Two-Proton Knockout Cross Section $\sigma_{-2p}(^{44}S \rightarrow ^{42}Si)$: Strong Evidence of Magicity and Sphericity of $^{42}_{14}Si_{28}$

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Abstract

The issue of whether $^{42}_{14}Si_{28}$ is doubly magical or not has been a contentious one. Fridmann *et al.* (Nature 435 (2005) 922) through studies of two-proton knockout reaction $^{44}_{16}S_{28} \rightarrow ^{42}_{14} Si_{28}$, presented a strong empirical evidence in support of magicity and sphericity of $^{42}_{14}Si_{28}$. However in complete conflict with this, Bastin *et al.* (Phys. Rev. Lett. 99 (2007) 022503) gave equally strong empirical evidences, to show that the N = 28 magicity had completely collapsed, and that $^{42}_{14}Si_{28}$ was a well deformed nucleus. At present the popular consensus (Gade *et al.*, Phys. Rev. Lett. 122 (2019) 222501) strongly supports the latter one and discards the former one. Here, while we accept the latter experiment as being fine and good, through a careful study of an RMF model calculation, we show that actually the experimental results of Fridmann are also independently good and consistent. As per the Fridmann experiment, the sphericity and magicity of $^{42}_{14}Si_{28}$ is manifested only through proton number Z=14 being a strong magic number, while the neutron magic number N=28 disappears (or goes into hiding); and still this nucleus is spherical. This is a new and amazing property manifesting itself in this exotic nucleus $^{42}_{14}Si_{28}$. In this paper we provide a consistent understanding of this novel reality within a QCD based model. This model, which has been successful in explanation of the halo phenomenon in exotic nuclei, comes forward to provide the physical reason as to why the Fridmann experiment is correct. This QCD based model shows that it is tritons, as elementary entity making up $^{42}_{14}Si_{28}$, which then provides consistency to the above amazing conclusions arising from the Fridmann experiment.

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The issue of whether ${}^{42}_{14}Si_{28}$ is magical or not has been a contentious one. Within a backdrop of conflicting claims as to the double magicity of ${}^{42}_{14}Si_{28}$ (see [1,2,3] for details), Fridmann *et al.* [1,2], through studies of two-proton knockout reaction ${}^{44}_{16}S_{28} \rightarrow^{42}_{14} Si_{28}$, presented a strong empirical evidence in support of magicity and sphericity of ${}^{42}_{14}Si_{28}$. However in complete conflict with this, Bastin *et al.* [3], gave equally strong evidences, but based on different empirical informations, to show that the N = 28 magicity had completely collapsed, and that ${}^{42}_{14}Si_{28}$ was a well deformed nucleus. So a priori there is a conundrum. However, the majority consensus at present is that, the latter experiment, indicating a strongly deformed ${}^{42}Si$, has completely demolished the previous experimental result which had supported magicity and sphericity of the same nucleus [4]. So finally the conclusion of magicity and sphericity of ${}^{42}Si$ as per Fridmann *et al.* [1.2] has been discarded.

A. Gade *et al.* as per their very recent paper, entitled "Is the Structure of ${}^{42}Si$ Understood?" [4], their final conclusion was unambiguously in the negative. As to the result by Fridmann *et al.* [1.2], Gade *et al.* clearly stated [4] that, "These speculations were resolved by the first successful spectroscopy of ${}^{42}Si$ [they quoted Ref. [3] here], revealing a surprisingly low-lying first 2^+ state, at $E(2^+) = 770(19)$ keV, the onset of collectivity, and the breakdown of the N=28 magic number in ${}^{42}Si$".

Now what are the "speculations" referred to in the above statement? As to theory one basic assumption is that [5], "In the shell model, the nucleus is actually described by two separate set of shells, one for protons and one for neutrons". Thus we call the nucleus ${}^{48}_{20}Ca_{28}$, as doubly magical because both the proton number Z=20 and the neutron number N=28 are separately magical. The next major assumption we make in the context of the study of exotic nuclei, is that the same proton and neutron remain the only relevant degree of freedom. Thus for our case here, ${}^{42}_{14}Si_{28}$ would be doubly magical only when both Z=14 and N=28 are separately and simultaneously magical, in such a neutron rich nucleus where triton degree of freedom stands out.

