On the stability and the similarity of $N = 82$ isotones

P. Arumugam, S.K. Patra, and A. Abbas

Institute of Physics, Sachivalaya Marg, Bhubaneswar - 751 005, India.

Here we study the stability and the similarity of all even $58 \leq Z \leq 70$, $N = 82$ isotones. We confirm the two decades old study of one of the authors (AA) regarding the extra-ordinary stability and the similarity of these nuclei. We present here a new evidence which shows very strongly the said magicity of those nuclei and as such there exists a new “plateau” of magicity. Three well studied theoretical models which have been successfully applied in nuclear physics are used here to study the above phenomena. None of these model is able to reproduce the similarity and the doubly magic character of these nuclei. Therefore this hints at “new physics” in these $N = 82$ isotones.

PACS numbers: 21.10.Dr, 21.10.Tg, 21.60.-n, 21.60.Fw

The $N = 82$ isotones display a high level of regularity and thus have been of great interest to both the experimentalists and the theorists (1,2,3,4,5). Though there have been claims that $Z = 64$ Gd isotope was something special, through systematic study of diverse empirical data, it was argued by one of the authors (AA) that there was a whole “plateau” of stability for all even $58 \leq Z \leq 70$, $N = 82$ isotones and that as such all these be treated as doubly magic nuclei (6). Also all these nuclei were found to be strikingly similar to each other (1). The idea of “changing magicities” was rather novel then. However today, one does speak of changing magicity for low mass nuclei, for example new magic numbers at $N = 6$, 14, 34 etc (6,7,8). In this letter we would like to re-examine this two decades old idea of Abbas (1) regarding the “plateau of doubly magic $N = 82$ isotones and their similarity. In particular we shall study a new “smoking gun” kind of evidence to confirm Abbas’ plateau of stability (1). We shall also study this “plateau” of stability using theoretical models like Skyrme–Hartree–Fock–Bogoliubov (HFB), relativistic mean field (RMF) theory etc. We find that all these models fail to reproduce the new magicities.

Abbas has studied even $58 \leq Z \leq 70$, $N = 82$ isotones through empirical evidence available then (i.e. 1983) (1). We have reexamined the same in the light of more accurate and recent experimentally available data. We reconfirm the analysis as per the empirical data. We would not like to repeat the same here and refer the reader to Ref. (1) as to the similarity and the magicity of these nuclei. However for the sake of completeness we would like to summarize and tabulate a few of the arguments therein (1).

(a) In $Z = 58$, 60, 62, 64, 66, 68, 70, $N = 82$ isotones the lowest first excited state (level $2^+$ or $3^-$) is very high and steady at about 1.6 MeV for all the nuclei.

(b) A study of low lying states in $N = 81$, 80, 79 and 78 isotones with $Z = 58$, 60, 62, 64, 66, 68, 70 indicates amazing similarity and stability.

(c) The ratio $E_1(4^+)/E_1(2^+)$ for all these nuclei is $\sim 1.3$. This puts all these nuclei in the category of “doubly-magic” as per standard interpretation.

(d) The rms radii change very slowly as mass number changes over this whole region. Plus many other arguments in support of the said statement regarding the similarity and the stability of these nuclei. Here we discuss a further “smoking gun” kind of evidence in support of the above idea.

To discuss magicity one normally plots separation energies $S_{1n}$ and $S_{2n}$ as a function of neutron number $N$ for a particular proton number $Z$ or plot $S_{1p}$ and $S_{2p}$ as a function of proton number $Z$ for a particular $N$. If we do so for $N = 82$ isotones then we would like to point out here that the evidences for magicity continue to be there but that it is not very prominent (1). It is very common to plot $S_{2p}$ and look for kinks as evidence for magicity (6,7,8). However it should be pointed out that this one in itself should not be taken as very conclusive evidence in favour or against magicity (1,10).

We therefore plot separation energies differently. We plot $S_{1n}$ as a function of proton number $Z$ for a particular $N$. We show this in Fig. 1 for the magic numbers $N = 28$ and $N = 50$ isotones. We immediately note that in $N = 28$ case the magic number $Z = 20$ and $Z = 28$ show up very prominently. For $N = 50$ case though the $Z$-number does not pass through any standard magic number it does indicate extra stability at $Z = 34$, 36 and 38. We know that the $Z = 38$ case $^{88}\text{Sr}$ anyway is known to form a stable structure, enabling good shell model description of $^{90}\text{Zr}$ excited states (1). These $N = 50$ isotones actually are precursors of a more interesting effect to be discussed below.

