Ground State Properties of Z=119 Isotopes in Relativistic Mean Field Theory

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Abstract. The properties of Z=119 isotopes in ground state are studied by relativistic mean field (RMF) theory with the force TM1. Based on the conventional Bardeen-Cooper-Schrieffer (BCS) approximation, which is used to study the pairing correlation, the unpaired odd nucleons are studied in the “blocking” method. The properties of average binding energies, the quadrupole deformation, occupation number $N_{\text{occu}}$, isotope shifts and the density distributions of neutron and proton for Z=119 isotopes are calculated and compared with the finite-range droplet model (FRDM).

1. Introduction
Recent years, the superheavy nucleus (SHN) synthesized has received much more attention, up to now the element Z=118 has been synthesized, and the next one will be element Z=119. There are many theoretical researches about element Z=119,120 synthesized [1-6]. The SHN is unlikely exist in nature, and difficult to synthesize. Hence theoretical studies for the properties become very important. It is well know that the relativistic mean field (RMF) is the most successful theory in describing the properties of SHN [7-13]. We use RMF+BCS with the TM1 parameters to calculate the properties of Z=119 isotopes and compare with the calculation form Ref. [14].

The paper is organized as follows. In Sec. 2 the RMF+BCS theory are described. In Sec. 3 the ground-state properties of the z=119 isotopes are studied in the RMF+BCS theory. The summary is given in Sec. 4.

2. The Relativistic Mean Field Theory
The effective Lagrangian density of the SHN system can be written as [15-16]:

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\begin{equation}
L = \bar{\psi}(i \gamma^\mu \partial_\mu - M)\psi + \frac{1}{2} \partial^\mu \sigma \partial_\mu \sigma - \left(\frac{1}{2} m_\sigma^2 + \frac{1}{3} g_\sigma \sigma^3 + \frac{1}{4} g_\sigma \sigma^4 \right) - g_\sigma \bar{\psi}\psi \sigma - \frac{1}{4} \Omega_\mu \Omega^{\mu} - \\
\left(\frac{1}{2} m_\omega^2 \omega_\mu \omega_\mu + \frac{1}{4} c_3 (\omega_\mu \omega_\mu)^2 \right) - g_\omega \bar{\psi} \gamma^\mu \psi \partial_\mu - \frac{1}{4} R_{\mu \nu} R^{\mu \nu} + \frac{1}{2} m_\rho^2 \rho_\mu \rho_\mu - g_\rho \bar{\psi} \gamma^\mu \tau \rho_\mu - \\
\frac{1}{4} F_{\mu \nu} F^{\mu \nu} - e \bar{\psi} \gamma^\mu \frac{1}{2} (1 + \tau_3) \psi A_\mu .
\end{equation}

Here $\psi$ and $M$ are the nucleon field and the mass, respectively. The meson field includes the isoscalar $\sigma$ meson, the isoscalar-vector $\omega$ meson, and the isovector-vector $\rho$, with mesons masses $m_\sigma, m_\omega,$ and $m_\rho$, respectively. The variates $g_\sigma, g_\omega$ and $g_\rho$ are the coupling constants for the mesons, respectively. The scalar meson field of vector isospin $\Omega^{\mu}$, the meson field isospin vector $R^{\mu}$ and the tensor of electromagnetic field $F^{\mu \nu}$ are given by

\begin{align}
\Omega^{\mu} &= \partial^\mu \omega^\nu - \partial^\nu \omega^\mu , \\
R^{\mu} &= \partial^\mu \rho^\nu - \partial^\nu \rho^\mu , \\
F^{\mu \nu} &= \partial^\mu A^\nu - \partial^\nu A^\mu ,
\end{align}

respectively. The pairing correlation of the neutron and proton from the BCS theory can be parameterized to following forms,

\begin{align}
G_n &= \frac{21}{A} \left(1 - \frac{N - P}{2A}\right) \text{MeV} , \\
G_p &= \frac{27}{A} \left(1 + \frac{N - P}{2A}\right) \text{MeV} ,
\end{align}

respectively. It can be found that the strength of pairing forces parameterization of the neutron and proton depend on the factor $\frac{N - P}{2A}$ and the mass number $A$. The forms of the pairing strengths are used to reproduce the pairing energy gaps $\Delta$ in the finite range droplet model (FRDM) \cite{11, 14} near the $\beta$-stable valley and beyond. We used a blocking method to calculate the unpaired nucleons of the last one \cite{10}, that the total single particle energy is a minimum value. The total single-particle energy can be written as

\begin{equation}
E_{\text{part}} = \varepsilon_k + 2 \sum_{i \neq k} \varepsilon_i v_i^2 - \Delta \sum_{i \neq k} u_i v_i ,
\end{equation}

where, the $\varepsilon_k$ is energy of the last odd nucleon $k$. The nucleon state $k$ is determined by variation of the total single particle energy $E_{\text{part}}$ about $k$. Therefore, the Fermi energy $\lambda$ and pairing energy gap $\Delta$, and $E_{\text{part}}$ depend on the choice of the last nucleon state $k$. 


