59 for n-p-n and -3.83 for p-n-p quasi-particles. The list of g_l and g_s factors for these quasi-particles is given below.

Quasi-particle	g_l	g_s
n-p	1/2 (due to ~ $2m_p$ mass)	1.76
n-p-n	1/3 (due to ~$3m_p$ mass)	5.59
p-n-p	2/3 (due to ~1/3 mass and 2 unit of charge)	-3.83

It is interesting to note that there is non-zero g_l factor for even-odd nuclei (having unpaired p-n-p quasi-particle) as opposed to independent particle motion in which g_l should be zero for last unpaired nuclei. Similar to independent particle model, present approach would give two lines for $j = l+s$ and $j = l-s$ for odd-even and even-odd nuclei. Additionally, it can be used to calculate the magnetic moment for odd-odd nuclei too (due to unpaired n-p quasi-particle, for example in ^{6}Li).

Quadruple moment : The nuclear quadrupole moment provide an estimation of departure from the spherical charge distribution. The independent particle model predicts only negative quadrupole moments (slightly oblate shape nuclei) for odd proton nuclei. For even-odd nuclei, there should not be any (or very small and negative) quadrupole moment as neutron is overall neutral particle [22]. But, the observed nuclear quadrupole moment defy the expected trends from independent particle model estimates. Most of the nuclei have positive quadrupole moments, much higher in magnitude compared to predicted values and only nuclei just after the shell closure (or magic numbers) show negative quadrupole moments which are near to the single particle values [22]. Even many of the odd neutron nuclei show much higher (compared to single particle estimates) and positive quadrupole moments. The very high quadrupole moments in the mid-shell nuclei must be due to cumulative effect of many nucleons [22].

In the present approach, since neutron is always accompanied by one (in n-p quasi-particle) or two (in p-n-p quasi-particle) protons, even-odd neutron nuclei will also have quadrupole moments. The odd-even and even-odd nuclei, just after magic number or shell closure will have negative quadrupole moments. For magic nuclei, the charge distribution is spherical but an additional quasi-particle will be creating an additional disk of charge with spin perpendicular to it. This would result in a oblate shape nuclei with negative quadrupole moment. The transition of quadrupole moments from negative (which correspond to oblate shape of nuclei), just after magic number, to large positive (highly deformed prolate shape nuclei) can be understood using two simple things. First, the quasi-particles in a shell will form pairs and the overall spin of nuclei is decided by last unpaired quasi-particle. Second, as already discussed in the present section, these quasi-particles will try to be in deepest possible Coulomb well (for better coupling of nucleonic wavefunctions). Hence, geometrically nearest orbitals of semi-filled shells will be filled progressively, elongating the nuclear shape and the plane of last unpaired quasi-particle would be more and more tilted w.r.t. the elongation axis. Since, the orbital angular momentum is perpendicular to particle plane, overall spin of last unpaired quasi-particle (and hence nuclear spin) will be aligned with elongation axis. This is equivalent to formation of prolate shape nucleus with large positive quadrupole moment (compared to single particle values) [23].

Spontaneous fission products: The fission of heavy nuclei is one of the most widely studied nuclear process. The fission events initiated by low energy particles or transitions or without any energy are termed as spontaneous fission. It proceeds by correlated nucleonic oscillations, formation of two lobes and neck shape connecting them (during which nucleonic exchange between two fragments can take place) and finally, separation of two fragments. A straightforward application of liquid drop model predicts symmetric mass distribution for two separating fragments while some modification of mass distribution due to slightly more stable magic nuclei, is expected in shell model analysis [3].

But the dominating mode of spontaneous fission for most of Actinide nuclei is asymmetric fission in which unequal mass fragments [3,4] are produced. The larger mass fragment contains about 140 nucleon (averagely) while the remaining nucleons (except few neutrons) are contained in the smaller fragment. The most probable protons in larger fragments are from 52 to 56 (with negligible fraction of magic nuclei Z = 50!). For some other Actinide nuclei (with less number of neutrons), symmetric fission mass distribution is more dominating one and a transition from symmetric to asymmetric fission, with increasing number of neutrons has been reported [4]. For example, a systematic transition, from dominating symmetric fission to asymmetric fission has been observed (shown in figure 3 of [4]) for Pa^{224} to Pa^{232} isotopes.