We plot $S_{1n}$ as a function of $Z$ for $N = 82$ in Fig. 2. The magicity at $Z = 50$ is very clearly demonstrated here. But amazingly exactly the same magicity is indicated, very prominently at $Z = 62$, 64, 68 and 70. The magnitude of $S_{1n}$ at all these neighbouring even $Z$-numbers is comparable to the magnitude of $S_{1n}$ at $Z = 50$. We know $Z = 50$ (Sn nucleus) is one of the “best” magic number in nuclear physics. As per Fig. 2 if we can call $Z = 50$ magic there is no reason why we should
FIG. 1: Experimental single-neutron separation energies for \( N = 28 \) and \( N = 50 \) isotones.

FIG. 2: Experimental single-neutron separation energies for \( N = 82 \), 80 and 78 isotones.

not do the same for all the even \( Z \) number discussed above. This “smoking gun” evidence supplemented with those already provided by Abbas [1] should convince one that all these nuclei are indeed “doubly magic”.

Does this magicity persist when two or even four neutrons are pulled out? The corresponding \( N = 80 \) plot (inset, Fig. 2) shows that indeed it is so. We also plot the same for \( N = 78 \) (inset, Fig. 2) which also continues to show stability. All this should be treated as strong evidence for double magicity of all these even \( Z \) nuclei. We would like to point out that we do see similar effect for \( N = 50 \), \( N = 48 \) case but some other evidences of double magicity and similarity are missing in these nuclei (as discussed in ref. [1]) and hence these should be actually treated as precursor of the amazing phenomenon pointed out in this paper.

Today we do have elaborate theoretical framework of various kind which are being successfully applied to study nuclear phenomena. We pick up three of these very successful models which are used in nuclear physics.

We have carried out extensive study microscopically in the nonlinear relativistic mean field theory of Boguta and Bodmer [11], an extended version of Walecka [12] theory. We have adopted the NL3 [13] interactions in our study. The NL3 interaction has been widely used in recent years in the calculation of varieties of nuclear properties like binding energy, rms radii and giant resonances etc. and have been accepted to be very successful. In the present study, we expanded the fields in harmonic oscillator basis and studied the stability of the result for each nucleus by varying the number of harmonic oscillator shells between \( N_F = N_B = 12 \) to 14. We did the same exercise taking quadrupole deformation in our calculation, where the basis deformation parameter \( \beta_0 \), was varied between \(-0.4 \) to 0.4 in the step of 0.1. We used a constant gap BCS pairing calculation to take into account the pairing correlation. The pairing constant gap is taken for the drip-line nuclei following the prescription of Medland and Nix [14]. The formalism and calculation are quite standard and have been widely used in the literature, the details of which can be seen in Refs. [15, 16]. It is to be noted that in the present study, we have performed three different calculations as to pairing, i.e. (a) taking pairing in both even and odd nucleons, (b) without pairing and (c) pairing correlation is considered for even nucleons and neglected for the odd case (mixed pairing). We found almost similar results for the without and the mixed pairing cases (cases (b) and (c)). However, we noticed only a smooth increasing in \( S_{1n} \) value for the case (a). In this case, the sudden rise of \( S_{1n} \) value at \( Z = 50 \)
could not be reproduced (not shown in Fig. 3), which anyway is experimentally observed. On the other hand for the other two cases ((a) and (b)), the characteristic jump at \( Z=50 \) is clearly visible (here we have plotted case (c) only in Fig. 3).

To see the other theoretical behaviour we have also displayed the calculated data of HFB \cite{17} and the infinite nuclear mass (INM) model \cite{18} calculations in Fig. 3. From the figure it is clear that the HFB and INM models are not even able to reproduce the magic jump at \( Z=50 \) for the \( N=82 \) isotonic series. A further inspection of the figure, makes it clear that the RMF formalism is somewhat able to reproduce the known jump of \( Z=50 \), whereas it fails to reproduce the odd-even type of staggering for \( Z = 58, 60, 62, 64, 66, 68, 70, N = 82 \) which are experimentally observed. However this model produces some spurious tendency like a sudden jump at \( Z = 56 \) for the \( N=82 \) nucleus, which is experimentally ruled out and some odd-even type of staggering in the heavier region of the \( N=82 \) isotonic series.

