Vol. 36 (2005) ACTA PHYSICA POLONICA B No 4

EVOLUTION OF SHELL AND COLLECTIVE STRUCTURES IN EXOTIC NUCLEI*

T. Otsuka[a,b,c], T. Suzuki[d], R. Fujimoto[a], T. Matsuo[a], D. Abe[a]
H. Grawe[e] and Y. Akaishi[f]

[a]Department of Physics, University of Tokyo, Tokyo, Japan
[b]Center for Nuclear Study (CNS), University of Tokyo, Tokyo, Japan
[c]RIKEN Wako, Saitama, Japan
[d]Nihon University, Tokyo, Japan
[e]GSI Darmstadt, Germany
[f]KEK Tsukuba, Japan

(Received December 16, 2004)

The evolution of shell structure in exotic nuclei due to the tensor interaction is discussed. It will be suggested that the tensor interaction can change the shell structure, for instance, by varying the spin–orbit splitting considerably as a function of N and Z.

PACS numbers: 21.10.Pc, 21.30.–x, 21.60.Cs

1. Introduction

We shall discuss, in this talk, on the single-particle structure of exotic nuclei, indicating that the shell structure can be varied in going from stable to exotic nuclei and such changes can be strongly related to certain properties of the nucleon–nucleon (NN) interaction. This paradigm, referred to as shell evolution [1, 2], should play one of the key roles in determining structure of exotic nuclei.

The nuclear shell model has been conceived by Mayer and Jensen by identifying its magic numbers and their origin [3]. The study of nuclear structure has been advanced on the basis of the shell structure thus proposed. In stable nuclei, the magic numbers suggested by Mayer and Jensen remain valid, and the shell structure can be understood well in terms of the harmonic oscillator potential with a spin-orbit splitting. Recently, studies on exotic nuclei far from the β-stability line have been started owing to development of radioactive nuclear beams, as discussed extensively in the this conference.

* Presented at the XXXIX Zakopane School of Physics — International Symposium "Atomic Nuclei at Extreme Values of Temperature, Spin and Isospin", Zakopane, Poland, August 31–September 5, 2004.

If single-particle energies are calculated by the Woods–Saxon potential, they change as the proton number (Z) or the neutron number (N) varies. In this case, the single-particle energies are shifted basically in parallel, keeping their relative energies (or mutual differences of the energies) almost unchanged. This kind of change is due to the variation of the potential radius depending on $A(= N+Z)$ and/or the shift of the potential depth associated with N/Z asymmetry. Note that, even with the Woods–Saxon potential, the relative energies can be changed near drip lines owing to varying influences of the centrifugal potential, but such changes are not the subject of this talk.

The shell evolution suggested in [1,2] means that, as N and/or Z changes, such relative energies can vary rather significantly due to the NN interaction, without approaching the dripline. If this energy change becomes sufficiently significant, even the shell gap can nearly disappear or a spin–orbit splitting may be reduced.

2. Proton–neutron spin-flip interaction and the shell evolution

The shell evolution has been discussed in the p-shell and sd-shell already [1]. In order to understand it, we use effective single-particle energies (ESPE's) which include monopole effects from valence nucleons [4–6]. Usually, the naive filling configuration is assumed to calculate ESPE's. If relevant ESPE's change significantly, it is called the shell evolution. The shell evolution discussed so far is shown to occur due to a common mechanism related to the spin-isospin dependent NN interaction, *i.e.*, a strong attraction between a proton and a neutron in the spin-flip partner orbits [1]. To be more concrete, if a proton is in $j_{>}= l+1/2$ and a neutron is in $j_{<}= l-1/2$ (or vice versa), they attract each other. This means that, as the proton $j_{>}$ orbit is filled, the neutron $j_{<}$ orbit is lowered and its ESPE becomes smaller.

The major origin of this spin-flip isospin-flip interaction turned out to be the tensor interaction. We shall start to discuss it now.

3. Tensor interaction and the shell evolution

It is well-known that the one-pion exchange process produces a tensor interaction. The tensor interaction can be written as

$$V_{\mathrm{T}} = \left([\vec{s_1}\vec{s_2}]^{(2)} \cdot Y^{(2)} \right) f(r)\,, \tag{1}$$

where $\vec{s}_{1,2}$ denotes the spin of nucleon 1 and 2, $[\;]^{(L)}$ means the coupling of two operators in the brackets to an angular momentum (or rank) L, Y implies the spherical harmonics for the relative orientation, and the symbol $(\,\cdot\,)$ means a scalar product.

