Superheavy Nuclei in a Chiral Hadronic Model

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Abstract

Superheavy nuclei are investigated in a nonlinear chiral SU(3)-model. The proton number Z=120 and neutron numbers of N=172, 184 and 198 are predicted to be magic. The charge distributions and α-decay chains hint towards a hollow stucture.

Reasonable descriptions of nuclei directly derived from QCD models are still not in sight. However, one can investigate effective models that incorporate basic symmetries of QCD, describing hadronic properties as well as nuclear matter and finite nuclei [1,2]. The approach discussed here [2] builds on chiral $SU(3)_{\rm L} \times SU(3)_{\rm R}$ symmetry and broken scale-invariance. The model incorporates relativistic baryonic and mesonic degrees of freedom (nucleons, hyperons, spin $\frac{3}{2}$ baryons, the spin-0 and spin-1 $SU(3)$-multiplets [2]). The hadron masses are generated dynamically via spontaneous symmetry breaking. The masses of the nucleons are generated by the interactions with a non-strange scalar field $\sigma \sim \langle \overline{u}u + \overline{d}d \rangle$ and a strange condensate $\zeta \sim \langle \overline{s}s \rangle$ as

$$m_{\rm N} = g_{{\rm N}\sigma}\sigma + g_{{\rm N}\zeta}\zeta. \tag{1}$$

Other baryonic masses are generated in the same manner. The pseudoscalar mesons obtain their masses by explicit symmetry breaking.
Our present investigation of superheavy nuclei uses three different sets of parameters. The calculations are performed in spherical symmetry adopting the mean-field approximation. Free parameters are fixed to vacuum properties of hadrons and ground state properties of infinite nuclear matter (Set C1) and via a χ^2-fit to properties of the spherical nuclei ^{16}O, ^{40}Ca, ^{48}Ca, ^{58}Ni, ^{90}Zr, ^{112}Sn, ^{124}Sn and ^{208}Pb (Set C1fit).
The χ^2-function is given by

$$\chi^2 = \sum_n \left(\frac{\mathcal{O}_n^{\rm exp} - \mathcal{O}_n^{\rm theo}}{\Delta \mathcal{O}_n} \right)^2 , \tag{2}$$

where $\mathcal{O}_n^{\rm exp}$ is the experimental value of the observable $\mathcal{O}_n$, while $\mathcal{O}_n^{\rm theo}$ is its calculated value. $\Delta\mathcal{O}_n$ is a weight given by the experimental error. However, because all observables are known experimentally to much better accuracy than provided by the model, we have decided to use the weights to make the fits comparable to other calculations. The observables used for the fits to the nuclei are the binding energy $E_{\rm B}$, the surface thickness σ and the charge diffraction radius $R_{\rm diff}$. For extrapolation to heavy nuclei one should replace ^{16}O by ^{264}Hs as done in the parameter set C1hs. All parameter sets give reasonable results in the region of known nuclei. This is a remarkable result particularly for the fit to hadron properties and nuclear matter (C1), which does not contain any information about finite nuclei. The fit to finite nuclei can be used to improve the χ^2. All parameter sets give the correct shell closures for magic nuclei up to 82 protons and 126 neutrons.

Several experiments have recently attempted to produce nuclei with proton numbers beyond the element $Z = 112$ that was found at GSI [4]. Experiments report observation of the nucleus $^{293}118_{175}$ [3]. Also $Z = 114$ has been reported [5].

The most important theoretical question is where new shell closures are to be expected. These nuclei could have very long lifetimes (minutes to years). This topic has been extensively investigated in Walecka type models [6] predicting $Z = 114$ and Z=120 as next shell closure. Let us now turn to the predictions of the chiral model. Figure 1 shows the finite-nucleus calculation (in the chiral model) of the two-proton gap