The spontaneous fission measurements for Hg isotopes, Hg^{198} and Hg^{180} are even more baffling. The fission fragments mass distribution for Hg^{198}, along with many other pre-Actinide nuclei, has been found to be symmetric [5]. From the fission measurements on pre-Actinide nuclei and the explanation offered for the observed fission distribution [6], symmetric fission distribution is expected for $A \leq 195$. For Hg^{180}, symmetric fission should be preferred due to additional weak shell effect in ${}_{40}Zr^{90}$. Surprisingly, mass distribution for Hg^{180} fission events is strongly asymmetric [6].

The evolution of fission fragment mass distribution with variation of neutrons and atomic number is not just a simple curiosity. The spontaneous fission fragments indicate about the underlying nuclear *substructures* (before separation) which survive the stochastic and chaotic nucleonic rearrangement during fission event. Any good nuclear model is expected to explain the spontaneous fission mass distribution without any additional assumption. Interestingly, the mass distribution of fission fragments for all the nuclei can be predicted using the present framework, without any additional assumption.

Since the nuclei are composed of mainly n-p and n-p-p quasi-particles, any excitation of heavy nuclei will initiate collective oscillations of these quasi-particles. Now, due to the different masses of n-p and n-p-n quasi-particles, oscillation time for n-p and n-p-n quasi-particles will be different, resulting in two separate lobes made up of entirely n-p and p-n-p quasi-particles. These lobes will be connected by neck formation and exchange of nucleons would take place between n-p and n-p-n quasi-particle lobes (spontaneous fission is a very slow process compared to time taken by quasi-particle to a complete one orbit) . Now, neutron exchange process (compared to proton exchange) between two lobes would have much higher probability as neutron exchange is not hindered by Coulomb barriers of n-p and n-p-n lobes. This would result in shifting of many neutrons (depending upon the stability requirements of n-p lobe) from the neutron rich n-p-n lobe to n-p lobe, while only few (or no) protons will be shifted from proton rich n-p to neutron rich n-p-n lobe. Moreover, protons (neutrons) can not be transferred from neutron(proton) rich n-p-n (n-p) quasi-particle lobe. Interestingly, this simple picture explains the fragment mass distributions for the entire range of spontaneous fission or fission events initiated by low energy excitation.

Lets us consider, U^{236} (U^{235} excited by one neutron capture) nucleus, in which there are 52 n-p-n quasi-particles (with total mass number 156) and 40 n-p quasi-particles (with total mass number 80). The collective oscillations in this nucleus would result in the formation of n-p-n and n-p quasi-particles lobes, connected by neck formation. Many neutrons would flow from n-p-n to n-p lobes and only few protons can be transferred from n-p to n-p-n lobe (due to Coulomb barrier of lobes). Now, the most stable isotopes for Z = 36-40 have about 10-14 extra neutrons (compared to number of protons) while most stable isotopes for Z = 52-56 have 20-26 extra neutrons. But, total number of extra available neutrons in n-p-n lobe is 52, resulting in shift of about 18-20 neutrons to n-p lobe, while only few of the protons will be shifted from n-p to n-p-n lobe (say 0 to 4 protons). This will result in mass of about 140 for the heavier lobe after separation and mass of about 92 for lighter lobe (assuming evaporation of few neutrons during neutron exchange from n-p-n to n-p lobe). Interesting, this simple picture at once explain the predominate presence of the nuclei with Z = 52 to 56 in heavier mass fragments and asymmetric nature of U^{236} fission. This also explain the absence of Sn isotopes, despite expected from the extra stability of the shell structure, in fission fragments. It is quite unlikely, even with the statistical nature of fission events, that protons will be shifted from neutron rich n-p-n lobe to proton rich n-p lobe.

Similar analysis can be made about fission process of any other nuclei. For example, Cf^{250}, in which there are 54 n-p-n and 44 n-p quasi-particles. During the spontaneous fission event heavier neutron rich n-p-n lobe will be of mass number 156 and n-p lobe will be of mass number 88. Again transfer of neutron from neutron rich n-p-n lobe to n-p lobe will lead to asymmetric fission with heavier fragment of Z = 54-58 and mass number about 140. The presence of extra 4 protons in n-p lobe (compared to U^{236} case), would allow shift of 20-24 neutrons from n-p-n lobe to n-p lobe. These conclusions are in excellent agreements with the observations [3].