The ground state properties for the Z=119 isotopic chain from A=284 to 339 were calculated with the parameter set of MT1\cite{17}: $M = 938.0\text{MeV}$, $m_\sigma = 511.198\text{MeV}$, $m_\rho = 783.0\text{MeV}$, $m_\omega = 770.0\text{MeV}$, $g_\sigma = 10.0289\text{MeV}$, $g_\omega = 12.6139\text{MeV}$, $g_\rho = 4.6322\text{MeV}$, $g_\omega = -7.2325\text{fm}^{-1}$, $g_3 = 0.6183\text{MeV}$, and $c_3 = 71.3075\text{MeV}$, that can give a suitable properties about the ground state of Z=119 isotopic chain. The parameter of MT1 contains the self-interaction term of the $\omega$ meson. Others parameter such as NL1, NL3H, and NL3\cite{18} only include the nonlinear $\sigma$ self-interactions term. The nonlinear vector meson $\omega$ self-interaction modifies the linear density which is depend on the vector potential in the RMF and could simulate the RDBH results discussed in Ref.\cite{17}. All of those parameter are adjusted to calculate the global properties of nuclear matter and some stable nuclei. They are also able to well describe properties of unstable nuclei, but may prediction have slightly different in drip lines and new shell structures for superheavy nuclei\cite{10,19-20}.

3. Ground State Properties of Z=119 Isotopes

The binding energies per nucleon of the Z=119 isotopes are plotted in Fig.1, the change trend of the result is basically consistent with calculation from the FRDM. The lowest point of binding energies per nucleon is A=291, 293 and 297 in the RMF, and for the FRDM is at A=293 and 297. It can be found that the nuclei for N=172, 174 and 178 are more stable than others.

![FIG. 1. The binding energy per nucleon for Z=119 isotopes.](image1)

![FIG. 2. The quadrupole deformation .](image2)

![FIG. 3. Occupation number $N_{\text{occu}}$ for Z=119 isotopes.](image3)

![FIG. 4. Fermi energy of neutron and proton for Z=119 isotopes.](image4)

The quadrupole deformation of the Z=119 isotopes are plotted in Fig.2. The results from RMF are partly consistent with the trend of the result from FRDM. It can be seen that the long ellipsoid and the oblate ellipsoid change alternately appearing in the range of entire isotopes chain. It is obviously found that the SHN have a long ellipsoid shape from the Fig.2.
Occupation number $N_{\text{occu}}$ of nucleon in nuclide continuous state of $Z=119$ isotopes chain are plotted in Fig.3. It can be found that the continuous state of the whole isotopes chain are occupied by the nucleon. In Fig.4, it can be found that the Fermi surface of both neutron and proton is far away from the continuous state around $A=312-327$, where the mean field is strong and the BCS theory works well. The Fermi surface is very close to the continuous state in the region $A=287-311$ and 328-339, while the $A<287$ Fermi surface is positive state, hence the BCS theory is completely inapplicable.

The single neutron separation energy shows obvious odd-even effect, and the single neutron and double neutron separation energy of RMF are agree with calculation from the FRDM plotted in Fig. 5 and Fig. 6. In addition, the separation energy of two neutrons and single shows that there exist a peak at $A=314 (N=195)$, which indicate that the stability of the nucleus is changing suddenly.

The root mean square radius of the last odd neutron can be found in the Fig. 7, which reflect the large mutation in the nucleus $A=324$, and is much more diffuse than the rest nuclei. In addition, we can found that the last odd neutron density in the superheavy mass region has a large diffuse relative to the others.

The isotope shift $r_x^2(A) - r_x^2(\text{ref})$ for $Z=119$ isotope chain with respect to a reference nucleus of $A=290$ is plotted as a function of mass number $A$. The isotopic shift changes slightly until it reaches the number $A=314$, 315 and 316. There is a kink at this point, such an anomalous behavior for a generic feature of deformed nuclei.