$$\delta_{2\rm p}(Z,N) = S_{2\rm p}(Z,N) - S_{2\rm p}(Z+2,N) \tag{3}$$

with the 2p-separation energy $S_{2\rm p}$ defined as

$$S_{2\rm p}(Z,N) = E_{\rm B}(Z-2,N) - E_{\rm B}(Z,N) \tag{4}$$

The calculation was done for a nucleus with $N = 172$. The signature for a shell closure is a pronounced peak in the two-nucleon gap. One can see that all three parameter sets show a shell closure at $Z = 120$. At $Z = 114$ a small peak is also visible. It is interesting to see that the weak peak at $Z = 114$ is suppressed, if the parameter set includes the binding energy of ^{265}Hs (C1hs), thus taking into account a known heavy nucleus in the vicinity of $Z \sim 114$. This seems to suggest that $Z = 114$ is not a magic number (C1hs should give the best prediction for superheavy nuclei). This result has recently also been obtained in Walecka-type models – the early famous Z=114 predictions are attributed to an incorrect spin-orbit force in nonrelativistic models [6]. The two-nucleon separation energy (4) shows that for a neutron number $N = 172$ the nucleus with $Z = 120$ is beyond the dripline ($S_{2\rm p} < 0$) in the calculation with the "nuclear matter" fit parameters C1 (Figure 2). However for the parameter sets C1fit and C1hs (adjusted to properties of finite nuclei) $^{292}120$ is a bound doubly magic nucleus, clearly above the dripline. And for 184 neutrons, $Z = 120$ yields $S_{2\rm p} > 0$ for all three parameter sets. $N = 172$, 184 and 198 are closed neutron shells. Figure 3 shows the predicted α particle decay chain of the nucleus $Z = 120$ and $N = 172$. The α energy decreases slightly towards the lighter daughter nuclei and drops to about 4 Mev for $Z = 106$. This overall trend is in qualitative agreement with the experimental finding of nearly constant α-energies for Z=118, N=175 [3]. One should keep in mind that this calculations are performed under the assumption of spherical symmetry which is probably not fulfilled for this nuclei, except $Z = 120$ which shall be magic.

The predicted charge distribution of $^{292}120$ is shown in figure 4. Note its strong depletion in the center of the nucleus. The same effect is seen in Walecka model calculations [7]. Hence one may speculate that the superheavy nuclei around Z=120 exhibit a Fullerene, bucky-ball structure built of 60 α-particles and ≈ 60 neutrons (See figure 5). The length of the links between the α-particles in a Fulleren-type structure for Z=120 (radius 8.0 fm) is about 3.5 fm. This is surprisingly close to twice the radius of ^{4}He ($R_{\rm diff} = 1.68$ fm). Such a structure naturally exhibits a depleted charge density in the center of the nucleus.