Now let us revisit the experimental result of Fridmann *et al.* [1,2]. What they essentially explored was the amazing persistence of the unique exotic nucleus ${}^{42}_{14}Si_{28}$ as a stable structure within the nucleus ${}^{48}_{20}Ca_{28}$; even after stripping off six-protons through the isotonic chain: ${}^{48}_{20}Ca_{28} \rightarrow^{46}_{18} Ar_{28} \rightarrow^{44}_{16} S_{28} \rightarrow^{42}_{14} Si_{28}$. Thus it is the novel stability of proton shell closure at Z=14 in ${}^{42}_{14}Si_{28}$, which is playing such a dominant role in ensuring its double magicity within ${}^{48}_{20}Ca_{28}$. Fridmann *et al.* [1], through studies of two-proton knockout reaction ${}^{44}_{16}S_{28} \rightarrow^{42}_{14} Si_{28}$, presented a strong empirical evidence in support of magicity and sphericity of ${}^{42}_{14}Si_{28}$. Thus the dominant role of magicity of Z=14 was basic. As such this experiment [1] was not making any direct statement about the magicity of the corresponding neutron number at N=28. However, on the basis of the above mindset [5], one had to make an extra assumption of independent existence of a stable neutron structure at N=28, to be able to treat this nucleus as being doubly magical. The role of the neutron number N=28 as to the magicity and sphericity of ${}^{42}_{14}Si_{28}$, was actually studied in their next paper [2]. where they showed [2] that reducing the shell gap for N=28 did not affect the two-proton knockout cross section. This fact is well known, e.g. as acknowledged by Jurado *et al.* [6], "However, in a more recent article it was recognized that the two proton knockout cross section populating ${}^{42}Si$ **is not sensitive** to the size of the N=28 gap".

Note that the insensitivity of N=28 magic number to the stability and sphericity imposed at proton number Z=14, is a completely new and unexpected reality of the structure of ${}^{42}_{14}Si_{28}$. The above word "insensitive" may now be taken to mean that here the neutron magic number N=28 has actually become inoperative, or that it has gone into hiding.

Now in as much as what the two-proton knockout reaction cross section, as studied by Fridmann *et al.* [1,2], leads to the above clear and direct conclusion; and which is that this strong shell closure of proton number at Z=14 is so dominant that it leads to extra stability, magicity and sphericity of ${}^{42}_{14}Si_{28}$, and that the same is independent of the neutron magic number, and which for this phenomenon, goes into hiding. Thus what Fridmann *et al.* have found is a new and novel structure of the exotic nucleus ${}^{42}_{14}Si_{28}$, and which goes beyond our conventional understanding of nuclear structure. In this paper we present a consistent understanding of this unique new property of ${}^{42}_{14}Si_{28}$.

But this novel property of ${}^{42}_{14}Si_{28}$ has been missed so far, mainly due to the dominating influence of the assumption that proton and neutron were the only degrees of freedom even in the exotic nuclei. Hence the strong desire to have neutron magicity imposed onto the magicity of ${}^{42}Si$, played the spoilsport. The fact that simultaneously there was another experiment [3], that showed the same nucleus as displaying strong deformation at N=28 through the study of a low lying 2^+ state, added to the confusion.

Thus it was difficult to disentangle the two experiments as actually displaying two different but simultaneous and coexisting realities. This point is consolidated by Jurado *et al.* [6] who in studying the masses, state in the Abstract that, "Changes in shell structure are observed around N=28 for

P and S isotopes but not for Si. This may be interpreted as a persistence of shell closure at N=28 or as the result of very sudden onset in deformation in ^{42}Si". Thus the two options may actually coexist simultaneously - to provide the essential duality here. In this paper we study the physical reality as manifested by the experiment of Fridmann *et al.*, from the two-proton knockout cross section $\sigma_{-2p}(^{44}S \rightarrow ^{42}Si)$ [1.2]. The other experiment, showing deformed ^{42}Si by Bastin *et al.*[3], shall be focus of a future paper.

