

Nonaxial-octupole Y_{32} correlations in $N = 150$ isotones from multidimensional constrained covariant density functional theories postprint

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Abstract

The non-axial reflection-asymmetric Y_{32} shape in some transfermium nuclei with $N = 150$, namely ^{246}Cm , ^{248}Cf , ^{250}Fm , and ^{252}No are investigated with multidimensional constrained covariant density functional theories. By using the density-dependent point coupling covariant density functional theory with the parameter set DD-PC1 in the particle-hole channel, it is found that, for the ground states of ^{248}Cf and ^{250}Fm , the non-axial octupole deformation parameter $\beta_3 > 0.03$ and the energy gain due to the Y_{32} distortion is larger than 300 keV. In ^{246}Cm and ^{252}No , shallow Y_{32} minima are found. The occurrence of the non-axial octupole Y_{32} correlations is mainly from a pair of neutron orbitals $[734]9/2$ ($j_{15/2}$) and $[622]5/2$ ($g_{9/2}$) which are close to the neutron Fermi surface and a pair of proton orbitals $[521]3/2$ ($f_{7/2}$) and $[633]7/2$ ($i_{13/2}$) which are close to the proton Fermi surface. The dependence of the non-axial octupole effects on the form of energy density functional and on the parameter set is also studied.

Full Text

Nonaxial-Octupole Y_{32} Correlations in $N = 150$ Isotones from Multidimensional Constrained Covariant Density Functional Theories

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Abstract

The non-axial reflection-asymmetric shape in some transfermium nuclei with $N = 150$, namely ${}^2\text{Cm}$, ${}^2\text{Cf}$, ${}^2\text{Fm}$, and ${}^2\text{No}$, is investigated using multidimensional constrained covariant density functional theories. By employing the density-dependent point-coupling covariant density functional theory with the parameter set DD-PC1 in the particle-hole channel, we find that for the ground states of ${}^2\text{Cf}$ and ${}^2\text{Fm}$, the non-axial octupole deformation parameter $\beta_3 > 0.03$ and the energy gain due to the distortion exceeds 300 keV. In ${}^2\text{Cm}$ and ${}^2\text{No}$, shallow minima are found. The non-axial octupole correlations arise primarily from a pair of neutron orbitals $[734]9/2$ ($j_7/2$) and $[622]5/2$ ($g_7/2$) near the neutron Fermi surface, and a pair of proton orbitals $[521]3/2$ ($f_7/2$) and $[633]7/2$ ($i_7/2$) near the proton Fermi surface. The dependence of the non-axial octupole effects on the form of the energy density functional and on the parameter set is also studied.

I. Introduction

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The majority of observed nuclei exhibit spheroidal shapes characterized by the quadrupole deformation parameter β_2 . The existence of non-axial quadrupole (triaxial) deformation [1-3] and axial octupole deformation [4] in atomic nuclei has been confirmed both experimentally and theoretically. However, there is no a priori reason to neglect non-axial octupole deformations, particularly the β_3 deformation [5-7]. The pure β_3 deformation possesses tetrahedral symmetry with the symmetry group T_d . The existence of non-trivial irreducible representations of this group enables nuclei to exhibit large energy gaps in their single-particle levels, thereby enhancing stability [8]. It has been anticipated that β_3 deformation may occur in the ground states of certain nuclei with special combinations of neutron and proton numbers [7-9]. Recently, numerous theoretical studies have focused on this nuclear shape, employing either T_d -symmetric single-particle spectra [7, 9-11] or various nuclear models including the macroscopic-microscopic model [9, 11-13], the Skyrme Hartree-Fock (SHF), SHF+BCS, or Skyrme Hartree-Fock-Bogoliubov approaches [11-18], and the Reflection Asymmetric Shell Model (RASM) [19, 20].