ACKNOWLEDGMENTS

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FIGURES

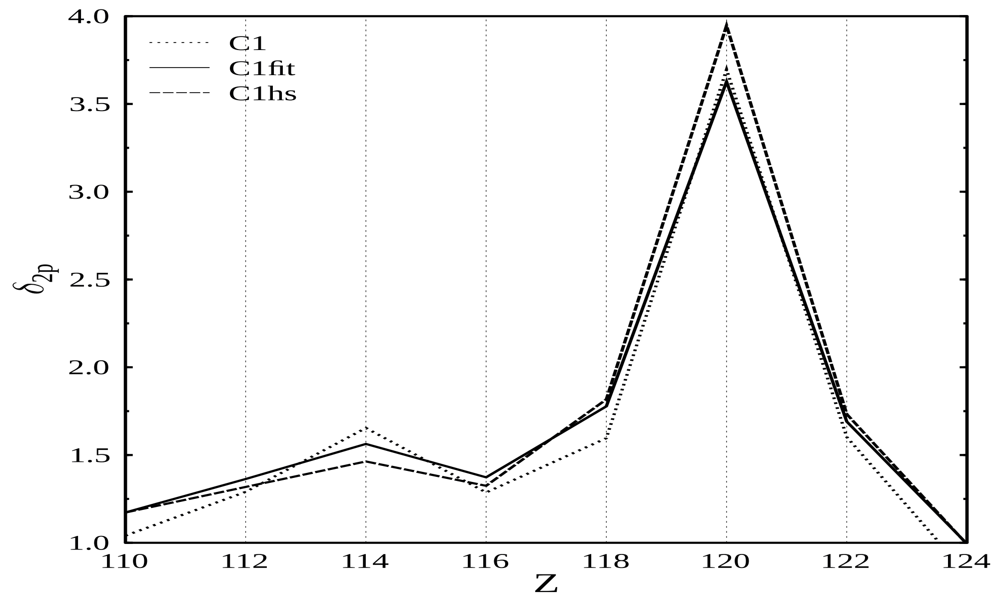

FIG. 1. Two-Proton Gap

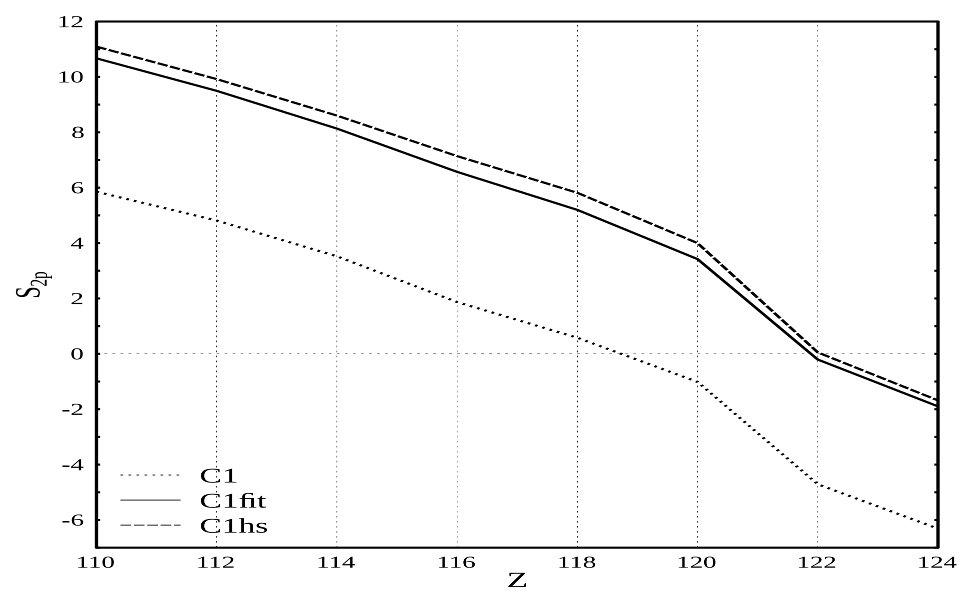

FIG. 2. Two Proton Separation Energy S_{2p} for N=172

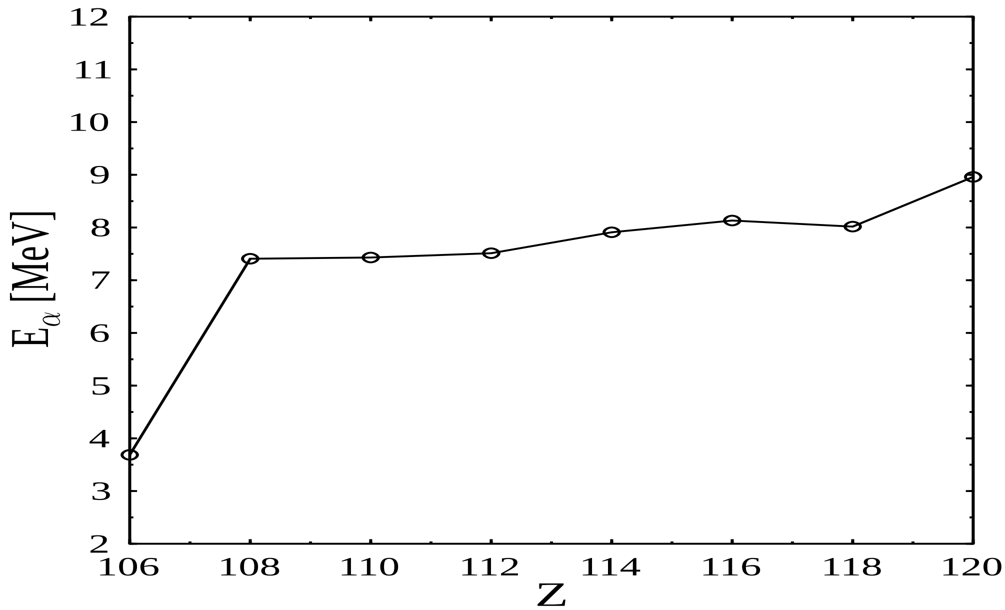

FIG. 3. Predicted Alpha Decay Energy for Superheavy Nuclei as a Function of Charge