We shall use the remarkable papers by Piekarewicz, Todd-Rudel and Cottle [7,8], which will help us unveil the actual reality of the underlying physics to be extracted from the experiments by Fridmann *et al.* [1,2]. In this paper, we shall find that ultimately the theoretical basis will be found from within the ambit of a Quantum Chromodynamics based model. This model will be shown to supply us with a consistent understanding of this puzzle.

Recently, one of the authors (SAA) has shown [9] that the fusion experiment [10,11] of an incoming beam of halo nucleus ^{6}He with the target nucleus ^{238}U, actually provided strong and unambiguous evidence that the structures of the target nucleus (having standard nuclear density distribution described with canonical RMS radius r = $r_0 A^{\frac{1}{3}}$ with $r_0 = 1.2$ fm) was completely different from that of the "core" of the halo nucleus, which does not follow the standard density distribution with the above RMS radius. In fact the core has the structure of a tennis-ball (bubble) like nucleus, with a "hole" at the centre of the density distribution. This provides us with a clear-cut support for our model of the halo nucleus [12]. This Quantum Chromodynamics based model [13,14], had succeeded in identifying all known halo nuclei and made clear-cut predictions for new and heavier halo nuclei, and which were subsequently confirmed empirically [9,14].

One point we would like to emphasize here - that right from the first proposal of the QCD based model in 2001 [12], and later [9,14], SAA had made unique prediction that the nucleus $^{42}_{14}Si_{28}$, is a clear tennis-ball (bubble) like nucleus with a hole at the centre of its density distribution.

The Fermi distribution matches the nuclear density distribution,

$$\rho(r) = \frac{\rho_0}{1 + \exp(\frac{r-c}{a})} \tag{1}$$

Here parameter c is defined as where the density comes down to $\frac{\rho_0}{2}$, with ρ_0 as the density at the centre; the surface thickness parameter $s = 4.40a \sim 2.40\ fm$. This standard nuclear density distribution is described by the canonical RMS radius r = $r_0 A^{\frac{1}{3}}$ with $r_0 = 1.2$ fm.

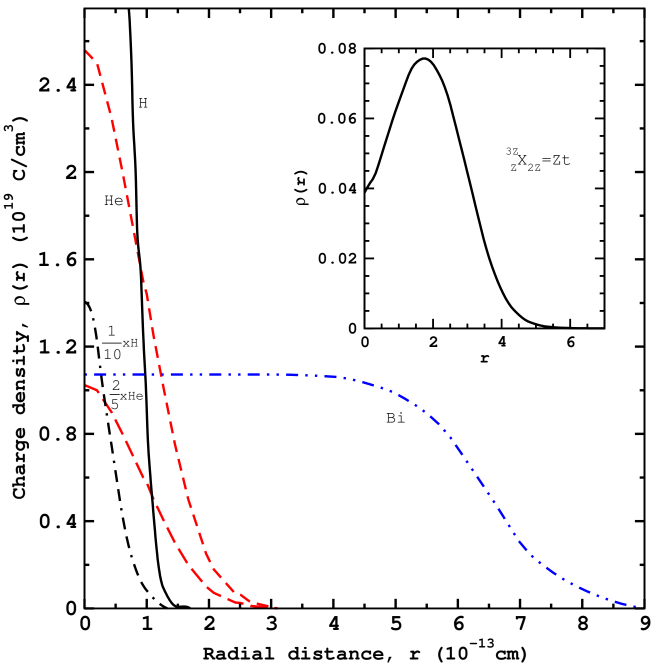

Figure 1: Schematic density distribution of nuclei as determined by electron scattering. Inset (t for triton) shows the same with a marked "hole" at the centre as that of the core of the halo nucleus, and what is called a tennis-ball (bubble) like structure. Note the basic difference between the two

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The density of the above target nucleus is clearly given by the above Fermi distribution. This is shown typically like that of say, bismuth in Fig. 1. But as per the conclusion of paper [9], the core of the halo-nucleus density distribution is clearly unlike it, and this has a hole at the centre, as shown schematically in the inset of Fig 1. So the core of the halo-density density distribution is fundamentally different from that of the standard target nucleus, What degree of freedom may explain this? In the paper [9], it was shown that this new degree of freedom was the triton. The neutron rich core nuclei ${}^{3\mathrm{Z}}_{\mathrm{Z}}\mathrm{X}_{2\mathrm{Z}}$, are made up of Z ${}^{3}_{1}H_2$ clusters, and these created the tennis-ball like structure as shown in the inset of Fig. 1. It is not made of simple proton and neutrons, but of clusters of tritons, treated as elementary entities.