Here, $f(r)$ is a function of the relative distance, r between the two nucleons. For the one-pion exchange process, the function $f(r)$ has been well-known.

We investigate how the (spherical) single-particle levels are shifted by the tensor interaction as other orbits are occupied. Since these single-particle levels are spherical ones, the monopole component of the interaction is responsible. In other words, we extract the following two-body matrix elements from a general interaction (similarly to the first type of the shell evolution [1]):

$$V^T_{j_1, j_2} = \frac{\sum_J (2J+1) \langle j_1\, j_2 | V | j_1\, j_2 \rangle_{JT}}{\sum_J (2J+1)}\,, \tag{2}$$

where $\langle j_1\, j_2 | V | j_1'\, j_2' \rangle_{JT}$ stands for the matrix element of V coupled to an angular momentum J and an isospin T. Here, J takes only values satisfying antisymmetrization. We then construct a two-body interaction, called V_{M} which is comprised of two-body matrix elements defined by the above equation. Apparently, this interaction, V_{M}, is monopole, and it represents the angular-averaged, *i.e.*, monopole property of the original interaction, V, which is the tensor interaction in the present case.

In this talk, we discuss situations shown in Fig. 1. Namely, protons are in either $j'_> = l' + 1/2$ or $j'_< = l' - 1/2$, while neutrons are in either $j_> = l + 1/2$ or $j_< = l - 1/2$. We further assume that proton and neutron orbits are of opposite parities. In Fig. 1, neutrons are in the shell just above the proton shell. The generalization of this is straightforward, but we remain in this situation.

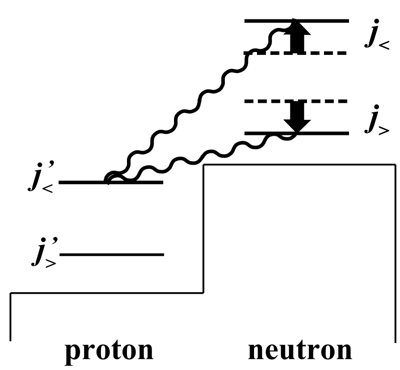

Fig. 1. Schematic picture of the monopole interaction produced by the tensor interaction. The wavy lines are monopole interactions with opposite effects.

With V being the tensor interaction, the following identity was found,

$$(2j_> + 1)\, V^T_{j'\,j_>} + (2j_< + 1)\, V^T_{j'\,j_<} = 0, \quad \text{for } T = 0 \text{ and } 1\,, \tag{3}$$

where j' is either $j'_>$ or $j'_<$. Note that $V^{T=0}_{j\,j'} = 3 \times V^{T=1}_{j\,j'}$.

This identity means that the tensor monopole interaction between proton $j'_<$ and neutron $j_>$ has the opposite effect to that between proton $j'_<$ and neutron $j_<$ (see Fig. 1). The same property holds for other but similar combinations of the orbits. For instance, in the closed (sub-) shell picture, the proton $p_{1/2}$ is empty in C isotopes, whereas fully occupied in O isotopes. In the latter case, this tensor monopole pulls down the neutron $d_{5/2}$ orbit, becoming the major reason for the $s_{1/2}$-$d_{5/2}$ inversion between C and O, and affecting the stability of N=14 subshell.

Here, one needs another argument to determine the sign of the effect. This can be given in an intuitive way. In the case that a nucleon on $j_>$ is colliding with another on $j'_<$, due to high relative momentum, the spatial wave function of their relative motion is narrowly distributed in the direction of the collision which is basically the direction of the orbital motion. The spins of two nucleons are parallel, giving rise to S=1 basically. Thus, the spatial distribution is narrower in the direction perpendicular to the composite spin S=1. From the analogy to the deuteron, the tensor force works attractively. The same mechanism holds for two nucleons in $j_<$ and $j'_>$. On the other hand, the tensor produces a repulsive effect for two nucleons in $j_>$ and $j'_>$ (or vice versa).