Both neutron and proton density distribution are plotted in Fig. 9 and Fig. 10. We can found that the quadrupole deformation of the nucleus($A=303$) is 0.027. It is shown that the nucleus is closed to
sphere, the nuclear volume is much smaller, and it is combined much closed. Although the quadrupole deformation of the $A=313$ nucleus is 0.016, which is small. The proton and the neutron distribution expands outward, and they are combined not very close. The quadrupole deformation of the $Z=332$ nucleus is much larger and has a relatively large deformation, and the long axis is longer, hence the proton density in the direction of the long axis is relatively large. By comparing the density distribution of the proton and the neutron, we can found that there still have neutron distribution in the region that the proton density distribution is zero, the neutron skin exist in this area. In addition, there is a peak value at a certain distance from the core in the Fig. 9 and Fig. 10. It shows a tendency to gather outward, and the tendency of the neutrons is weak, which is mainly caused by Coulomb interaction.

4. Summary
We have studied the ground state properties of $Z=119$ isotopes in the framework of the RMF model. A blocking approximation is used to calculation of the unpaired nucleon, and the pairing correlation is treated in the BCS theory. The binding energies of the $Z=119$ isotopes are studied, it shows that the nuclei for $N=172$, 174 and 178 are more stable than others. The SHN have a long ellipsoid shape from the quadrupole deformation, and have a tendency to gather outward, and the Fermi surface of both neutron and proton is far away from the continuous state around $A=312$-327, where the mean field is strong and the BCS theory works well. The Fermi surface is very close to the continuous state in the region $A=287$-311 and 328-339, while the $A<287$ Fermi surface is positive state, hence the BCS theory is completely inapplicable.

In our calculation, All those properties are basically agreement with those in the FRDM. So the RMF model could successfully describe the properties of superheavy nucleus (SHN), such as the binding energies, the deformations, and isotopic shifts.

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References
[1] K. P. Santhosh and V. Safoora, Phys. Rev. C 96, 034610 (2017).
[2] Long Zhu, Wen-Jie Xie, and Feng-Shou Zhang, Phys. Rev. C 89, 024615 (2014).
[3] Nan Wang, En-Guang Zhao, Werner Scheid, and Shan-Gui Zhou, Phys. Rev. C 85, 041601(R) (2012).
[4] D. N. Poenaru and R. A. Gherghescu, *Phys. Rev. C* **97**, 044621 (2018).
[5] Fan Li, Long Zhu, Zhi-Han Wu, Xiao-Bin Yu, Jun Su, and Chen-Chen Guo. *Phys. Rev. C* **98**, 014618 (2018).
[6] Santhosh and B. Priyanka, *Phys. Rev. C* **87**, 064611 (2013).
[7] Y. K. Gambhir, P. Ring and A. Thimet, *Ann. Phys.(N.Y.)* **198**, 132 (1990).
[8] P. Ring, Y. K. Gambhir and G. A. Lalazissis, *Commun. Comput. Phys.* **105**, 77 (1997)
[9] G. A. Lalazissis, M. M. Sharma, P. Ring and Y. K. Gambhir, *Nucl. Phys. A* **608**, 202 (1996).
[10] Junqing Li, Zhongyu Ma, Baoqiu Chen and Yong Zhou, *Phys. Rev. C* **65**, 064305 (2002).
[11] Hongfei Zhang, Junqing Li, Wei Zuo, Zhongyu Ma, Baoqiu Chen and Soojae Im, *Phys. Rev. C* **71**, 054312 (2005).
[12] M. M. Sharma and A. R. Farhan, *Phys. Rev. C* **71**, 054310 (2005).
[13] Haifei Zhang, Hongfei Zhang, Junqing Li. *Commun. Theor. Phys.* **58**, 544 (2012)
[14] P. Moller, J.R. Nix, W. D. Myers, and W. J. Swiatecki, *Atomic Data and Nuclear Data Tables* **59**, 185 (1995).
[15] B. D. Serot and J. D. Walecka, *Adv. Nucl. Phys.* **16**, 1 (1986).
[16] P. G. Reinhard, *Rep. Prog. Phys.* **52**, 439 (1989).
[17] Y. Sugahara and H. Toki, *Nucl. Phys. A* **579**, 557 (1994).
[18] P. Ring, Prog. Part. *Nucl. Phys.* **37**, 193 (1996).
[19] M. Bender, K. Rutz, P. G. Reinhard, J. A. Maruhn and W. Greiner, *Phys. Rev. C* **60**, 034304 (1999).
[20] S.K. Patra, Chen-Li Wu, C.R. Praharaj, Raj K.Guptac, *Nucl. Phys. A* **651**, 117(1999).