Now, let us consider the transition of predominately asymmetric to dominantly symmetric fusion mass distributions for Pa^{232} to Pa ^{224} isotopes. As shown in the table below, Pa^{232} have 50 n-p-n and 41 n-p quasi-particles, resulting in mainly asymmetric fission mass distribution. On the other hand, there are only 42 n-p-n and 49 n-p quasi-particles in Pa^{224}. Shift of about 20-24 neutrons from n-p-n to n-p lobe and shift of few protons from n-p to n-p-n lobes would results in almost symmetric mass fragments as observed [4]. Of course, for Pa isotopes with mass number from 232 to 224, transition from asymmetric to symmetric fission mass distribution will take place and can be analyze used similar picture. Similarly, one can easily explain the systematic transition from symmetric to asymmetric fission mass distribution with increasing numbers of neutrons for Th isotopes also (measurements are shown in [4]. Hence, the fission mass distribution simply depends on relative number of n-p and n-p-n quasi-particles.

The same analysis can be used to understand the symmetric nature of fission mass distribution for most of the nuclei below Actinide nuclei as observed in [5]. For example, in Hg^{198}, there are 38 n-p-n quasi-particles and 42 n-p quasi-particles. The n-p-n and p-n lobes have similar number of protons and shift of neutrons from n-p-n and shift of few protons from n-p lobe would result in symmetric distribution of fission fragments. This is confirmed by observations too.

Similarly, it is straightforward to predict the nature of fission mass distribution for more exotic nuclei like Hg^{180}. There are only 20 n-p-n quasi-particles (with total mass number of 60 for n-p-n lobe), while there are 60 n-p quasi-particles (with total mass number of 120 for n-p lobe). The neutrons shift from neutron rich n-p-n lobe to n-p lobe and proton shift from proton rich n-p to n-p-n, will result in asymmetric mass distribution for fission fragment. Exactly similar observation have been reported [5].

Hence, it can be seen that the apparently puzzling observations of fission mass distribution of various nuclei are in fact, straightforward to understand. The present approach can explain and provides a simple picture, without any additional assumption, about the fission events of wide range of nuclei. A summary table about the observed and predicted fission mass distribution is given below.

Nucleus	Proton Number	Neutron Number	n-p-n quasi-	Mass of n-p-n quasi-	n-p quasi-	Mass of n-p quasi-	Observed Fragment	Predicted Fragment

			particles	particles	particles	particles	Distribution	Distribution
Pa^{232}	91	141	50	150	41	82	Asymmetric	Asymmetric
U^{236}	92	144	52	156	40	80	Asymmetric	Asymmetric
Pu^{240}	94	146	52	156	42	84	Asymmetric	Asymmetric
Am^{243}	95	148	53	159	42	84	Asymmetric	Asymmetric
Cm^{244}	96	148	52	156	44	86	Asymmetric	Asymmetric
Cf^{250}	98	152	54	162	44	86	Asymmetric	Asymmetric
Pa^{224}	91	133	42	126	49	98	Dominating Symm.	Dominating Symm.
At^{213}	85	128	43	129	41	82	Symmetric	Symmetric
Hg^{198}	80	118	38	114	42	84	Symmetric	Symmetric
Hg^{180}	80	100	20	60	60	120	Asymmetric	Asymmetric

Further, few general conclusions can be drawn from the present proposed approach. First, it can provide an easy justification for the IBM approach of considering two and three nucleon quasi-particles for valance nucleons. Second, formation of tightly bound quasi-particles, by parton rearrangement, would lead to significant change of form factors of nucleons inside tightly bound nuclei (compared to free nucleons), thus leading to EMC like effect. Third, the proton rich nucleus like ^{23}Al will have more than one p-n-p quasi-particles and eager to shake off some protons to reach the more stable nucleus. It can simply eject two correlated protons from an p-n-p quasi-particle [16]. Forth, the present approach can resolve the awkward situation faced by independent particle model which needs very long mean free path for well defined nucleonic orbits but the observed mean free path of nucleons is very short (which is justified by continues pion exchange model between moving nuclei). In the present approach, only nucleons forming a quasi-particles are affected by nuclear force (arising from the parton rearrangements of nucleons), but these quasi-particles are moving inside the overall Coulomb well. Such positive charged quasi-particles will not collide with each other (similar to the case of multi-electron atom, where electrons do not collide with each other), resulting in well defined shells. In present approach, there is no need to invoke the picture of continuous pion exchange between moving nucleons. Here, nuclear forces are considered as the residual interaction of constituent partons of nucleons forming a quasi-particle. In such a system, incoming nucleons will have short mean free path but still a quasi-particle will move without colliding with other quasi-particles. Fifth, in independent particle shell model, the phenomenological potentials (for example, Wood-Sexon potential) used to calculate the nuclear shells is quite different from the nucleon-nucleon potential calculated from scattering experiments. But in the present approach, nucleon-nucleon interaction, leading to the formation of short-ranged quasi-particle must be short ranged and spin dependent as observed in nucleon-nucleon scattering experiments. Of course, shells of quasi-particles will be defined by overall Coulomb potential.

