論文の内容の要旨

In-beam gamma-ray spectroscopy of ^{78}Ni
（^{78}Niのインビームガンマ線核分光）

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Our understanding of the atomic nucleus is largely built on the information collected on nuclei at and close to the valley of nuclear stability. More than a half century has passed since the magic numbers of nuclei were correctly described theoretically: when the number of either protons or neutrons is equal to 2, 8, 20, 28, 50, 82 or 126, nuclei, which exhibit a local maximum of stability, were found to have closed shells by introducing spin-orbit interactions. However, after the construction of accelerators to produce Radioactive Ion Beams created the opportunity to study nuclei very far from stability in an energy domain from rest to a few GeV/nucleon, magic numbers turned out not to be universal. Such phenomenon of disappearance of known shell closures and appearance of new ones, which is called shell evolution, influence the theoretical understanding of the nuclear interactions.

^{78}Ni, which has 28 protons ($Z = 28$) and 50 neutrons ($N = 50$), 14 additional neutrons bound from the last stable nickel isotope ^{64}Ni, is one of the most intriguing in the chart of nuclei. It is the most neutron-rich, exotic "doubly magic" nucleus that can be produced at present state-of-the-art facilities. So far, no spectroscopic information for ^{78}Ni was obtained. In this work, excited states of the most neutron-rich doubly magic isotope, ^{78}Ni, were investigated by means of in-beam γ-ray spectroscopy for the first time, taking advantage of the combination of detector devices, MINOS and DALI2, at the world's cutting-edge accelerator facility, RIBF at RIKEN, Japan. ^{79}Cu and ^{80}Zn beams were produced at BigRIPS spectrometer by in-flight fission of ^{238}U primary beam with an energy of 345 MeV/u accelerated by cyclotron complex. To achieve a high γ-ray yield, the detection system comprised of a 10 cm-thick liquid hydrogen target with a recoil proton tracking system, MINOS, and a surrounding NaI(Tl) based γ-ray detection array, DALI2. Eventually, 310 and 222 events with at least one detected γ-ray with more than 300 keV with the $(p,2p)$ and the $(p,3p)$ reactions, respectively, were obtained.

The ^{79}Cu$(p,2p)^{78}$Ni and ^{80}Zn$(p,3p)^{78}$Ni reaction channels were analyzed separately. From the γ-ray spectra, several transition candidates were observed. To resolve these transitions, the spectra were fitted by the response functions of the γ-ray detector, simulated by a Monte-Carlo based simulation package, GEANT4, by maximizing the likelihood with a multivariable probability density function. Six candidates of γ-ray peaks, five in the $(p,2p)$ reaction channel and one additionally in the $(p,3p)$ channel, were examined by significance levels calculated from a likelihood ratio test. Furthermore, a γ-γ coincidence analysis was performed. By summarizing the experimental facts of the intensity relationships, significance levels, and the γ-γ correlations, the following conclusions were achieved:

- The most intense γ-ray transitions at 2600(33) keV and 2910(43) keV for the $(p,2p)$ and the $(p,3p)$ channel, respectively, were confirmed with 7.6σ and 3.9σ significance levels.
- They were understood as the transitions from the first and second 2^+ states decaying directly to the ground state.
- According to the γ-γ coincidence analysis, the four other γ-ray transitions confirmed in the $(p,2p)$ channel do not decay directly to the ground state but passed through the 2^+_1 state.
- Additional γ-γ coincidence analysis, the intensity relationships, and the evaluated neutron separation energy $S_n = 5160(780)$ keV indicated that there are at least three bound excited states at 3180(55) keV, 3700(36) keV, and 5290(59) keV.
- The states at 2910(43) keV and 3980(46) keV, which were recognized only in the $(p,3p)$ channel, might have strong connection with the two proton knockout reaction.

The obtained experimental level scheme described above was compared with several state-of-the-art theoretical predictions, large-scale shell-model, mean-field, and *ab initio* calculations. While the first 2^+ state was reproduced well among these calculations, the second 2^+ state was explained only by two large-scale shell-model calculations with large model spaces for neutrons, full sdg shell above $N = 50$ gap. Both shell-model predictions indicate the 2^+_2 state is an "intruder" state with more than $2p$-$2h$ excitations for both proton and neutron configurations. While the ground and excited states observed in the $(p,2p)$ reaction are expected to be of spherical shape, the "intruder" states are supposed to be deformed states establishing rotational excitations. Thus, a shape-coexistence feature is emerging. In addition, the shell-closure of both proton and neutron is predicted to be quenched for more neutron-rich isotopes and isotones. Namely, ^{78}Ni is expected to be a nuclei at an anchor point against the deformation.