Hence let us treat all ${}^{3\mathrm{Z}}_{\mathrm{Z}}\mathrm{X}_{2\mathrm{Z}}$ nuclei as being a bound state of Z-number of tritons (${}^{3}_{1}H_2$). Viewed in this manner, the relevant degrees of freedom are tritons which are treated as "elementary" entities.

In analogy with the fact that we know as per mean field concept, that a bunch of protons and neutrons in a nucleus, would create an average binding potential for each nucleon, we assume that a bunch of tritons in a nucleus too would create an average binding potential for each triton in a nucleus. It is such a potential, which is binding tritons in these neutron rich nuclei with ${}^{3\mathrm{Z}}_{\mathrm{Z}}\mathrm{X}_{2\mathrm{Z}} = Z{}^{3}_{1}\mathrm{H}_2$; that is, these nuclei are made up of Z number of tritons.. Thus we extract one-triton separation energies of these pure triton constituent nuclei. Let us define

$$S_{1t} = \mathrm{B}({}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}_{2\mathrm{Z}}) - \mathrm{B}({}^{\mathrm{A}-3}_{\mathrm{Z}-1}\mathrm{Y}_{2\mathrm{Z}-2}) - \mathrm{B}({}^{3}_{1}\mathrm{H}_2) \tag{2}$$

where, $\mathrm{B}({}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}_{\mathrm{N}})$ is the binding energy of the nucleus ${}^{\mathrm{A}}_{\mathrm{Z}}\mathrm{X}_{\mathrm{N}}$. Recently we have conducted a comprehensive theoretical study within the ambit of the field of the RMF model structure with three good and successful interactions. We predicted [15] six prominent magic nuclei: ${}^{24}_{8}\mathrm{O}_{16}$, ${}^{60}_{20}\mathrm{Ca}_{40}$, ${}^{105}_{35}\mathrm{Br}_{70}$, ${}^{123}_{41}\mathrm{Nb}_{82}$, ${}^{189}_{63}\mathrm{Eu}_{126}$ and ${}^{276}_{92}\mathrm{U}_{184}$.

The experimental binding energies[16] are not available beyond $\mathrm{N}_t = 17$ bound systems. Our prediction of double magicity of nucleus ${}^{24}_{8}O_{16}$, has been shown to hold good by Kanungo *et al.* [17]. We also made unique prediction, of magicity for ${}^{60}_{20}Ca_{40}$, and which has since then been confirmed by Tarasov *et al.* [18]. These thus gave strong empirical support to our model.

However as our focus in this paper is the issue of magicity of ${}^{42}_{14}Si_{28}$, we concentrate on the study of nuclei in the vicinity of this nucleus. In Fig 2 we display our RMF result with NL3 interaction along with the presently

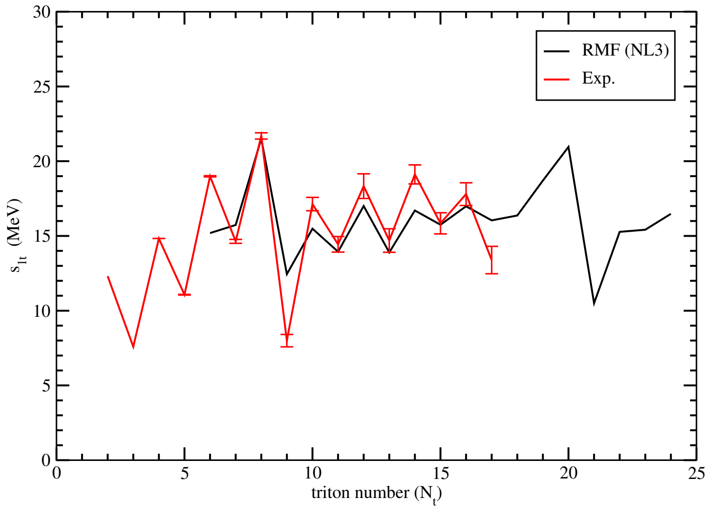

Figure 2: Triton separation energy [15]

available experimental data [16] also. Note the clear RMF model prediction of magicity of ${}^{24}_{8}O_{16}$ and ${}^{60}_{20}Ca_{40}$.