For new magicities at \( N = 6, 14, 16, 34 \) etc, all kind of new ideas are being proposed \cite{1,2,3}. We also feel that the new magicities at \( Z = 58, 60, 62, 64, 66, 68, 70 \) are also indicative of new physics. From our present investigation, it may be seen that the HFB and INM models are missing some important physics to incorporate the experimental staggering for the considered region. On the other hand, the RMF explains the characteristic jump at \( Z=50 \), but fails to reproduce other odd-even effects. The reproduction of odd-even trends for heavier mass nuclei of the \( N=82 \) isotonic series in the frame work of RMF model, gives some hints that the progress of relativistic mean field formalism may be in the proper direction. However, it is still missing some important ingredients. As it has been argued by several authors, the inclusion of self-coupling of scalar fields simulate the effect of three-body forces. But still the absence of many-body correlations is very much there in this theory. A possible improvement of the RMF theory may be to include the higher order couplings as it is suggested in Ref. \cite{19}. The other possible feature, which is not taken either in the RMF or in the HFB or the INM models is the possibility of \( A = 3, 4 \) clustering \cite{20}. Once these two effects are taken into account, we hope that the theories may be compatible with the experimental data. Work in this direction is in progress \cite{21}.

\begin{thebibliography}{99}

\bibitem{1} A. Abbas, Phys. Rev. C 29, 1033 (1984).
\bibitem{2} J. H. Hamilton, Treatise on Heavy Ion Science, Vol 8 (Ed. D. A. Bromley), Plenum Press, (1988) p. 1.
\bibitem{3} F. Andreozzi, A. Covello, A. Gargano, and A. Porrino, Phys. Rev. C 41, 250 (1990).
\bibitem{4} A. Holt, T. Engelund, E. Osnes, M. Hjorth-Jensen and J. Suhonen, Nucl. Phys. A618, 107 (1997).
\bibitem{5} T. Matsuzawa, H. Nakada, K. Ogawa, and G. Momoki, Phys. Rev. C 62, 054304 (2000).
\bibitem{6} I. Tanihata, Nucl. Phys. A685, 80c (2001).
\bibitem{7} P. G. Thirolf, B. V. Pritchenko, B. A. Brown, P. D. Cottle, M. Chromik, T. Glasmacher, G. Hackman, R. W. Ibbotson, K. W. Kemper, T. Otsuka, L. A. Riley and H. Scheib, Phys. Lett. B485, 16 (2000).
\bibitem{8} Z. Dlouhy, D. Baiborodin, J. Mrdzek and G. Thiamova, Nucl. Phys. A722, 36c (2003).
\bibitem{9} M. Theohenos, T. Baumann, J. Enders, N. H. Frank, P. Heckman, J. P. Seitz and E. Tryggestad, Nucl. Phys. A722, 61c (2003).
\bibitem{10} M. Ploszajezak and M. Faber, Phys. Scr. 24, 243 (1981).
\bibitem{11} J. Boguta and A. R. Bodmer, Nucl. Phys. A292, 413 (1977).
\bibitem{12} J.D. Walecka, Ann. Phys. (N.Y.) 83, 491 (1974).
\bibitem{13} G. A. Lalazissis, J. König and P. Ring, Phys. Rev. C55 (1997) 540; M.M. Sharma, A.R. Farhan and S. Mythili Phys. Rev. C61 (2000) 054306.
\bibitem{14} D.G. Madland and J.R. Nix, Nucl. Phys. A476 (1988) 1.
\bibitem{15} Y.K. Gambhir, P. Ring and A. Thimet, Ann. Phys. (N.Y.) 198 (1990) 132.
\bibitem{16} S. K. Patra and C.R. Praharaj, Phys. Rev. C44 (1991) 2552.
\bibitem{17} M. Samyn, S. Goriely, P.-H. Heenen, J. M. Pearson and F. Tondeur, Nucl. Phys. A700, 142 (2001).
\bibitem{18} R.C. Nayak and L. Satpathy, At.Data and Nucl. Data Table, 73, 213 (1999).
\bibitem{19} P. Arumugam, B.K. Sharma, P.K. Sahu, S.K. Patra, Submitted to Phys. Rev. Lett. (nucl-th/0308050).
\bibitem{20} A. Abbas, Mod. Phys. Lett. A16, 755 (2001).
\bibitem{21} P. Arumugam, S.K. Patra and A. Abbas (Work in progress)
\end{thebibliography}