Establishing the dominance of the closed-shell configuration in ^{54}Ca

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One of the interesting properties of nuclei far from β stability is the modification of the shell structure. For stable nuclei, the conventional nuclear magic numbers, 2, 8, 20, 28, 50, 82, are known to occur. These numbers arise from the shell structure produced by the Woods-Saxon (or harmonic-oscillator) potential with a strong spin-orbit interaction introduced. For unstable nuclei, on the other hand, it is known that some of those magic numbers disappear and that new magic numbers emerge instead. For instance, the N=20 magic number breaks down for neutron-rich nuclei around ^{32}Mg, whose first excited levels are much lower than those of other N=20 isotones. It is also widely accepted that a new magic number N=16 appears for ^{24}O on the basis of its high first excited level and the large binding energy compared to surrounding nuclei.

What is the driving force of such changing shell structure in neutron-rich nuclei? One of the most probable candidates is the tensor force [1]. The tensor force provides attraction between a proton in the $j_>$ orbital (j=l+1/2) and a neutron in the $j'_<$ orbital (j'=l'-1/2), and also repulsion between a proton in the $j_>$ orbital and a neutron in the $j'_>$ orbital. Therefore, as the proton $j_>$ orbital is filled, the spin-orbit splitting of the neutron l' orbitals reduces. In other words, the neutron spin-orbit splitting is enhanced with decreasing protons in the $j_>$ orbital. One of the actual cases is presented in Fig. 1. Since Ca isotopes have almost no proton fractions in the $f_{7/2}$ orbital, their neutron spin-orbit splitting is predicted to be larger than that of Ni isotopes, thus locating the neutron $f_{5/2}$ orbital high and producing new subshell gaps (or magic numbers if they are large enough) at N=32 and N=34.

The occurrence of the N=34 magic number in neutron-rich nuclei was proposed in 2001 [2]. While the existence of the large shell gap at N=32 was found in the 1980s, no experimental information on the shell gap at N=34 had been available until the measurement of the first excited level in ^{54}Ca was reported in 2013 [3]. The measured quantity, 2.04 MeV, is larger than that of singly-magic nuclei such as ^{42,44,46,50}Ca, but is smaller than that of doubly magic nuclei ^{40,48}Ca. Although the occurrence of a new magic number N=34 was concluded in Ref. [3], more experimental information is needed to establish its magic nature.

The most direct way to prove the magic nature is, by definition, to show the dominance of the closed-shell configuration. This

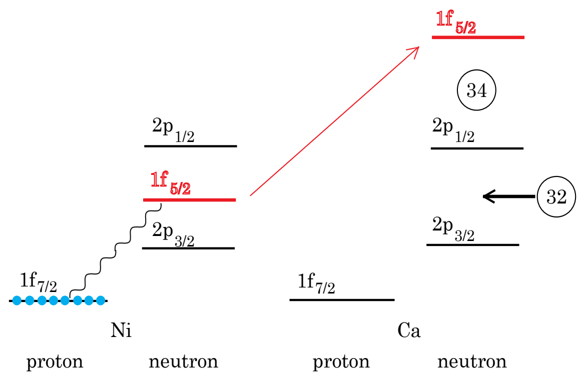

Fig. 1 Schematic illustration of the appearance of the N=32 and N=34 magic numbers in Ca isotopes due to the tensor force. Taken from [1].

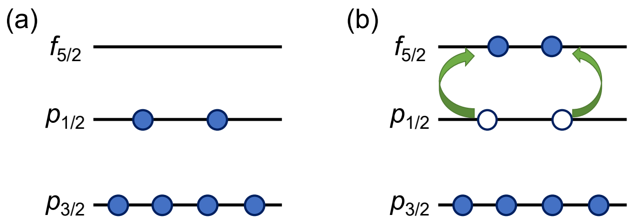

Fig. 2 Illustration of the neutron (a) closed-shell and (b) 2p-2h excited configurations for ^{54}Ca.

idea is realized in Ref. [4] using a single-neutron knockout reaction ^{54}Ca(p, pn)^{53}Ca performed at RIBF in RIKEN in combination with up-to-date nuclear reaction and structure theories. This experiment is a part of the SEASTAR campaign that aims at probing changing shell structures in neutron-rich nuclei, and our theory group is deeply involved in submitting the experimental proposal [5]. The outline of this study is illustrated in Fig. 2. If one assumes the ground state of ^{54}Ca is composed of the closed-shell configuration alone, either a neutron in $p_{1/2}$ or $p_{3/2}$ can be knocked out for producing low-lying states of ^{53}Ca [see Fig. 2(a)]. On the other hand, an $f_{5/2}$ neutron can be knocked out from the configuration with 2p-2h excitations involved [see Fig. 2(b)], which mostly goes to the $5/2^-_1$ state in ^{53}Ca. Thus, the cross section to produce the $5/2^-_1$ state is the key quantity to assessing the magic nature of ^{54}Ca.

Experimental details of this study are described in Ref. [3]. The measured cross section to produce the $5/2^-_1$ state is 1.0(3) mb. By using the reaction calculation based on the distorted wave impulse approximation (DWIA), this cross section is converted to the spectroscopic factor, which characterizes the occupation of the orbital of interest. The deduced spectroscopic factor C^2S=0.24(7) is in good agreement with that obtained from our shell-model calculation, C^2S=0.19, indicating the closed-shell probability 1-0.24(7)/2=0.88(4) derived under a simple but reasonable nuclear-structure assumption. The nearly ninety-percent close-shell probability thus derived is large enough to claim the occurrence of the new N=34 magic number in ^{54}Ca.

We stress that quantifying the spectroscopic factor and the closed-shell probability carried out in this study would be impossible without the highly descriptive power of the DWIA calculation. This theory has recently been extended to probing α clustering through the α knockout (p, $p\alpha$) reaction [6].

References

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