However, on closer scrutiny of the structure between the two extremes of the strongly magical nuclei: ${}^{24}_{8}O_{16}$ and ${}^{60}_{20}Ca_{40}$, we notice a prominent broad hump or "plateau of stability". We may treat this hump as a broad "peak" of stability, and take it as all those being magical, and so justifiably call it a "plateau of magicity". This plateau of magicity is being defined by the two boundary towering peaks of magicity at $N_t = 8 \;=\; {}^{24}_{8}O_{16}$ and $N_t = 20 \;=\; {}^{60}_{20}Ca_{40}$ respectively. However equally significant, in defining this plateau of magicity, are the two boundary nuclei manifesting themselves as extremely-deep-trenches at $N_t = 9 \;=\; {}^{27}_{9}F_{18}$ and $N_t = 21 \;=\; {}^{63}_{21}Sc_{42}$. Thus both the boundary states, of the two towering peaks, and of the two deep trenches, provide a physically identifiable character of magicity and stability to the whole range of nuclei, Z = 10, 12, 14, 16 and 18.

However, this is not the first case of such a plateau of magicity in nuclear physics. This particular plateau of magicity has striking resemblance to a pretty old plateau of magicity/stability, first pointed out by one of the authors SAA in 1984 [19]. In that paper [19] diverse experimental information was analyzed to show that each one of the N=82 isotones, with Z = 58, 60, 62, 64, 66, 68 and 70, are all amazingly doubly magic nuclei.

However, even in that plateau of stability of N=82 isotones, one particular nucleus was somewhat special in one particular aspect of magicity, and which distinguished it from the other members of the plateau. And that was the isotope of gadolinium ${}^{146}_{64}Gd_{82}$. This particular nucleus existed at the "center" of the N=82 magicity plateau. The lowest excited state in even-even nucleus generally is 2^+ state. However, in the case of ${}^{146}_{64}Gd_{82}$, the lowest excited state was 3^-. Only, the doubly magic nucleus ${}^{208}_{82}Pb_{126}$ has 3^- as its lowest excited state. In fact this parallelism between ${}^{146}_{64}Gd_{82}$ with ${}^{208}_{82}Pb_{126}$, was what prompted people to start treating the former as a potential doubly magic nucleus.

Also here too, within our "plateau of magicity", in Fig. 2, there appears, a slight kink ("slight", in the context of the large towering peaks at ${}^{24}_{8}O_{16}$ and ${}^{60}_{20}Ca_{40}$), at ${}^{42}_{14}Si_{28}$, and which is somewhat more stable than the nuclei surrounding it, viz ${}^{36}_{12}Mg_{24}$ and ${}^{48}_{16}S_{32}$. This is also placed at the centre of its plateau of magicity. Thus ${}^{42}_{14}Si_{28}$ should be considered as more of a doubly magic nucleus than the other members of the plateau of magicity. Thus this provides an understanding of the extra magicity and sphericity of ${}^{42}_{14}Si_{28}$ and which has been brought out by the experiments of Fridmann *et al.*[1,2].

Now how do we understand the extra stability, magicity and sphericity of ${}^{42}_{14}Si_{28}$ and as exhibited in the experimental results of Fridmann *et al.* [1,2]? It has been a long standing paradigm in nuclear physics that the central potential is proportional to the ground state baryon density and a spin-orbit potential proportional to the derivative of the same central potential. Remarkably Todd-Rudel, Piekarewicz and Cottle [7] found that the dramatic decrease in spin-orbit splitting as seen in exotic nuclei is not caused by the neutron density in the nuclear surface but by proton density in the nuclear interior. In that paper [7] they found within RMF model calculations with NL3 interaction, that as two-protons are removed from ${}^{48}Ca \rightarrow {}^{46}S$, the standard density of ${}^{48}Ca$ (e.g. as in Fig. 1 for nuclei like Bismuth) quickly transforms into a hole-like nucleus for ${}^{46}S$ itself. But this fails to reproduce the basic putative property of the amazing persistence of the nucleus ${}^{42}_{14}Si_{28}$ as a stable structure within the nucleus ${}^{48}_{20}Ca_{28}$.