In particular, Dudek et al. predicted that a negative-parity band in ${}^1\text{Gd}$ represents a favorable candidate for manifesting tetrahedral symmetry [13], which has stimulated several interesting experimental investigations [21, 22].

Presently, the study of nuclei with $Z \sim 100$ has become increasingly important

because it not only reveals the structure of these nuclei themselves but also provides crucial information for superheavy nuclei [23–26]. One relevant and intriguing topic is the explanation of low-lying 2^- states in certain $N = 150$ even-even nuclei. In these nuclei, the bandhead energy $E(2^-)$ of the lowest 2^- bands is exceptionally low [27]. It is widely accepted that octupole correlations are responsible for this phenomenon. For example, a quasiparticle phonon model incorporating octupole correlations was used to explain the excitation energy of the 2^- state in $N = 150$ isotones, with octupole correlations arising primarily from the neutron two-quasiparticle configuration $9/2^- [724] \ 5/2^- [622]$ and proton two-quasiparticle configurations $9/2^- [633] \ 5/2^- [521]$ or $7/2^- [633] \ 3/2^- [521]$ [28]. In all these configurations, the third components of the angular momenta of like quasiparticles (K) differ by 2, indicating that Y -correlations should play an important role.

In Ref. [20], Chen et al. proposed that non-axial octupole Y -correlations give rise to the experimentally observed low-energy 2^- bands in $N = 150$ isotones, and RASM calculations reproduce the experimental observables of these 2^- bands well. It was also predicted that strong non-axial octupole effects may persist up to element 108 [20] and play a crucial role in determining shell stability in even heavier nuclei [29]. Pronounced shell effects were also found for $N = 16, 40$, and 110 when combining non-axial octupole deformations [30].

In this Brief Report, we present a microscopic and self-consistent study of Y effects in $N = 150$ isotones within the framework of covariant density functional theory (CDFT) [31–36]. We employ the recently developed multi-dimensional constraint (MDC) CDFT [37, 38], which breaks both axial [39, 40] and reflection symmetries [41]. For the parametrization of nuclear shape, we adopt the conventional ansatz from mean-field calculations $R = (3/AR^{\lambda}) Q$, where $Q = r^{\lambda} Y$ is the mass multipole operator. In MDC-CDFT, the nuclear shape is assumed invariant under reversal of the x and y axes; i.e., the intrinsic symmetry group is V , and all shape degrees of freedom deformations with even λ are allowed. The CDFT functional can take one of four forms: meson-exchange or point-coupling nucleon interactions combined with either non-linear or density-dependent couplings [37, 38]. In the present work, pairing effects are treated using the BCS approximation with a separable pairing force [42–44].

II. Results and Discussion

A. Ground-State Properties

We first investigate the ground states of ^{252}Cm , ^{252}Cf , ^{252}Fm , and ^{252}No using the density-dependent point-coupling covariant density functional theory with the parameter set DD-PC1 in the particle-hole channel [46]. The quadrupole deformations β_2 , non-axial octupole deformations β_3 , hexadecapole deformations β_4 , and binding energies E_{cal} are listed in Table I. The non-axial quadrupole and axial octupole deformation parameters vanish for all these nuclei. As seen in Table I, the calculated binding energies agree very well with experimental

data. All four nuclei are well-deformed with quadrupole deformation parameters $\beta_2 \approx 0.3$ and hexadecapole deformations $\beta_4 \approx 0.1$. Superimposed on these large quadrupole and hexadecapole deformations, finite non-axial octupole deformation parameters β_3 are obtained for these $N = 150$ isotones.

TABLE I. The quadrupole deformation β_2 , non-axial octupole deformation β_3 , and hexadecapole deformation β_4 together with binding energies E_{cal} for the ground states of $N = 150$ nuclei calculated with DD-PC1. E_{depth} denotes the energy difference between the ground state and the point with $\beta_3 = 0$ in the potential energy curves shown in Fig. 1 [Figure 1: see original paper]. E_{exp} denotes experimental binding energies taken from [45]. All energies are in MeV.