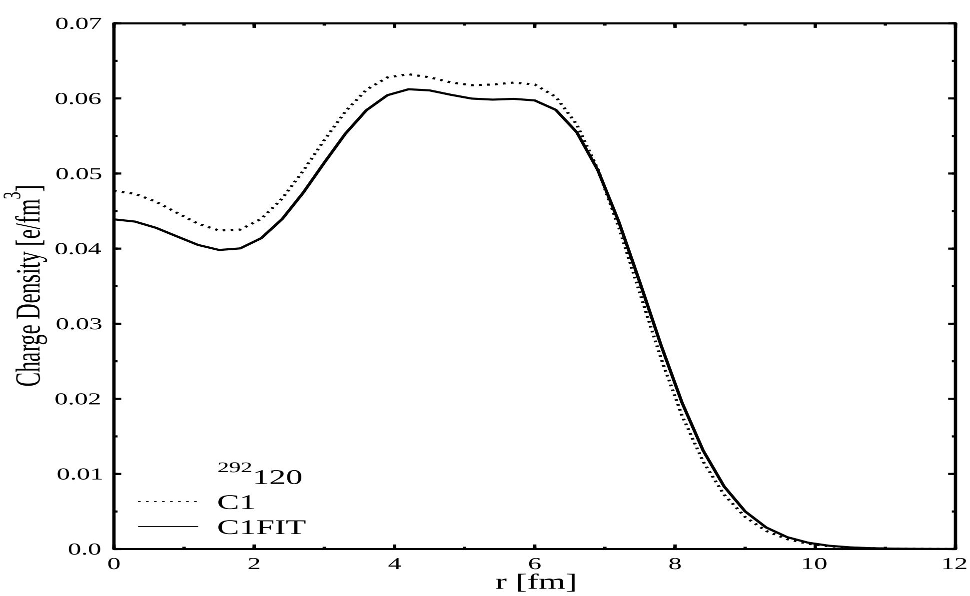

FIG. 4. Charge Density Distribution of $Z = 120$, $N = 172$

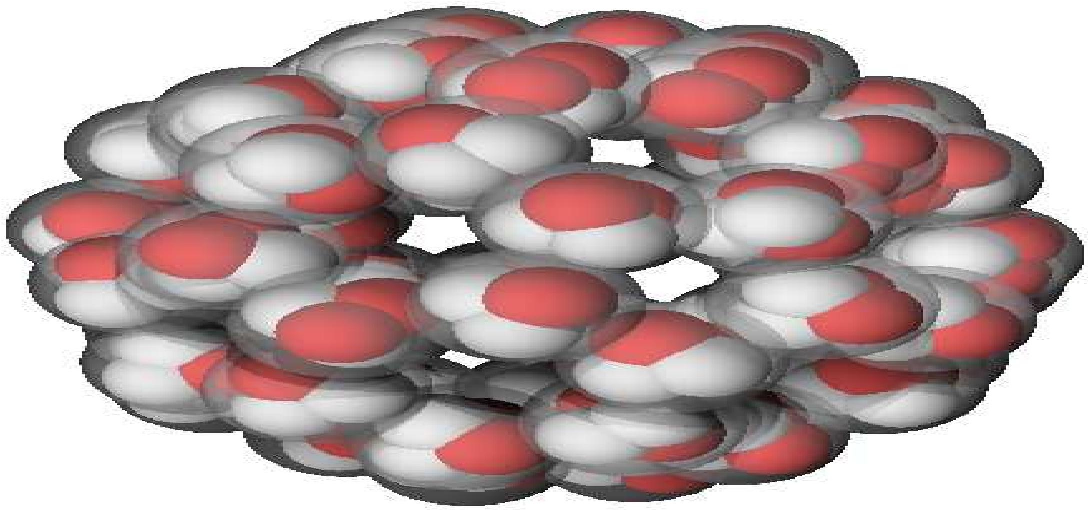

FIG. 5. Alpha-Cluster with 60 α-Particles