What is the reason for the RMF model with NL3, to have failed to reproduce this essential property of ${}^{42}_{14}Si_{28}$. Piekarewicz realized [8] that this had to do with the fact that the NL3 interaction was failing to produce the $1d^{\frac{3}{2}} - 2s^{\frac{1}{2}}$ proton gap in ${}^{40}Ca$, in the first place. It gave a proton gap of only 0.83 MeV, while experimentally it was about 2.8 Mev. So he tweaked the

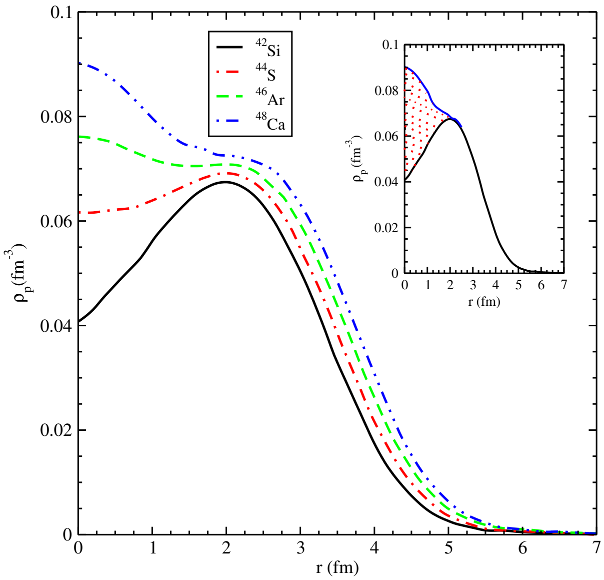

Figure 3: Point proton density of N=28 isotonic chain - schematic plot from Fig. 4 of [8]

NL3 parameters slightly, in a minimal manner, so that this basic problem of the Calcium-chain was rectified.

Right away he could get consistent point proton density distribution of all the nuclei in the basic six-protons stripping isotonic chain: ${}^{48}_{20}Ca_{28} \rightarrow {}^{46}_{18}Ar_{28} \rightarrow {}^{44}_{16}S_{28} \rightarrow {}^{42}_{14}Si_{28}$. We reproduce his Fig. 4 [8], as our Fig. 3 here. In the inset we show how this is almost equivalent to stripping six-protons from ${}^{48}_{20}Ca_{28}$ itself.

Most significant is that the density distribution of ${}^{42}_{14}Si_{28}$ has a hole at the centre. So it looks like a tennis-ball (bubble) like nucleus. This is a most direct confirmation of SAA's original predictions of 2001 [12], and discussed in detail in [9]. This confirms our above discussion of the extra stability and sphericity of ${}^{42}_{14}Si_{28}$.

Most remarkably Piekarewicz was thus able to explain physically as to what was happening in the experiment by Fridmann *et al.* [1]. First the study of proton single particle spectrum of RMF model calculations in the chain ${}^{40}_{20}Ca_{20} \rightarrow {}^{48}_{20}Ca_{28} \rightarrow {}^{42}_{14}Si_{28}$, showed near degeneracy of proton orbital

$1d^{\frac{3}{2}} - 2s^{\frac{1}{2}}$ in ${}^{48}_{20}Ca_{28}$, and the emergence of a strong Z=14 gap in ${}^{48}_{20}Ca_{28}$, and which persisted robustly in ${}^{42}_{14}Si_{28}$ [see his [8] Fig. 1].