Nucleus	β_2	β_3	β_4	E_{cal} (MeV)	E_{depth} (MeV)	E_{exp} (MeV)
^{212}Cm	0.296	0.020	0.126	-1847.932	0.034	-1847.819
^{212}Cf	0.299	0.037	0.111	-1857.853	0.351	-1857.776
^{212}Fm	0.293	0.034	0.097	-1865.843	0.328	-1865.520
^{212}No	0.293	0.025	0.083	-1872.133	0.104	-1871.305

B. Potential Energy Curves

To more clearly examine the development of non-axial octupole deformation along the $N = 150$ isotonic chain, we perform one-dimensional constrained calculations to obtain potential energy curves—the total binding energy as a function of β_3 . At each point on a potential energy curve, the energy is automatically minimized with respect to other shape degrees of freedom such as β_2 , β_4 , β_6 , and β_8 . Figure 1 [Figure 1: see original paper] shows the potential energy curves for these $N = 150$ isotones. For ^{212}Cm , the ground-state deformation is $\beta_3 = 0.020$ (see Fig. 1 and Table I). The potential energy curve is rather flat around the minimum. We denote the energy difference between the ground state and the point with $\beta_3 = 0$ as E_{depth} , which measures the energy gain from distortion. For ^{212}Cm , E_{depth} is only 34 keV. For ^{212}Cf , ^{212}Fm , and ^{212}No , the minima occur at $\beta_3 = 0.037$, 0.034, and 0.025, respectively, with corresponding energy gains $E_{\text{depth}} = 0.351$, 0.328, and 0.104 MeV.

It may be difficult to conclude from these results that these nuclei possess static non-axial octupole deformations because the potential energy curves are flat around the minima and E_{depth} values are small. However, the present calculations at least indicate strong Y -correlations in these nuclei. Both the non-axial octupole parameter β_3 and the energy gain E_{depth} reach maximum values at ^{212}Cf among the four nuclei along the $N = 150$ isotonic chain. This is consistent with the analysis in Refs. [20, 28] and with the experimental observation that the 2⁺ state in ^{212}Cf is the lowest among these nuclei.

FIG. 1. (Color online) The binding energy E (relative to the ground state) for $N = 150$ isotones ^{212}Cm (dashed line), ^{212}Cf (solid line), ^{212}Fm (long-dashed

line), and ${}^2{}^2\text{No}$ (dotted line) as a function of the non-axial octupole deformation parameter β_3 .

C. Microscopic Origin

Triaxial octupole Y effects stem from coupling between pairs of single-particle orbits with $\Delta j = \Delta l = 3$ and $\Delta K = 2$, where j and l are the total and orbital angular momenta of single particles, respectively, and K is the projection of j on the symmetry axis. If a nucleus' s Fermi surface lies close to such a pair of orbitals and these two orbitals are nearly degenerate, a strong non-axial octupole effect is expected.

Figure 2 [Figure 2: see original paper] shows the proton and neutron single-particle levels near the Fermi surface for ${}^2\text{Cf}$ as functions of quadrupole deformation β_2 (left panels) and of β_3 with β_2 fixed at 0.3 (right panels). In Fig. 2(a), a strong spherical shell closure appears at $Z = 92$. As discussed in Ref. [47], this shell closure is spurious and commonly predicted in relativistic mean-field calculations. The spherical proton orbitals $2f_{7/2}$ and $1i_{13/2}$ are very close to each other, and this near-degeneracy results in octupole correlations. The two proton levels $[521]3/2$ (originating from $2f_{7/2}$) and $[633]7/2$ (originating from $1i_{13/2}$) satisfy the $\Delta j = \Delta l = 3$ and $\Delta K = 2$ condition and remain very close as β_3 varies from 0 to 0.3. Consequently, non-axial octupole Y correlations develop, and an energy gap emerges at $Z = 98$ as β_3 increases from zero. The appearance of the spurious shell gap at $Z = 92$ arises mainly from the lowering of the $1h_{9/2}$ orbital, which also causes the proton $[514]7/2$ level to lie between $[521]3/2$ and $[633]7/2$, making the gap at $Z = 98$ smaller and weakening the Y correlation.