After this mechanism had been found, there have been many numerical works to assess the effects with $\pi + \rho$ or G-matrix potential. Several experimental cases have been noticed [9]. These will be published soon [11], although some of them were presented in the talk. We also mention that predictions can be made based upon the above mechanism [11]. For instance, as shown in Fig. 2 the spin-orbit splitting of the $d_{5/2}$ and $d_{3/2}$ of protons becomes smaller from ^{40}Ca to ^{48}Ca [12]. This is a combined effect of the attraction between proton $d_{3/2}$ and neutron $f_{7/2}$ and the repulsion between proton $d_{5/2}$ and neutron $f_{7/2}$.

Similarly, it is predicted that the $Z = 28$ gap of protons in the pf-shell becomes smaller from ^{68}Ni to ^{78}Ni, as shown in Fig. 3. This is again a combined effect of the attraction between proton $f_{5/2}$ and neutron $g_{9/2}$ and the repulsion between proton $f_{7/2}$ and neutron $g_{9/2}$.

The $N = 51$ isotones provide us with another example. As the proton number increases from $Z = 40$ to 50, the $1g_{9/2}$ orbit is filled by protons. These protons pull, through the tensor interaction, the neutron $1g_{7/2}$ orbit, whereas the neutron $1h_{11/2}$ orbit is pushed up, as shown in Fig. 4.

It should be mentioned also that the inversion between the neutron $d_{5/2}$ and $s_{1/2}$ orbits in moving between carbon and oxygen isotopes [10] is also largely related to the tensor interaction. A recent shell model calculation for carbon isotopes has succeeded in explaining small $B(\mathrm{E2})$ value of ^{16}C, owing partly to this mechanism.

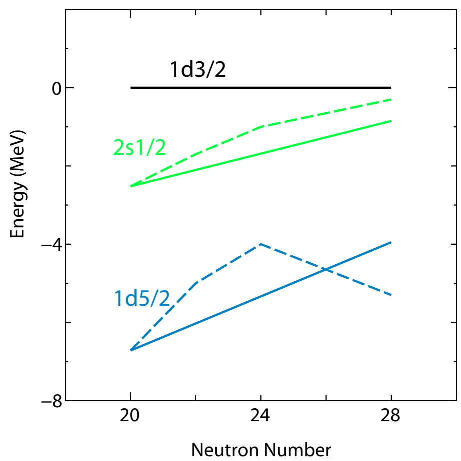

Fig. 2. Proton single-particle energies in Ca isotopes as a function of the neutron number. The values are relative to that of $1d_{3/2}$, and their changes due to the tensor interaction are shown by solid lines, starting from experimental ones for ^{40}Ca. Experimental values reported in [12] are plotted by dashed lines.

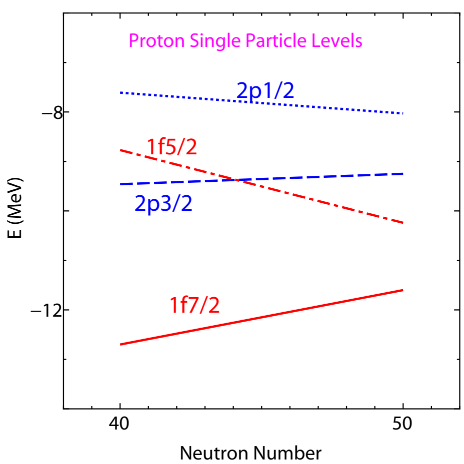

Fig. 3. Proton single-particle energies in exotic Ni isotopes as a function of the neutron number. The single-particle energies obtained for ^{68}Ni by the GXPF1 interaction are used for $N = 40$. These energies changed by the tensor interaction are shown.

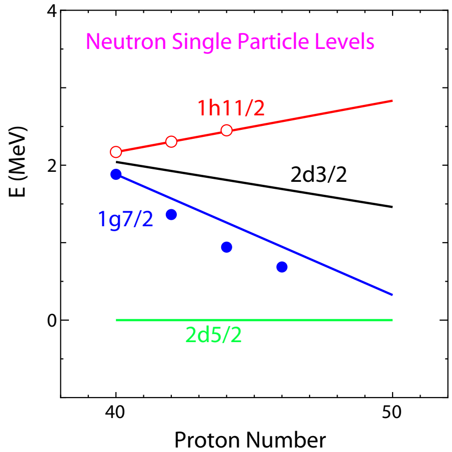

Fig. 4. Neutron single-particle energies in $N = 51$ isotones as a function of the proton number, starting from experimental values at $Z = 40$. The energies are shown relative to the $2d_{5/2}$ level. Changes due to the tensor interaction are shown by solid lines. Experimental excitation energies are also plotted.