Next, most amazing was how the neutron single particle spectrum behaved. Best to quote him [8], "Yet the present relativistic mean-field model **predicts** that as protons are progressively removed from the $1d^{\frac{3}{2}} - 2s^{\frac{1}{2}}$ orbitals, $1f^{\frac{7}{2}}$ neutron orbit returns to its parent fp-shell- leading to the disappearance of the magic number N=28. Thus in the present model the proton removal is ultimately responsible for the return of the $1f^{\frac{7}{2}}$ neutron orbit to its parent shell".

This disappearance of the N=28 magic number is exactly what Fridmann *et al.* had extracted experimentally [1,2] as we had discussed above. We had noted the remarkable insensitivity of N=28 magic number to the stability and sphericity imposed at proton number Z=14. We had suggested that this new physical process may now be taken to mean that here the neutron magic number N=28 has actually become inoperative or that it has gone into hiding.

We have seen how Piekarewicz paper [8] is able to explain and justify the empirical conclusions of Fridmann *et al.* work [1,2]. However that work has been ignored [4]. Note Gade *et al.*'s paper title, "Is the Structure of ${}^{42}Si$ Understood?" [4]. Several of the authors of [4], who discarded the results of Fridmann *et al.* [1,2], were also co-authors of that same paper too. In fact Piekarewicz as a co-author of another later paper [20], with the title, "Bubbles in ${}^{34}Si$ and ${}^{22}O$?", though talked of hole/bubble structure of ${}^{46}Ar$ as given in their first paper [7], however ignored his own work [8] on hole/bubble in ${}^{42}Si$ in that paper [20]. So unfortunately, both Fridmann *et al.* experiments [1,2] and its explanation within the work of Piekarewicz [8], has been rejected and/or ignored as of now.

Now as to the sphericity and magicity of ${}^{42}_{14}Si_{28}$, its manifestation through only the proton number Z=14, and disappearance of the magic number N=28, is extremely puzzling. So far we have been used to talking of sphericity and magicity when both the proton and neutron numbers are separately and simultaneously magical. However here we are being compelled by the empirical reality, to talk of sphericity and magicity of ${}^{42}_{14}Si_{28}$ where only proton number Z=14 shell closure is playing a role, while the corresponding neutron number magic number N=28 has disappeared and gone into hiding. This demands an understanding within our theoretical picture of nuclear physics.

Indeed, this is being provided by SAA's work of 2001 [12] and discussed recently [9]. This QCD based model had predicted that ${}^{42}_{14}Si_{28}$ has the structure of a tennis-ball/bubble like nucleus. Also it was made up of fourteen-tritons. Now triton has the structure ${}^{3}_{1}H_2$. Thus 14-tritons are a bound state in a potential binding these tritons as elementary entities. This nucleus is an extra-bound state as it is closing the triton-shell orbital $d^{\frac{5}{2}}$ at triton-number $N_t = 14$. This is the same as proton number Z=14, and thus this is what is seen in our shell model analysis. As to neutrons, however, as each triton has two neutrons hidden inside a triton (similar to the way that 2-u and 1-d quarks are hidden inside a proton inside a nucleus), in all 28-neutrons are hidden inside the 14-tritons in this magical and spherical tritonic nucleus ${}^{42}_{14}Si_{28}$. Thus physically relevant is only one magical number $N_t = 14 \sim Z = 14$. And it is tennis-ball/bubble like at that. Most important that this model predicts the hidden-ness of the N=28 neutrons within the 14-tritons. Thus our model is able to give a consistent understanding and thus justification of the experimental result of Fridmann *et al.* [1,2].

In summary, ${}^{42}_{14}Si_{28}$ is made up of $N_t = 14$ number of tritons. This is the same as the number of protons making up this exotic nucleus. This one degree of freedom triton-shell model, needs this triton number to close the $d^{\frac{5}{2}}$ orbital. The neutrons here are hidden inside these 14-tritons and thus physically they go out of contention in this case. So we may actually treat these 14-tritons as 14-quasi-protons, with the same charge as protons but each being much heavier due to the two neutrons hidden within its guts. Thus ${}^{42}_{14}Si_{28}$ is magical and spherical too. Most significantly, it has a hole at the centre of its density distribution. This is exactly what Fridmann *et al.* [1,2] have found experimentally.

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