Similarly, the spherical neutron orbitals $2g_{7/2}$ and $1j_{13/2}$ are very close. The two neutron levels $[734]9/2$ (from $1j_{13/2}$) and $[622]5/2$ (from $2g_{7/2}$) are also near each other and lie just above and below the Fermi surface. This leads to the development of a gap at $N = 150$ as β_3 increases. Thus, the Y correlation in $N = 150$ isotones originates from both protons and neutrons, being most pronounced in ${}^2\text{Cf}$. The gap around $N = 150$ is larger than that around $Z = 98$, suggesting that the non-axial octupole effect from neutrons is stronger than that from protons. Without the spurious shell gap at $Z = 92$, even more pronounced non-axial octupole correlations from protons could be expected.

FIG. 2. (Color online) The single-particle levels near the Fermi surface for (a) protons and (b) neutrons in ${}^2\text{Cf}$ as functions of quadrupole deformation β_2 (left side) and of β_3 with β_2 fixed at 0.3 (right side).

D. Dependence on Energy Density Functionals

To examine the dependence of our results on the functional form and effective interaction, we also studied ${}^2\text{Cm}$, ${}^2\text{Cf}$, ${}^2\text{Fm}$, and ${}^2{}^2\text{No}$ using other covariant density functionals and several typical parameter sets: PC-PK1 [48], DD-ME1 [49], and DD-ME2 [50]. The results are listed in Table II.

TABLE II. The quadrupole deformation β_2 , octupole deformation β_3 , hexadecapole deformation β_4 , and binding energies E for the ground states of $N = 150$ nuclei calculated with parameter sets PC-PK1, DD-ME1, DD-ME2, and DD-PC1. E_{depth} denotes the energy difference between the ground state and the point constrained to $\beta_3 = 0$. All energies are in MeV.

Nucleus	Parameter Set	β_2	β_3	β_4	E (MeV)	E_{depth} (MeV)
^{2}Cm	PC-PK1	0.296	0.020	0.126	-1847.932	0.034
	DD-ME1	—	—	—	-1846.273	0.129
	DD-ME2	—	—	—	-1847.205	0.126
	DD-PC1	0.306	0.031	0.113	-1857.327	0.139
^{2}Cf	PC-PK1	0.299	0.035	0.107	-1857.718	0.278
	DD-ME1	0.300	0.039	0.105	-1857.088	0.474
	DD-ME2	0.299	0.037	0.111	-1857.853	0.351
	DD-PC1	0.302	0.029	0.098	-1865.301	0.128
^{2}Fm	PC-PK1	0.293	0.033	0.093	-1866.425	0.305
	DD-ME1	0.292	0.034	0.091	-1865.505	0.416
	DD-ME2	0.293	0.034	0.097	-1865.843	0.328
	DD-PC1	0.300	0.013	0.085	-1870.414	0.001
^{2}No	PC-PK1	0.293	0.023	0.080	-1873.412	0.089
	DD-ME1	0.292	0.024	0.078	-1872.235	0.125
	DD-ME2	0.293	0.025	0.083	-1872.133	0.104
	DD-PC1	—	—	—	-1846.662	0.125

Overall, the results are similar across different parameter sets: β_2 and β_4 vanish in all cases, and for a given nucleus, the calculated β_3 values and binding energies E agree across parametrizations. For ^{2}Cm , three parameter sets (PC-PK1, DD-ME1, and DD-ME2) predict $\beta_3 = 0$. With DD-PC1, a shallow potential energy curve with a minimum at $\beta_3 = 0.020$ is obtained, indicating very weak octupole correlation in ^{2}Cm .