4. Summary and perspectives

In summary, we discussed two mechanisms of the shell evolution. As the second mechanism of the shell evolution, we mentioned the tensor interaction. The tensor interaction can change crucially the shell structure of exotic nuclei [11]. The significant role of the tensor interaction as rather direct effects of π and ρ mesons seems to be related to the Chiral Perturbation idea of Weinberg [13]. The $1/N_c$ expansion of QCD supports also the importance of the tensor interaction [14]. Although the tensor effect on the mean field was discussed, for instance, in [15] with the δ-function type tensor interaction leading to a rather different conclusion, the finiteness of the interaction should be important.

The origin of the spin-flip isospin-flip interaction has been discussed in terms of the $\tau\tau\sigma\sigma$ interaction [1,2]. The tensor and $\tau\tau\sigma\sigma$ interactions indeed have quite similar monopole properties within one major shell. However, since the tensor interaction is much stronger than the $\tau\tau\sigma\sigma$ interaction, the major origin of the spin-flip isospin-flip monopole interaction should be the tensor interaction. This point has been studied quite extensively in a recent shell model study with the GXPF1 interaction and its revision [16, 17]. We also point out that the spin-flip isospin-flip property of the $\tau\tau\sigma\sigma$ interaction is for one major shell, whereas the tensor interaction has its distinct property also between two shells, as is the case in Fig. 1.

We point out also that the tensor effect and neutron skin effect are comparable.

This work has been a part of the RIKEN-CNS joint research project on large-scale nuclear-structure calculations. This work was supported in part by a Grant-in-Aid for Specially Promoted Research (13002001) from the MEXT.

REFERENCES

[1] T. Otsuka, R. Fujimoto, Y. Utsuno, B.A. Brown, M. Honma, T. Mizusaki, *Phys. Rev. Lett.* **87**, 082502 (2001).

[2] T. Otsuka, *Prog. Theor. Phys. Suppl.* **146**, 6 (2002).

[3] M.G. Mayer, *Phys. Rev.* **75**, 1969 (1949); O. Haxel, J.H.D. Jensen, H.E. Suess, *Phys. Rev.* **75**, 1766 (1949).

[4] R.K. Bansal, J.B. French, *Phys. Lett.* **11**, 145 (1964).

[5] A. Poves, A. Zuker, *Phys. Rep.* **70**, 235 (1981).

[6] Y. Utsuno, T. Otsuka, T. Mizusaki, M. Honma, *Phys. Rev.* **C60**, 054315 (1999).

[7] M. Hjorth-Jensen, T.T.S. Kuo, E. Osnes, *Phys. Rep.* **261**, 125 (1995).

[8] T. Suzuki, R. Fujimoto, T. Otsuka, *Phys. Rev.* **C67**, 044302 (2003).

[9] H. Grawe *et al.*, *Nucl. Phys.* **A704**, 211 (2002).

[10] H. Grawe, *Acta Phys. Pol. B* **34**, 2264 (2003).

[11] T. Otsuka, T. Suzuki, R. Fujimoto, H. Grawe, Y. Akaishi, to be published.

[12] P.D. Cottle, K.W. Kemper, *Phys. Rev.* **C58**, 3761 (1998).

[13] S. Weinberg, *Phys. Lett.* **B251**, 288 (1990).

[14] D.B. Kaplan, A.V. Manohar, *Phys. Rev.* **C56**, 76 (1997).

[15] Fl. Stancu, D.M. Brink, H. Flocard, *Phys. Lett.* **B68**, 108 (1977).

[16] M. Honma, T. Otsuka, B.A. Brown, T. Mizusaki, *Phys. Rev.* **C65**, 061301(R) (2002).

[17] M. Honma, T. Otsuka, B.A. Brown, T. Mizusaki, *Phys. Rev.* **C69**, 034335 (2004).