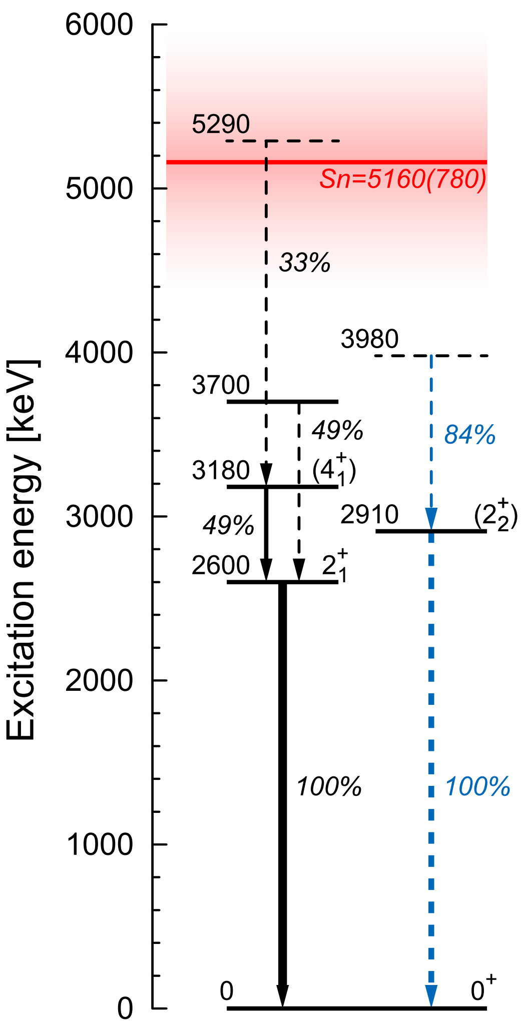

Fig. 1: Proposed level schemes of ^{78}Ni. The arrows represent the γ-ray transitions with their relative intensities to the intensity of the transition to the ground state. The black arrows are mainly observed in the $(p,2p)$ channel, while the blue arrows are from the $(p,3p)$ channel.

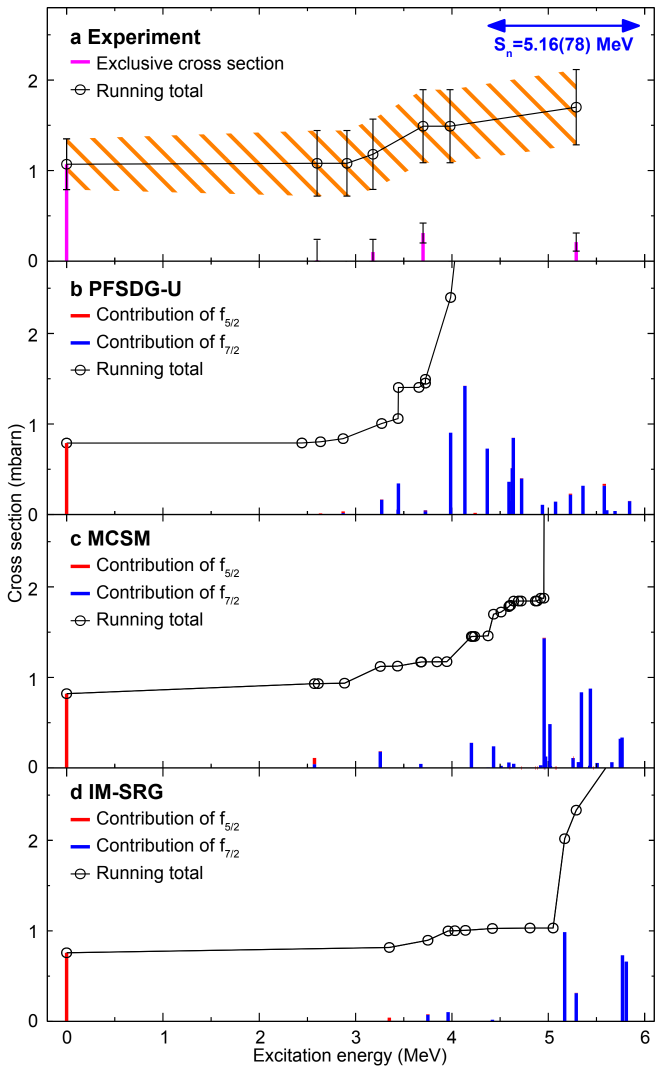

Fig. 2: Evolutions of the experimental and theoretical cross sections as a function of excitation energy for ^{79}Cu$(p,2p)^{78}$Ni reaction. Experimental cross sections and shell-model spectroscopic factors convoluted with DWIA single-particle cross sections are displayed.

Even though the "intruder" states were not reproduced by other calculations, this hypothesis is partially supported. The mean-field calculations agreed with the spherical feature of the ground state, but also suggested that the excited states cannot be depicted as a simple vibrational excitation but rather explained well with an assumption of a mixture with both vibrational and rotational degrees of freedom. Likewise, the *ab initio* computational results inferred that contributions from the $2p$-$2h$, $3p$-$3h$ and even more p-h excitations take important roles in the excited states. These explanations of the missing strengths underlined the possible shape-coexistence and shell-quenching phenomena towards nuclei far from the stability line.

The reaction cross sections to produce ^{78}Ni from ^{79}Cu and ^{80}Zn were turned out to be significantly lower than in neighbouring nuclei, 1.7(4) mb and 16(6) μb, respectively. A possible explanation is that the excitation energy after the knockout reactions is higher than the neutron separation energy, owing to a large shell gap at $Z = 28$ between $f_{5/2}$ and $f_{7/2}$ orbitals. In a naive picture of the nuclear reaction, while the final states after removing the proton in $f_{5/2}$ is preferred to be the ground state of ^{78}Ni, the knockout reaction from the $f_{7/2}$ orbit can be assumed to be several states with high excitation energies. To figure out the origin of such a low cross section in the $(p,2p)$ reaction, an advanced theoretical framework for calculating a quasi-free one nucleon knockout reaction was applied in combination with the spectroscopic factors of shell-model calculations. The theoretical results were in good agreement with the experimental cross sections: the ground and spherical excited states were favored, while the deformed states were not populated. Additionally, as it was expected, most of the cross sections after the reaction were found to feed states above the neutron separation energy threshold, which eventually evaporates one or more neutrons.

In summary, the spectroscopic study of ^{78}Ni was performed for the first time, and at least two excited 2^+ states and other higher lying states were found. This fact casts a question about the nature of the shell-closure in ^{78}Ni and the possible shape coexistence character in such an exotic nuclei apart from stability. Though the doubly magic nature was confirmed to be persistent, at the same time, the shell gap is anticipated to vanish beyond ^{78}Ni.