Both the magnitude of β_3 and the energy gain E_{depth} from β_3 distortion indicate that density-dependent functionals produce stronger Y effects than functionals with non-linear self-coupling. Among the density-dependent functionals, the meson-exchange nucleon interaction with parameter set DD-ME2 yields the largest energy gain E_{depth} for ^{2}Cf , ^{2}Fm , and ^{2}No . The evolution of non-axial octupole effects along the $N = 150$ isotonic chain is nearly independent of the energy density functional form and parameter set: the Y effects are strongest in ^{2}Cf , except that DD-ME1 gives a smaller energy gain for ^{2}Cf than for ^{2}Fm .

III. Summary

In summary, we have studied non-axial octupole Y effects in the $N = 150$ isotones ^{2}Cm , ^{2}Cf , ^{2}Fm , and ^{2}No using multi-dimensional constrained covari-

ant density functional theories. Due to interactions between a pair of neutron orbitals ($[734]9/2$ from $j /$ and $[622]5/2$ from $g /$) and a pair of proton orbitals ($[521]3/2$ from $f /$ and $[633]7/2$ from $i /$), rather strong non-axial octupole Y effects have been found in ${}^2\text{Cf}$ and ${}^2\text{Fm}$, which are both well-deformed with large axial quadrupole deformations $\beta_2 \approx 0.3$. For ${}^2\text{Cm}$ and ${}^2\text{No}$, shallow minima develop along the deformation degree of freedom. The evolution of non-axial octupole effects along the $N = 150$ isotonic chain is not highly sensitive to the form of the energy density functional or the parameter set employed. Finally, we note that a nucleus with a very flat potential energy curve E may not possess a static non-axial octupole deformation. The ground-state wave function should be a strongly correlated superposition of different shapes with similar energies. This suggests that further investigations of these nuclei should incorporate beyond-mean-field effects using, for example, the generator coordinate method [16, 51].

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References

- [1] K. Starosta, T. Koike, C. J. Chiara, D. B. Fossan, D. R. LaFosse, A. A. Hecht, C. W. Beausang, M. A. Caprio, J. R. Cooper, R. Krucken, J. R. Novak, N. V. Zamfir, K. E. Zyromski, D. J. Hartley, D. L. Balabanski, J.-y. Zhang, S. Frauendorf, and V. I. Dimitrov, *Phys. Rev. Lett.* 86, 971 (2001).
- [2] S. W. Odegard, G. B. Hagemann, D. R. Jensen, M. Bergstroem, B. Herskind, G. Sletten, S. Toermaenen, J. N. Wilson, P. O. Tjom, I. Hamamoto, K. Spohr, H. Huebel, A. Goergen, G. Schoenwasser, A. Bracco, S. Leoni, A. Maj, C. M. Petrache, P. Bednarczyk, and D. Curien, *Phys. Rev. Lett.* 86, 5866 (2001).
- [3] J. Meng and S. Q. Zhang, *J. Phys. G: Nucl. Phys.* 37, 064025 (2010).
- [4] P. A. Butler and W. Nazarewicz, *Rev. Mod. Phys.* 68, 349 (1996).
- [5] I. Hamamoto, B. Mottelson, H. Xie, and X. Z. Zhang, *Z. Phys. D* 21, 163 (1991).
- [6] J. Skalski, *Phys. Rev. C* 43, 140 (1991).
- [7] X. Li and J. Dudek, *Phys. Rev. C* 49, R1250 (1994).

