Abstract. We studied tensor-force effects on nuclear shell structures by mean-field calculations. We have found that the tensor force affects single-particle energies of nuclei, for example, F and Sb isotopes, in interesting ways different from what the spin-orbit force produces.

The novel effects of the tensor force on single-particle properties have been pointed recently [1]. In this study, tensor-force effects are investigated by means of mean-field calculations with a new Gogny-type interaction, called “GT2” [2]. The GT2 includes a tensor force explicitly, and the other parameters are adjusted to reproduce properties of nuclear matter and binding energies of $^{16}\text{O}$, $^{40}\text{Ca}$, $^{48}\text{Ca}$, $^{56}\text{Ni}$, $^{132}\text{Sn}$ and $^{208}\text{Pb}$. Our calculations are carried out within the spherical Hartree-Fock method with the gradient method[3]. We shall compare results obtained from GT2 with those from D1S [4] which is the traditional parameter set of the Gogny force. We shall discuss several phenomena for which usual mean-field calculations encounter some difficulties to describe. Unlike other frequently used mean-field interactions, GT2 can provide us with unusual behaviors of single-particle energies in both stable and unstable nuclei. They are subject to the repulsive tensor-force effect between $j_\gamma = l + 1/2$ and $j'_\gamma = l' + 1/2$ (or $j_\gamma = l - 1/2$ and $j'_\gamma = l' - 1/2$), or the attractive one between $j_\gamma$ and $j'_\gamma$ (or $j_\gamma$ and $j'_\gamma$) [1].

In $^{51}\text{Sb}$ isotopes, the experiment in Ref.[5] indicates that the energy gap between proton $11/2^-$ and $7/2^+$ states becomes wider with the neutron excess. This behavior of the energy gap from $N = 64$ to $N = 82$ is reproduced by GT2 as primarily a tensor-force effect, consistently with the previous shell model study [1]. As shown in Fig. 1, the result obtained with GT2 shows a good agreement with the experimental data. In this case, the repulsive tensor-force effect between proton $1h_{11/2}$ and neutron $1h_{11/2}$ and the attractive effect between proton $1h_{11/2}$ and neutron $1g_{7/2}$ produce such widening of the energy gap. As the neutron number increases, the D1S result shows an increase from $N = 94$ to $N = 104$ as a neutron-skin effect. The tensor-force effect in this case vanishes because both proton $1h_{11/2}$ and $1h_{9/2}$ are occupied, ending up with spin-saturation.

One of the most recent results is on the proton single-particle states in F isotopes, where the energy gap between the first $3/2^+$ state and the first $5/2^+$ state decreases from 5.00 MeV to 4.06 MeV, when the neutron number increases from $N = 8$ to $N = 14$[6]. The shell-model calculation with the most recent effective interaction, SDPF-M [7], actually overestimates this decrease [6]. As the tensor-force works between a proton in $1d_{3/2}$ and neutrons in $1d_{3/2}$, the proton $1d_{3/2}$ single-particle level is expected to come down. This effect is seen in Fig. 2 (b)
for the GT2 result, whereas not in Fig. 2 (a) for the D1S result. Thus, the decrease can be understood naturally with the tensor force.

The next question is why the decrease is smaller than expected from the simple tensor effect. We now answer to this question. Figure 2 (a) shows also the change of proton $1d_{5/2} - 1d_{3/2}$ gap due to the 2-body spin-orbit force (shown as LS in the figure). This LS effect increases the gap by 2 MeV from $N=8$ to $N=14$. The neutron skin is supposed to decrease this gap. However, the proton $1d_{3/2}$ orbit is unbound in $^{17}$F, and its resonance state appears at lower excitation energy than what one can expect if it were bound. As more neutrons are added, the $1d_{3/2}$ orbit becomes more bound, and the gap $1d_{5/2} - 1d_{3/2}$ is enlarged, maybe even to a value exceeding the normal one. This addition is 2-3 MeV. Since this effect is not included in shell model calculations, it must be added to the shell model result. Since the tensor force is already included in the SDPF-M interaction to a good extent, the origin of the discrepancy between shell model calculations and experiment seems to be in the enlargement of $1d_{5/2} - 1d_{3/2}$ splitting by the 2-body LS force. In fact, in a naive picture, as shown in Fig. 2 (b), the $5/2^+ - 3/2^+$ gap decreases by about 1 MeV from $N=8$ to 14 with GT2 consistently with the experiment, whereas it increases by about 2 MeV with D1S. This difference is basically due to the tensor force. Certainly, this is a very naive picture, and more details should be investigated.

In the next step, we will take into account paring correlation and deformation for the purpose of further investigations of the tensor-force effect in nuclei.

Figure 1. Evolution of proton $1h_{11/2}$ and $1g_{7/2}$ energy gap, starting from $N = 64$. Proton $3s_{1/2}$, $2d_{5/2}$ and $1h_{11/2}$ are assumed to be degenerate.

Figure 2. Change of proton $1d_{5/2} - 1d_{3/2}$ gap, starting from $N = 8$. Contributions of central potential+kinetic energy, LS force and tensor force are separately shown.

[1] T. Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005).
[2] T. Matsuo, Ph. D. Thesis, University of Tokyo (2004).
[3] H. J. Mang et al., Z. Phys. A279 (1976) 325.
[4] J. F. Berger et al., Nucl. Phys. A428 (1984) 23c.
[5] J. P. Schiffer et al., Phys. Rev. Lett. 92, 162501 (2004).
[6] S. Michimasa et al., Phys. Lett. B 638, 146.
[7] Y. Utsuno et al., Phys. Rev. C 60, 054315 (1999); Y. Utsuno et al., Phys. Rev. C 70, 044307 (2004).