4. Possible tests of current approach

The most straightforward test for the current approach would be to perform the quasi-elastic scattering experiments using electron beam (which is a cleaner tool compared to proton/neutron beams) and analyzing the ejected nucleons. To measure the relative abundance of n-p, n-p-n and p-n-p quasi-particles inside the nuclei, three particle and four particle coincidence experiments are required which can identify outgoing electron, proton (protons) and neutron (neutrons). Unfortunately, the current detector system in Jafferson lab can perform three particle coincidence experiments to identify the presence of n-p quasi-particles (which it has done nicely). A 4π detector system (along with a electron accelerator facility) with capability to identify the outgoing electrons, protons and neutrons can be a ideal tool to investigate the numbers of n-p, n-p-n and p-n-p quasi-particle in various nuclei. Similar experiments can be performed using intense neutrino beams in facility like Fermi lab but identification of the outgoing nucleon after deep inelastic scattering even by neutrino would be a challenging task.

Even with the current detector system in Jafferson lab, it should be possible to verify the relative abundance of n-p and n-p-n quasi-particles using energetic electron beam. The energy and angular correlations between the neutron and proton coming from n-p quasi-particles will be slightly different from the neutron and proton originating from n-p-n quasi-particles. The energy and angular profile of correlated neutrons and protons coming out of nuclei like Ca^{40} (where only n-p quasi-particles are possible) must be different to that of nuclei like Pb^{208} (where n-p and n-p-n quasi-particles are present in similar amount).

5. Summary and future outlook

There exists a range of nuclear models based upon the ideas of liquid drop model and independent particle models. But, each of these models can be used to account only certain nuclear properties for selected nuclei and even for a single nucleus, different models are need to understand the different nuclear properties. None of the present nuclear model provides a unifying view of nuclear properties and observables. Further, there is variety of new and old experimental results in nuclear physics which can not be explained using any existing model. Some of such observations are discussed in the present paper too.

For progress of nuclear physics research, there is an urgent need to develop an unified approach for nuclear structure which can used to understand the nuclear features explained by liquid drop model as well as by models based upon independent particle picture. The new approach must be able to resolve, or at least provide a qualitative picture for the puzzling observations like asymmetric/symmetric fission fragment mass distribution for different nuclei, observation of short-ranged correlated neutrons and protons, EMC effect, success of IBM, almost constant binding energy per nucleon, interaction of neutrino with nuclei etc.

Using the various experimental and theoretical developments, it has been proposed that nucleons are moving as tightly bound n-p, n-p-n and p-n-p quasi-particles in overall Coulomb well due to all other quasi-particles. The Coulomb well helps in better localization of nucleonic wavefunctions and thus increase the extent of overlapping of neutron and proton wavefunctions. The main portion of observed binding energy is coming from the binding of nucleon in these quasi-particles, thus resulting in almost constant binding energy per nucleon from ^{4}He to heaviest observed nuclei (after considering extra Coulomb energy).

The proposed approach can be used to explain many of the nuclear properties like quadrupole moments, magnetic moment, mirror nuclei properties etc. Further, it can be used to justify the approach of independent particle model. It provides a straightforward explanation for the observed fission mass distribution. Hence, the present model provides an unified approach for understanding the various nuclear properties described by liquid drop model and shell model approaches. It automatically resolves many of the puzzling experimental results and provides further insight in nuclear forces.

The present paper discuss the new approach for nuclear structure and its ramifications in a qualitative way only. To explore the finer details of the current approach quantitatively, coherent and sustained efforts from nuclear physics community will be required.

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