- [8] J. Dudek, A. Gozdz, Mazur, H. Molique, K. Rybak, and B. Fornal, *J. Phys. G: Nucl. Phys.* 37, 064032 (2010).
- [9] J. Dudek, A. Gozdz, N. Schunck, and M. Miskiewicz, *Phys. Rev. Lett.* 88, 252502 (2002).
- [10] J. Dudek, A. Gozdz, and N. Schunck, *Acta Phys. Pol. B* 34, 2491 (2003).
- [11] J. Dudek, J. Dobaczewski, N. Dubray, A. Gozdz, V. Pangon, and N. Schunck, *Int. J. Mod. Phys. E* 16, 516 (2007).
- [12] N. Schunck, J. Dudek, A. Gozdz, and P. H. Regan, *Phys. Rev. C* 69, 061305(R) (2004).
- [13] J. Dudek, D. Curien, N. Dubray, J. Dobaczewski, V. Pangon, P. Olbratowski, and N. Schunck, *Phys. Rev. Lett.* 97, 072501 (2006).
- [14] M. Yamagami, K. Matsuyanagi, and M. Matsuo, *Nucl. Phys. A* 693, 579 (2001).
- [15] P. Olbratowski, J. Dobaczewski, P. Powalowski, M. Sadziak, and K. Zberecki, *Int. J. Mod. Phys. E* 15, 333 (2006).
- [16] K. Zberecki, P.-H. Heenen, and P. Magierski, *Phys. Rev. C* 79, 014319 (2009).
- [17] S. Takami, K. Yabana, and M. Matsuo, *Phys. Lett. B* 431, 242 (1998).
- [18] K. Zberecki, P. Magierski, P.-H. Heenen, and N. Schunck, *Phys. Rev. C* 74, 051302(R) (2006).
- [19] Z.-C. Gao, Y.-S. Chen, and J. Meng, *Chin. Phys. Lett.* 21, 806 (2004).
- [20] Y.-S. Chen, Y. Sun, and Z.-C. Gao, *Phys. Rev. C* 77, 061305(R) (2008).
- [21] R. A. Bark, J. F. Sharpey-Schafer, S. M. Maliage, T. E. Madiba, F. S. Komati, E. A. Lawrie, J. J. Lawrie, R. Lindsay, P. Maine, S. M. Mullins, S. H. T. Murray, N. J. Ncapayi, T. M. Ramashidza, F. D. Smit, and P. Vymers, *Phys. Rev. Lett.* 104, 022501 (2010).
- [22] M. Jentschel, W. Urban, J. Krempel, D. Tonev, J. Dudek, D. Curien, B. Lauss, G. de Angelis, and P. Petkov, *Phys. Rev. Lett.* 104, 222502 (2010).
- [23] R.-D. Herzberg, P. T. Greenlees, P. A. Butler, G. D. Jones, M. Venhart, I. G. Darby, S. Eeckhaudt, K. Eskola, T. Grahn, C. Gray-Jones, F. P. Hessberger, P. Jones, R. Julin, S. Juutinen, S. Ketelhut, W. Korten, M. Leino, A.-P. Leppanen, S. Moon, M. Nyman, R. D. Page, J. Pakarinen, A. Pritchard, P. Rahkila, J. Saren, C. Scholey, A. Steer, Y. Sun, C. Theisen, and J. Uusitalo, *Nature* 442, 896 (2006).
- [24] Z.-H. Zhang, J.-Y. Zeng, E.-G. Zhao, and S.-G. Zhou, *Phys. Rev. C* 83, 011304(R) (2011), arXiv:1101.3607 [nucl-th].

- [25] Z.-H. Zhang, X.-T. He, J.-Y. Zeng, E.-G. Zhao, and S.-G. Zhou, *Phys. Rev. C* 85, 014324 (2012), arXiv:1110.6134 [nucl-th].
- [26] Z.-H. Zhang, J. Meng, E.-G. Zhao, and S.-G. Zhou, “Rotational properties of the superheavy nucleus ^{212}Rf in particle-number conserving cranked shell model,” arXiv:1208.1156v1 [nucl-th] (2012).
- [27] A. P. Robinson, T. L. Khoo, I. Ahmad, S. K. Tandel, F. G. Kondev, T. Nakatsukasa, D. Seweryniak, M. Asai, B. B. Back, M. P. Carpenter, P. Chowdhury, C. N. Davids, S. Eeckhaudt, J. P. Greene, P. T. Greenlees, S. Gros, A. Heinz, R.-D. Herzberg, R. V. F. Janssens, G. D. Jones, T. Lauritsen, C. J. Lister, D. Peterson, J. Qian, U. S. Tandel, X. Wang, and S. Zhu, *Phys. Rev. C* 78, 034308 (2008).
- [28] R. V. Jolos, L. A. Malov, N. Y. Shirikova, and A. V. Sushkov, *J. Phys. G: Nucl. Part. Phys.* 38, 115103 (2011).
- [29] Y. Chen et al., submitted to *Phys. Rev. Lett.*
- [30] W. D. Heiss, R. A. Lynch, and R. G. Nazmitdinov, *Phys. Rev. C* 60, 034303 (1999).
- [31] B. D. Serot and J. D. Walecka, *Adv. Nucl. Phys.* 16, 1 (1986).
- [32] P. G. Reinhard, *Rep. Prog. Phys.* 52, 439 (1989).
- [33] P. Ring, *Prog. Part. Nucl. Phys.* 37, 193 (1996).
- [34] M. Bender, P.-H. Heenen, and P.-G. Reinhard, *Rev. Mod. Phys.* 75, 121 (2003).
- [35] D. Vretenar, A. Afanasjev, G. Lalazissis, and P. Ring, *Phys. Rep.* 409, 101 (2005).
- [36] J. Meng, H. Toki, S. G. Zhou, S. Q. Zhang, W. H. Long, and L. S. Geng, *Prog. Part. Nucl. Phys.* 57, 470 (2006), arXiv:nucl-th/0508020.
- [37] B.-N. Lu, E.-G. Zhao, and S.-G. Zhou, *Phys. Rev. C* 85, 011301(R) (2012), arXiv:1110.6769 [nucl-th].
- [38] B.-N. Lu, E.-G. Zhao, and S.-G. Zhou, in preparation.
- [39] J. Meng, J. Peng, S. Q. Zhang, and S.-G. Zhou, *Phys. Rev. C* 73, 037303 (2006), arXiv:nucl-th/0510071.
- [40] B.-N. Lu, E.-G. Zhao, and S.-G. Zhou, *Phys. Rev. C* 84, 014328 (2011), arXiv:1104.4638 [nucl-th].
- [41] L.-S. Geng, J. Meng, and H. Toki, *Chin. Phys. Lett.* 24, 1865 (2007).
- [42] Y. Tian, Z. Ma, and P. Ring, *Phys. Lett. B* 676, 44 (2009).
- [43] Y. Tian, Z.-y. Ma, and P. Ring, *Phys. Rev. C* 80, 024313 (2009).

- [44] T. Niksic, P. Ring, D. Vretenar, Y. Tian, and Z.-y. Ma, Phys. Rev. C 81, 054318 (2010).
- [45] G. Audi and M. Wang, Private Communication, AME2011.
- [46] T. Niksic, D. Vretenar, and P. Ring, Phys. Rev. C 78, 034318 (2008).
- [47] L.-S. Geng, J. Meng, H. Toki, W.-H. Long, and G. Shen, Chin. Phys. Lett. 23, 1139 (2006).
- [48] P. W. Zhao, Z. P. Li, J. M. Yao, and J. Meng, Phys. Rev. C 82, 054319 (2010).
- [49] T. Niksic, D. Vretenar, P. Finelli, and P. Ring, Phys. Rev. C 66, 024306 (2002).
- [50] G. A. Lalazissis, T. Niksic, D. Vretenar, and P. Ring, Phys. Rev. C 71, 024312 (2005).
- [51] J. M. Yao, J. Meng, P. Ring, and D. Vretenar, Phys. Rev. C 81, 044311 (2010).

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